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Preliminary investigation into the fall-arresting effectiveness of ladder safety hoops

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RESEARCH REPORT 258

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Preliminary investigation into the fall-arresting effectiveness of ladder safety hoops

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Safety hoops are an assembly of circular and vertical steel bars that are fastened to the stiles of fixed ladders and are arranged so as to enclose the path of a worker when climbing the ladder. Ladders so enclosed are also known as caged or hooped ladders.

Various legislative and guidance documents specify safety hoops and give the impression that the purpose of the hoops is to protect workers from falling to the ground or other platform. Previous research has indicated that there is virtually a total lack of knowledge in regard to what ladder safety hoops are and do, and in conjunction with anecdotal accident evidence and a lack of test methods, uncertainties have been raised by persons conducting working at height risk assessments as to whether safety hoops can provide any form of fall-arresting capability.

The overall aim of this preliminary investigation was to update the current state of knowledge and understanding in regard to what ladder safety hoops actually are, what their intended purpose is, and to establish by preliminary testing whether or not they could provide any form of fall-arresting capability.

This investigation reports on: results of a literature search, a survey on fixed ladder manufacturers and users, accident information, and test results. The tests used an anthropomorphic test dummy to simulate a worker falling off a caged ladder, and compared the results with those obtained on ladder-mounted fall-arrest systems using the same test conditions.

Twenty-three recommendations are made in regard to the findings of this research, including directions for further work.

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EXECUTIVE SUMMARY

Various legislative and guidance documents specify ladder safety hoops on fixed access ladders, (alternatively rendered as caged ladders), and give the impression that the purpose of the hoops is to protect workers from falling to the ground or other platform. Previous research has indicated that there is virtually a total lack of knowledge in regard to ladder safety hoops, and in conjunction with anecdotal accident evidence and a lack of test methods, uncertainties have been raised by persons conducting working at height risk assessments as to whether safety hoops can provide any form of fall-arresting capability.

The overall aim of this preliminary investigation was to update the current state of knowledge and understanding in regard to what ladder safety hoops actually are, what their intended purpose is, and to establish by preliminary testing whether or not they could provide any form of fall-arresting capability.

To address these questions, a literature search was undertaken, and a study of nearly 100 references was made. This included legislation, official guidance, standards, research papers and miscellaneous publications from both national and international sources. This was supplemented by a small scale survey of fixed ladder manufacturers and users, who were contacted to see if they could answer questions that had not been satisfactorily answered from the results of the literature search. This included on-site studies of hooped ladders and approaches to standards-writing committees. Permission was also obtained from the Health and Safety Executive to study accident cases recorded in their Field Operations Directorate database.

The test programme consisted of two phases. In the first phase, seven drop-tests were conducted with a 3-upright caged ladder conforming to BS 4211 (1994) using a Sierra Stan 50^{th} percentile anthropomorphic test dummy (ATD), of 71 kg mass, as a substitute for a human being. Upon release, deceleration with respect to time was recorded in the three principal axis (x, y, z) via a tri-axial accelerometer mounted to the thoracic area of the ATD's spine, and the fall trajectory was recorded using high speed digital video at 250 pictures per second.

With the hoops and uprights of the cage removed, a further eleven drop-tests were conducted using five different kinds of ladder-mounted fall-arrest system (FAS). Each FAS consisted of a rail which was centrally attached to the rungs of the ladder, a sliding arrest device and a full body harness. The purpose of these tests was to compare the fall-arresting effectiveness of FAS to ladder safety hoops using the same ATD, test method, instrumentation and recording techniques.

After studying the information from the references, the survey, from the accident database and the results from testing, it seems clear that caged ladders cannot provide positive fall-arrest capability, especially in the case of the three-upright design which was tested as part of this research. There is every possibility of a fall down the cage to the ground or other platform.

There would appear, or so it seems, a possibility to stop the fall of a worker in certain circumstances, but this depends upon the attitude of the worker both before the fall and during the fall, and whether or not the worker manages to catch part of his or her body in one of the cage apertures, or manages to trap themselves in the cage some other way. In any event, it is a chance occurrence, and the opinion is that even if the worker could be caught by the cage, it could lead to significant if not fatal injury.

The accidents reviewed indicate that workers fall down cages to the next level and are rarely caught. Injuries have been reported. Even if a fall is halted by limb entanglement within a cage, rescue would be extremely difficult process to carry out successfully.

No test methods were discovered in this research for testing the fall-arresting effectiveness of caged ladders, whereas there are a number of standards in existence for FAS.

Inferences from the documentation reviewed make it clear that caged ladders do not provide the same level of protection as ladder-mounted FAS, although a number indicate that the protection methods are on a par, but confuse the issues or use evasive language. The vast majority, when referring to protective measures, tend to avoid the subject completely by referring to FAS specifically in terms of their fall-arresting effectiveness, and then to caged ladders only in a general protective sense. The whole matter of caged ladder protection is often left vague.

In regard to the ladder-mounted FAS testing, with some exceptions, the majority of the tests showed that the FAS were able to arrest the fall of a worker much more positively, effectively and safely than caged ladders could. However a number of tests revealed that the FAS so tested have a much poorer stopping distance in realistic fall conditions than when tested in a laboratory in accordance with standards that contain minimum performance requirements. This aspect is caused by delayed locking-on of the arrest device and appears to be a factor in a number of European accidents.

Twenty-three recommendations are made in regard to the findings of this research, including directions for further work.

1. INTRODUCTION

1.1 PURPOSE

The purpose of the research was to update the current state of knowledge and understanding in regard to what ladder safety hoops actually are, what their purpose is, and to establish by preliminary testing whether or not they could provide any form of fall-arresting capability.

The intention behind the testing was to give a better understanding into the capability of ladder safety hoops. This information could then be made available to personnel who conduct risk assessments, and to personnel who write legislation, codes of practice, guidance and standards.

1.2 BACKGROUND

Safety hoops are an assembly of circular and vertical steel bars that are fastened to the stiles of fixed ladders. These ladders are permanently installed on buildings, structures and plant and provide access from one level to another in the vertical or near-vertical plane.

Safety hoops are arranged so as to enclose the path of a worker when climbing the ladder, (Figures 1, 2 and 3). They are also known as “safety cages” or “baskets”, or are alternatively rendered as a “caged ladder” or “hooped ladder”.

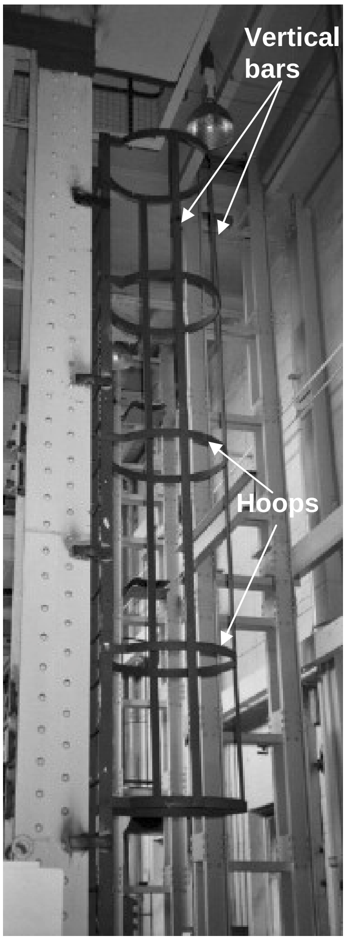

Figure 1 Caged ladder (side view)

Figure 2 Caged ladder showing safety hoops (view looking up inside hoops)

Figure 3 Climbing up caged ladder

Both nationally and internationally, various legislation, codes of practice and standards require or recommend that safety hoops or fall-arresting systems (FAS) are to be fitted to fixed ladders for the purposes of protecting workers from falling to the ground. Examples include: the UK's Workplace Health, Safety and Welfare Regulations incorporating the Approved Code of Practice and Guidance L24 (1992), British Standard BS 4211 (1994), and the U.S.A.'s Code of Federal Regulations (1996). Safety hoops have the perceived advantage over FAS of being a collective form of protection, i.e. in theory they can protect several persons over a period of time, with no supervision, training or special equipment being needed.

However, should a worker fall from a hooped ladder, very little is known about the ability of the safety hoops to arrest such a fall, in contrast to ladder-mounted FAS, (Figure 4), which have a known fall-arresting performance based on procedures in standards, e.g. EN 353-1 (2002).

Previous research by the author into this subject has revealed that very little information is documented about ladder safety hoops, Riches (1999). Extensive database searches conducted by the British Library have produced disappointing yields, as have other forms of enquiry.

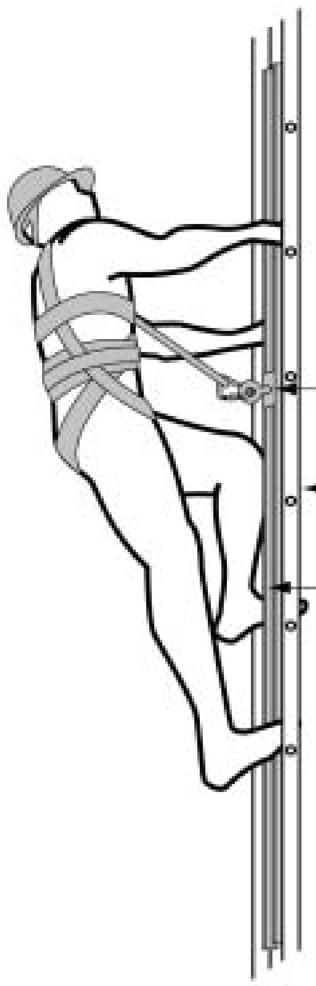

Figure 4 Example of a ladder-mounted fall-arresting system

1.3 RESEARCH METHOD

The following method was used to deliver the research.

1.3.1 Literature search and review

A computerised search was undertaken for documents with the assistance of the British Library Research Service, which utilised the DIALOG and GEM on-line host services. The following key words and phrases were used:

- ladder safety hoops
- ladder safety cages
- ladder baskets
- ladder guards
- ladder hoops
- access ladders

The databases searched were:

- INSPEC – a database for physics, electronics and computing, with articles dating back to 1898.

- NTIS – National Technical Information Service database consisting of summaries of unclassified, publicly available US government-sponsored research, development and engineering, from agencies such as NASA, DOD, DOE, HUD, DOT, Dept of Commerce and some 240 other agencies.

- Ei Compendex – an engineering database which provides abstracts from the world's significant engineering and technological literature. This covers approximately 4,500 journals and selected government reports and books, and additionally over 480,000 records of proceedings from engineering and technical conferences.

- TRIS – Transportation Research Information Services – a database relevant to the planning, development, operation and performance of transportation systems, providing international coverage of ongoing research projects, journal articles, state and federal government reports, conference proceedings, research and technical papers and monographs.

- Energy Science and Technology – a database containing worldwide references to basic and applied scientific and technical research literature.

- SciSearch – a scientific database of a international multidisciplinary nature, covering science, technology, biomedicine and related disciplines produced by the Institute for Scientific Information (ISI).

- UBM Industry News – contains the full text content of 57 leading UK business publications covering a broad range of industrial sectors.

- Occupational Safety and Health (NIOSH) – a database which includes citations to more than 400 journal titles as well as over 70,000 monographs and technical reports, covering all aspects of occupational safety and health.

- PIRA Management and Marketing Abstracts (MMA) - provides information on all aspects of management and marketing practice and customer and industrial relations in the single European market and worldwide.

- RAPRA – database dedicated exclusively to rubbers, plastics, adhesives and polymeric composites covering technical, academic commercial and marketing aspects of the industry.

- AEROSPACE (formerly Aeroplus) – containing the International Aerospace Abstracts (IAA), is one of the world's most comprehensive sources for published literature in the field of aerospace (aeronautics and astronautics) and the related areas of chemistry, materials, geosciences, physics and computer sciences.

- COPAC – an on-line database and a consortium of 24 UK University libraries holding 20 million items.

- NASA 1 and 95 - National Aeronautics and Space Administration databases which hold approximately 250,000 references each.

Articles were also searched for using the names Chaffin D. B. and Stobbe T. J. as these were known authors in the human access/ergonomics research field.

Relevant articles were obtained from the British Library Document Supply Centre, which has access to at least 150 million books, journals, reports and theses, covering almost every subject in every language.

Other articles were retrieved from general internet research, and Safety Squared's own library holdings, which included standards, legislation, official guidance, accident statistics and research papers.

1.3.2 Small-scale survey of ladder suppliers and users

A small-scale survey of fixed ladder suppliers and users was undertaken. This took the form of an informal search and enquiry for information rather than a structured survey. It attempted to establish reliable historical, technical and accident information by way of telephonic and internet enquiry. Suppliers and users were contacted who were most likely to be able to contribute some level of knowledge. No interviews or group discussions were conducted. Questions were limited in number and complexity in order to reduce the burden on respondents. Best survey practice was employed.

Questions asked were:

- What are ladder safety hoops?
- What do they do?
- What is their historical background and development?
- What is their fall-arrest capability?
- Has any research being conducted?
- What documents, currently available, contain any information on ladder safety hoops?
- Are ladder safety hoops fitted in preference to a ladder-mounted FAS as the preferred protection method or vice versa? Why?

National and European standards-making committees were also contacted as part of the above exercise.

1.3.3 HSE FOD database

In order to try and supplement accident evidence obtained from elsewhere, permission was obtained to study cases recorded in the HSE Field Operations Directorate (FOD) database. The search used the keywords and phrases: "HOOPED LADDERS" "PERMANENT / FIXED ACCESS LADDERS" "LIFELINES" "FALL-ARREST" and "LANYARDS". The search revealed that 270 accidents contained one or more of the keywords, occurring between April 2001 - June 2003.

1.3.4 Test programme

The first phase of the test programme involved the simulation of falls from within a hooped ladder, which was fixed to the test structure, by using an anthropomorphic test dummy in various pre-fall climbing postures. A tri-axial accelerometer was internally mounted to the spine of the dummy, enabling deceleration in the major body axes to be simultaneously measured during the fall simulation.

The hoops were removed for the second phase, in which five typical ladder-mounted FAS[1] were tested for direct comparison purposes with the hooped ladder. Utilising the same dummy and accelerometer set-up as above, simulations of falls from the ladder were conducted with the dummy in various pre-fall climbing postures, whilst being attached to the FAS.

Fall trajectories in both phases were recorded onto VHS video and CD-ROM using high speed videoing techniques, enabling subsequent analysis of slow motion playback, and providing photographic stills.

Photographically, where necessary, all distinguishing markings or features were deliberately deleted or disguised to prevent the manufacturing origins of the FAS from being identified.

1.4 DEFINITIONS

For the purposes of this report the following definitions are used, together with the corresponding SI units of measurement:

1.4.1 Anthropomorphic

Resembling or having human form with human attributes; ascribing human characteristics to non-human things.

1.4.2 Anthropometry

Comparative study of sizes and proportions of the human body.

1.4.3 5th percentile

Only 5% of measured values in a given population are smaller than the 5th percentile measurement.

1.4.4 50th percentile

50% of measured values in a given population are smaller than the 50th percentile measurement and 50% are larger; the median value.

1.4.5 95th percentile

Only 5% of measured values in a given population are larger than the 95th percentile measurement.

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[1] *The FAS concerned all used a rail which was fixed to the rungs of the ladder*

1.4.6 Acceleration due to gravity (g)

The natural acceleration of free fall due to gravity, equal to 9.81 m/s^2.

1.4.7 Acceleration

Rate of change of velocity with respect to time in metres per second squared (m/s^2). Where acceleration is expressed in units of “g”, for example an acceleration of 5g, this corresponds to an acceleration of 5 times the acceleration due to gravity, that is 49.05 m/s^2.

1.4.8 Jolt (or Jerk)

Rate of change, or rate of onset of acceleration with respect to time in metres per second cubed (m/s^3). Where jolt is expressed in units of “g/s”, for example a jolt of 500g/s, this corresponds to a jolt of 500 times the acceleration due to gravity per second, that is 4905 m/s^3.

1.4.9 Centre of gravity

The point where the result of all the weights of each individual part of an object is said to act. The position of this point is often used in calculations.

1.4.10 Bio-fidelity

The degree of transferability of a test surrogate’s response characteristics to that of the human body in identical test conditions.

1.4.11 Cadaver

A human corpse utilised as a surrogate in impact biomechanics research testing.

1.4.12 Kinematics

The study of the motion of bodies and containment systems without reference to mass or force.

1.4.13 Fall protection

Protective measures taken to either prevent a fall from a height from taking place, or stopping a fall from a height very quickly after it has taken place. This latter category amounts to “arresting” a falling person before they impact the ground or other substantial platform. This measure is traditionally described in industry as “fall-arrest”.

1.4.14 Flight height

The vertical distance between two successive platforms, where ladder runs are staggered or broken by platforms at regular intervals, (see figure 6).

1.4.15 Impact biomechanics

An area of research concerned with the prevention of injury to human beings in situations where loads are applied to the body at high rates of jolt and with durations of less than one second. It encompasses (i) mechanisms of injury, (ii) human response to impact, (iii) human tolerance to impact and (iv) human surrogate development for impact simulation.

1.4.16 Body centred geometry system

The convention used to describe the direction of impact accelerations is based on the orientation of the accelerometer installation used in the testing phase, as shown in Figure 5 and Table 1. Axes are colour-coded to correspond to the accelerometer readings shown in the acceleration-time graphs in Appendix 1 and 2.

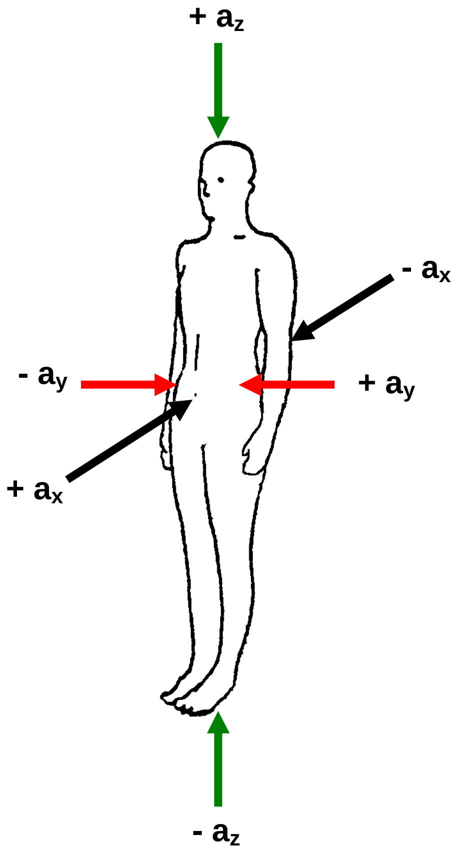

Figure 5 Body centred geometry system to describe the direction of impact accelerations

Table 1
Body centred convention and acceleration descriptive

Body centred convention	*Acceleration descriptive*	*Vernacular descriptive**
- a_x	Forwards	Eyeballs in
+ a_x	Backwards	Eyeballs out
+ a_z	Footwards	Eyeballs up
- a_z	Headwards	Eyeballs down
+ a_y	Sidewards to right	Eyeballs left
- a_y	Sidewards to left	Eyeballs right

*(eyeballs movement in inertial response to applied acceleration)

2. LITERATURE REVIEW

As experienced in previous ladder safety hoop research, Riches (1999), the literature search produced a very small yield of relevant titles, even when extending the time envelope of the search back over a number of decades. The results of the search and other discoveries are reviewed here.

The main documents that were found to be of interest were items of legislation, official guidance and voluntary standards.

Full reference details are given of all the documents that were studied, (see Section 9), and the reader is encouraged to obtain these if further reading on the subject is desired. Statements in quotation marks are direct quotations from the document under consideration, in order to differentiate between information contained in the document and the author's comments.

2.1 UNITED KINGDOM LEGISLATION

In the Workplace (Health, Safety and Welfare) Regulations (1992), the approved code of practice under Regulation 13 provides practical guidance in respect of measures to prevent injury from falling.

In respect of fixed ladders, the code says that "ladder runs of more than 6.0 m should normally have a landing or other adequate resting place at every 6.0 m point. ***Each run should, where possible, be out of line with the last run, to reduce the distance a person might fall***", Figure 6 refers. This would seem to indicate that a fall of 6.0 m is acceptable, which would be stopped by the landing. This is contradictory to the actual legislation which requires that, "so far as is reasonably practical, suitable and effective measures shall be taken to prevent ….\any person ***falling a distance likely to cause personal injury***". A person would be travelling at approximately 24 miles per hour after falling through a distance of 6.0 m [2], so the injury at least would be very severe.

The code goes on to say that "fixed ladders at an angle of less than 15° to the vertical which are more than 2.5 m high should where possible be fitted with suitable safety hoops or permanently fixed FAS. Hoops should be at intervals of not more than 900 mm measured along the stiles, and should commence at a height of 2.5 m above the base of the ladder". This opening at ground level allows a person to gain access inside the cage formed by the hoops, Figure 7 refers. Furthermore, "the top hoop should be in line with the top of the fencing served by the ladder". This provides some measure of a barrier when the climbing motion changes direction from the vertical plane of the ladder to the horizontal plane of the platform, or vice versa..

Circumstances where a single hoop is required are described as "where a ladder rises less than 2.5 m, but is elevated so that it is possible to fall a distance of more than 2.0 m, a single hoop should be provided in line with the top of the fencing. Where the top of a ladder passes through a fenced hole in the floor, a hoop need not be provided at that point".

This seems to be making the point that over the shortest ladder run, a single hoop can provide some form of guard at the top of the ladder, when the worker's motion changes direction from the vertical to the horizontal, or vice versa. In effect, the guard railing on the platform integrates with the "guard railing" on the ladder.

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[2] *Using the constant acceleration formula $v^2 = u^2 + 2gs$ where s = distance fallen through, g = acceleration due to gravity, u = initial velocity at onset to fall (zero), and v = velocity at impact.*

It should be noted that Regulation 13 of the Workplace (Health, Safety and Welfare) Regulations (1992) is likely to be replaced with updated requirements under the proposed Working at Height Regulations, the draft of which, Health and safety Commission Consultation Document 192 (2003), is currently (April 2004) under consultation.

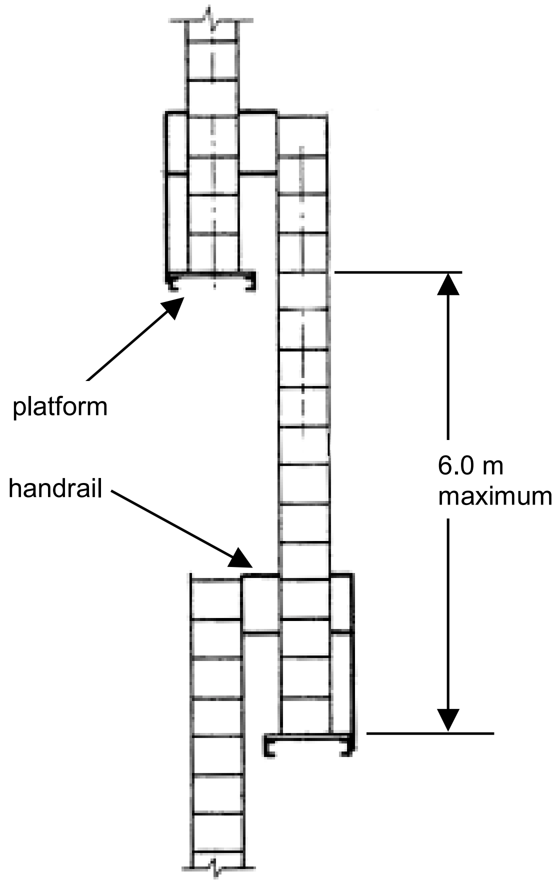


Figure 6 Staggered runs with platforms

In the Construction (Working Places) Regulations (1966) the maximum vertical run of a ladder was set as 30 feet (9.15 m). Any height beyond this required a platform such that the maximum height between platforms was to be 9.15 m. No fall protection is stipulated whilst climbing the ladder. These regulations were completely revoked by the Construction (Health, Safety and Welfare) Regulations (1996), which continued the rule of a maximum of 9.0 m between “safe landing areas or rest platforms”.

The Building Regulations (1991) and 1997 amendment lay down requirements for fixed industrial ladders. The Building Regulations Approved Document K (1998), which gives practical guidance on meeting those requirements, refers the design and construction of such ladders to either BS 5395 Part 3 (1985) or BS 4211 (1987).

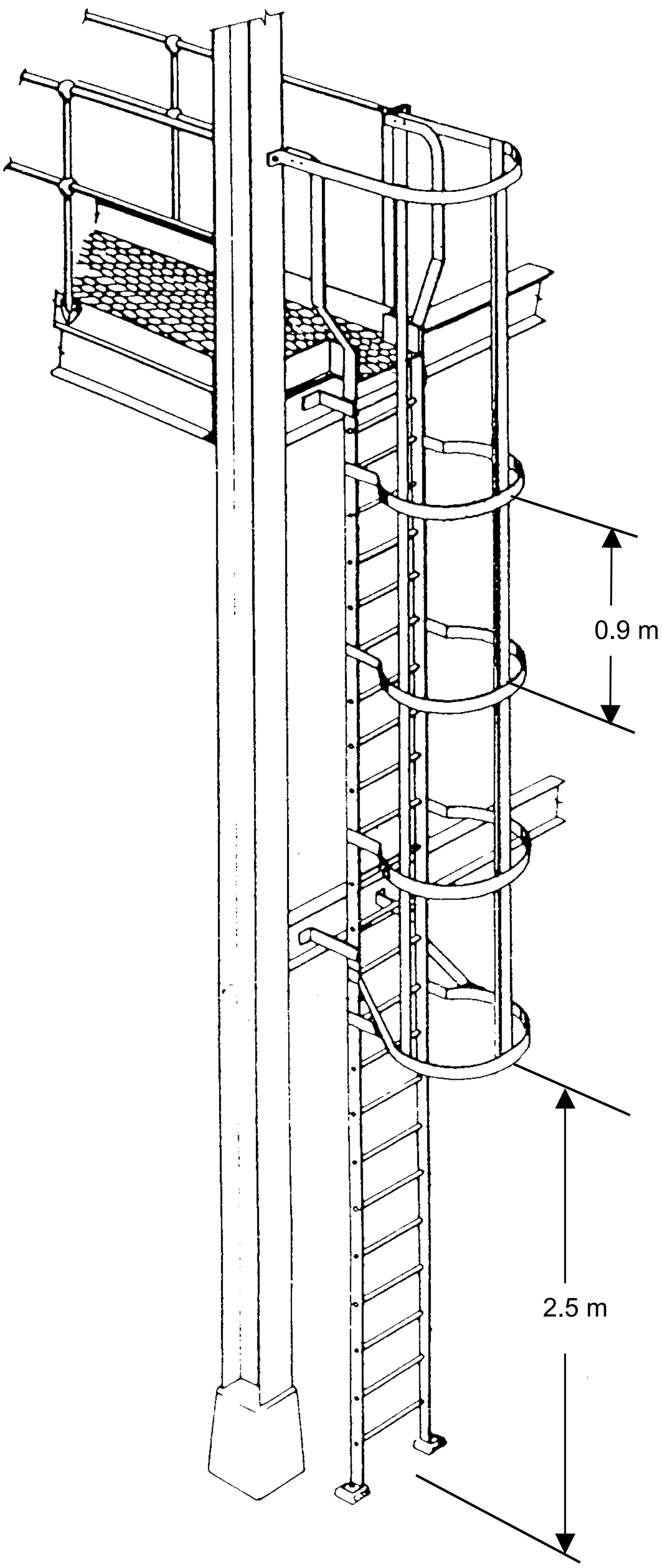


Figure 7 Typical arrangement of hooped ladder joining platform

The Approved Code of Practice L42 (1993) describes methods of meeting the requirements of the Mines (Shafts and Winding) Regulations (1993). Where winding apparatus cannot be installed in shafts where personnel have to travel in, ladder-ways can be utilised. The maximum run of a ladder is cited as 5.0 m between platforms, also: "Ladder-ways should be provided with suitable fencing ***which will prevent persons falling further than the distance between adjacent platforms***……", and: "at new installations, if space permits, ***ladders should be suitably inclined***". This statement seems to indicate that a fall of 5.0 m is acceptable, and then tries to allay the risk by emphasising the preference for inclined ladders.

2.2 UNITED STATES LEGISLATION

2.2.1 CFR 29 Parts 1910.21 and 1910.27

Detailed information can be found in regard to fixed ladders and safety hoops in the United States' Code of Federal Regulations 29 Parts 1910.21 and 1910.27 (1996). Many of the measurements familiar in ladder design and use are specified, e.g. rung width and diameter, but only those factors concerning ladder safety hoops and fall protection are considered here.

Under Subpart D of the said regulations – entitled " Walking-Working Surfaces", Part 1910.21, the following definitions are made:

- Cage: "A cage is a guard that may be referred to as a cage or basket guard which is an enclosure that is fastened to the side rails of the fixed ladder or to the structure to encircle the climbing space of the ladder for the safety of the person who must climb the ladder".

- Well: "A well is a permanent complete enclosure around a fixed ladder, which is attached to the walls of the well. Proper clearances for a well will give the person who must climb the ladder the same protection as a cage".

- Ladder safety device: "A ladder safety device is any device, other than a cage or well, designed to eliminate or reduce the possibility of accidental falls and which may include such features as…..friction brakes and sliding attachments".[3]

What is interesting from these definitions is that the cage and well are for the "safety of the person" whereas the ladder safety device is "designed to eliminate or reduce the possibility of accidental falls". There appears to be a discrimination in the levels of safety afforded by the two methods.

Climbing clearances

The first point of note in Part 1910.27 of the said regulations concerns the clearance on the climbing side of the ladder, Figure 8. The regulations state that: "on fixed ladders, the perpendicular distance from the centreline of the rungs to the nearest permanent object on the climbing side of the ladder shall be 30 inches (762 mm) for a pitch of 90°". ***In effect, this is an anthropometric clearance, which allows a worker to climb a ladder without obstruction, taking into account both the human form and climbing movement.*** Similarly, "a clear width of at least 15 inches (381 mm) shall be provided each way from the centreline of the ladder in the climbing space". This takes into account shoulder width, Figure 9.

[3] *A ladder mounted FAS*

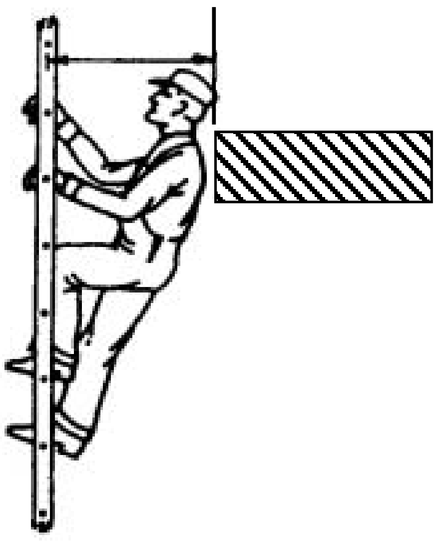


Figure 8 Anthropometric clearance requirement (side view) for climbing vertical, fixed ladder after Code of Federal Regulations 29 Parts 1910.21 and 1910.27 (1996)

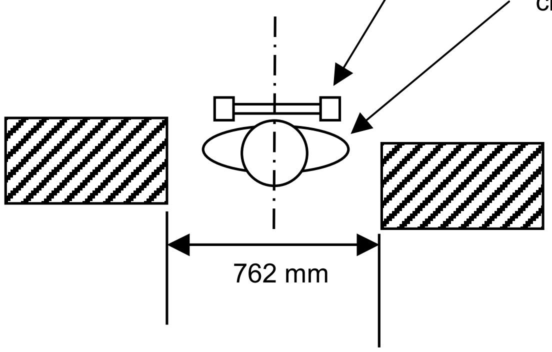


Figure 9 Anthropometric clearance requirement (plan view) for climbing vertical, fixed ladder

Cage dimensions

Requirements for cages are then specified, and: "shall be provided on ladders of more than 20 feet (6.1 m) to a maximum unbroken length[4] of 30 feet (9.15 m)". It is very interesting to note that the 6.1 m figure correlates to the maximum unbroken run of ladder under the code of practice from the UK's Workplace (Health, Safety and Welfare) Regulations (1992), and that the 9.15 m correlates to the maximum unbroken run of ladder under the UK's Construction (Health, Safety and Welfare) Regulations (1996). ***It would seem that the U.S. legislation has specified the two figures as a dimensional tolerance, whilst the UK has applied the two limits to two different types of legislation.***

Additionally: "cages shall extend a minimum of 42 inches (1067 mm) above the top of a landing". This, as shown in Figure 7, appears to provide a guard when a worker's motion changes from the climb to the platform, and vice versa, i.e. a time when the worker may be particularly prone to falling.

At the bottom of the ladder, in a similar manner to Figure 7, "cages shall extend down the ladder to a point not less than 7 feet (2.13 m) nor more than 8 feet (2.44 m) above the base of the ladder, with bottom flared not less than 4 inches (101.6 mm)". This allows easy access either into, or from the cage at ground level.

The Code goes on to specify particular dimensions for cages, also refer to Figure 10: "Cages shall not extend less than 27 inches (685.8 mm) nor more than 28 inches (711.2 mm) from the centreline of the rungs of the ladder. The cage shall not be less than 27 inches (711.2 mm) in width. The inside shall be clear of projections. Vertical bars shall be located at a maximum spacing of 40° around the circumference of the cage; this will give a maximum spacing of approximately 9.5 inches (241.3 mm), centre to centre." Distance between hoops is set at 4 feet (1.2 m) centres. ***The setting of these dimensions obviously reflect some kind of anthropometric basis.***

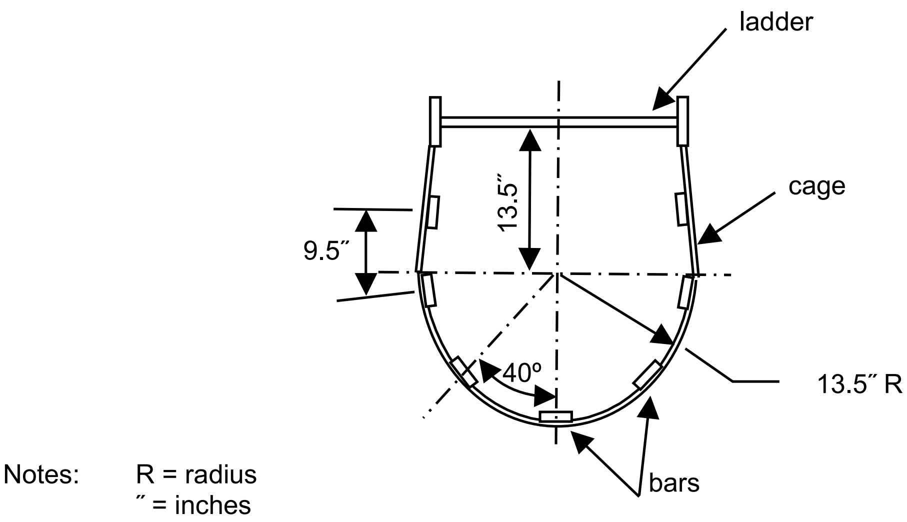
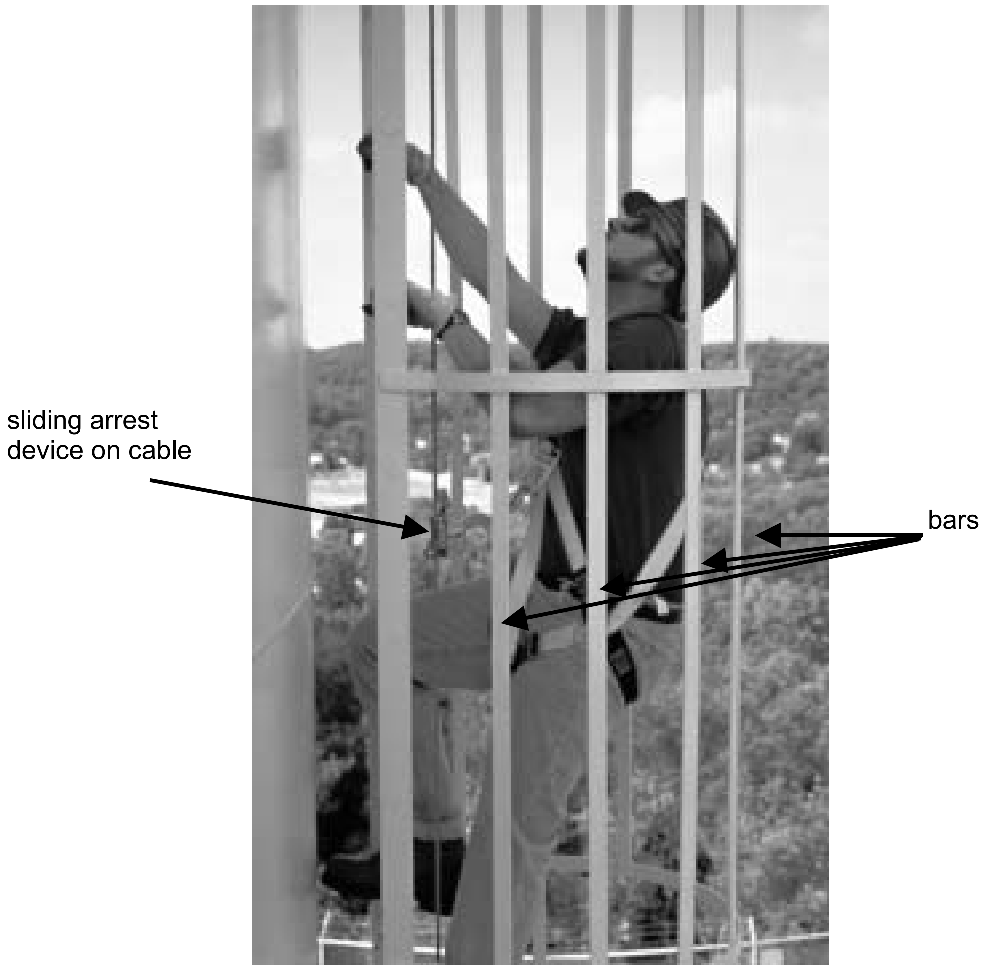


Figure 10 Plan view of cage dimensions after Code of Federal Regulations 29 Parts 1910.21 and 1910.27 (1996)

[4]*The term "unbroken" referring to a straight run, i.e. a run without platforms or staggers, Figure 6 refers*

The spacing between respective bars is an interesting point, since cages according to this Code will have 7 vertical bars around the circumference (Figure 11) as opposed to the characteristic three bars in the UK[5], (Figures 1-3). ***This virtually eliminates the possibility of a person falling through the apertures formed by respective bars and hoops, and hence out of the cage.***



Note: the worker is also attached to a cable-based FAS

Figure 11 Worker climbing up caged ladder with 7 vertical bars

Difference in free climbing room and corresponding caged dimension room

In comparing the dimension shown in Figure 8 with the respective dimension in Figure 10, one can see a difference. The amount of free room for climbing in Figure 8 is set as 762 mm, whereas the same dimension in Figure 10, but with a cage in place is given a tolerance of between 685.8 and 711.2 mm. ***According to these figures, the climber will have to "squeeze into" a smaller dimension when climbing a caged ladder, i.e. they will have to climb in a more erect position, Figure 12.***

[5]*Discussed later under "standards"*

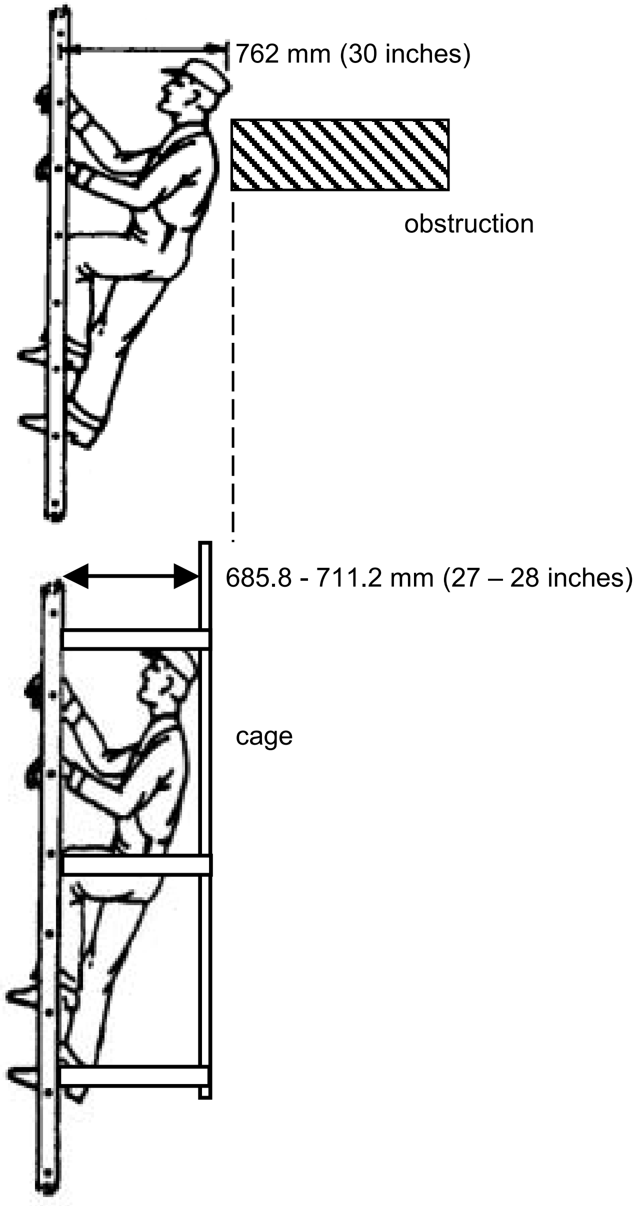


Figure 12 Difference in free climbing room and corresponding caged dimension according to Code of Federal Regulations 29 Parts 1910.21 and 1910.27 (1996)

The "squeeze" may only be between 52 and 76 mm, but this may be significant, anthropometrically, as it gives rise to three possible inferences:

- the reduced dimension may have been aimed at providing security in a psychological sense (i.e. been able to sense the immediate proximity of the back of the cage)

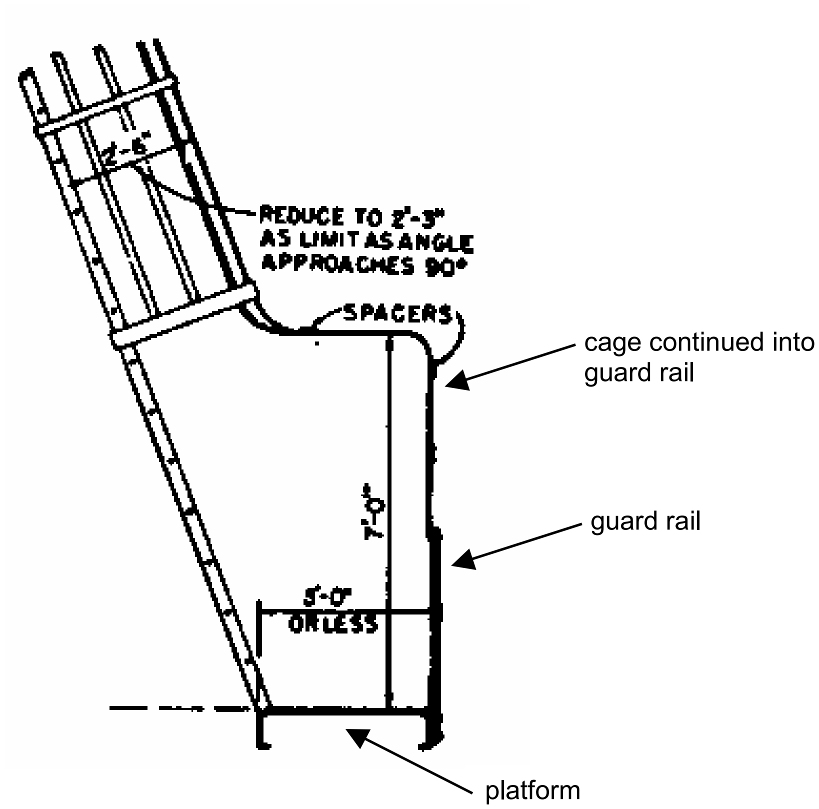
- the reduced dimension may have been aimed at providing a resting position (i.e. the worker would be able to lean back against the back of the cage and rest the arms, in particular)

- the reduced dimension may have been aimed at an attempt to cause the worker's body to lock or jam in the confined space of the cage if they slipped off the ladder.

The same "squeeze" is true when comparing the width dimensions in Figures 9 and 10. The amount of free room for climbing in Figure 9 is set as 762 mm, whereas the same dimension in Figure 10, but with a cage in place is 685 mm.

Bottom of ladder exiting in close proximity to a guard rail bordering an elevated platform

Another important point in the Code is the special case where the bottom of a ladder exits in close proximity to a guardrail bordering an elevated platform. This is shown in Figure 13.



Notes: (i) 5' 0" dimension = 1.52 m; 7' 0" dimension = 2.13 m
(ii) slightly wider 2' 6" (762 mm) cage dimension allowed on inclined ladder, presumably from the "reduce to" caption, to allow for the different body attitude adopted when in the incline

Figure 13 Bottom of ladder exiting in close proximity to a guard rail bordering an elevated platform after Code of Federal Regulations 29 Parts 1910.21 and 1910.27 (1996)

In this case the cage is continued into the guard rail from the bottom of the ladder in order to form a one-piece structure. ***This ensures that if a worker falls or stumbles backwards when exiting the ladder, any momentum will not cause them to fall over the guard rail since any unguarded space between the guard rail and ladder cage is blocked.***

Landing platform intervals

The Code then specifies landing platform intervals: "When ladders are used to ascend heights exceeding 20 feet (6.1 m)…..landing platforms shall be provided for each 30 feet (9.15 m) of height or fraction thereof, except that, where no cage or ladder safety device[6] is provided, landing platforms shall be provided for each 20 feet (6.1 m) of height or fraction thereof. Each ladder section shall be offset from adjacent sections". (This is shown in Figure 6).

The question is then raised as to why offset landing platforms should be provided at 9.15 m intervals for ladders protected by cages or ladder safety devices, and at 6.1 m intervals for unprotected ladders. Considering the conventional landing platform function as a rest platform between ladder runs, it is difficult to see why the frequency of the platforms should be reduced for unprotected ladder runs, unless the real function of the landing platform is in fact to catch a falling person. The logical deduction is that a person is more than likely to fall when climbing an unprotected ladder, so the distance between offset runs should be less than the situation with protection***. In effect this Code appears to be saying that a fall of 6.1 m onto a platform is acceptable.***

Ladder mounted FAS

The ladder platform interval subject is further complicated when the use of FAS are considered. The Code states: "Ladder safety devices may be used on tower, water tank and chimney ladders over 20 feet in unbroken length in lieu of cage protection. No landing platform is required in these cases". ***The question is the raised as to why no landing platforms are needed when FAS are employed.*** It seems logical to deduce that landing platforms are connected with method of fall protection.

The conclusion drawn from the preceding paragraphs is that the Code appears to be using offset landing platforms as a means to catch falls. A 6.1 m fall appears to be survivable whereas a 9.15 m fall is not. Also a 9.15 m fall may be slowed down by a caged ladder, but needs a landing platform to stop it completely. The ladder safety device requires no landing platforms because it will stop the fall of a worker relatively quickly.

This deduction was confirmed in Firl (1999), which described the market conditions for ladder fall protection requirements at the time. ***The perception was that ladder cages could not stop the fall of a worker with any measure of confidence so, more and more, ladder mounted FAS were being installed on ladders which had cages fitted as part of the original installation.*** So both cage and FAS were being fitted to ladders, see Figure 11.

2.2.2 CFR 29 Part 1926.1053

Similar detailed information to that contained in the United States' Code of Federal Regulations 29 Parts 1910.21 and 1910.27 (1996), as described above, can be found in Code of Federal Regulations 29 Part 1926.1053 (1996), and so is not repeated. However there are certain differences, which may be due to the fact that these regulations are more applicable to the U.S. construction industry.

This Code states that: "Fixed ladders shall be provided with cages, ladders safety devices[7] or self-retracting lifelines[8] where the length of climb is less than 24 feet (7.3 m) but the top of the ladder is at a distance greater than 24 feet (7.3 m) above lower levels".

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[6] *A ladder mounted FAS*
[7] *A ladder mounted FAS*

"Where the total length of the climb equals or exceeds 24 feet (7.3 m), fixed ladders shall be equipped with one of the following:

- ladder safety devices; or
- self-retracting lifelines, and rest platforms at intervals not to exceed 150 feet (45.7 m)
- multiple caged ladder sections, each ladder section not to exceed 50 feet (15.2 m) in length. Ladder sections shall be offset from adjacent sections, and landing platforms shall be provided at maximum intervals of 50 feet (15.2 m)."

This appears to suggest the following:

- Ladder safety devices are capable of reliably arresting a fall and hence need no additional protective measures.

- Self retracting lifelines are capable of reliably arresting a fall, but a rest platform should be installed every 45.7 m. This either reflects the tiring effects of climbing whilst connected with the lifeline attached to the body[9], or more likely the maximum length of self retracting lifeline produced, which is 50 m.

- Caged ladder sections cannot be relied on to arrest a fall, therefore they need to be offset and need catching platforms at maximum intervals of 15 m.

Dimensionally there are only small differences to those contained in Code of Federal Regulations 29 Parts 1910.21 and 1910.27 (1996). Referring to Figure 10, the 27 to 28 inch (685.8 to 711.2 mm) dimension from rung to back of hoop is slightly bigger at 27 to 30 inches (685.8 to 762 mm) in the construction CFR. Also the clear width dimension of 27 inches (685.8 mm) is slightly bigger at 30 inches (762 mm) in the construction CFR.

This means that the "squeezing effect" mentioned previously is not applicable to the construction CFR.

Ladder mounted FAS

Ladder safety devices have requirements in the construction CFR, and these are mentioned here as a matter of interest and in respect of the testing that is mentioned further on in the report. The construction CFR require that such FAS:

- shall be capable of withstanding without failure a drop test consisting of an 18 inch (41 cm) drop of a 500 lb (226 kg) weight;

- shall permit the employee using the device to ascend or descend without continually having to hold, push or pull any part of the device, leaving both hands free for climbing;

- shall be activated within 2 feet (0.61 m) after a fall occurs, and limit the descending velocity of an employee to 7 ft/s (2.1 m/s) or less[10];

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[8] *Retractable type fall arresters*

[9] *A retractable type fall arrester which would allow a climb over 45 m would contain a very powerful motor spring, to enable the full 45 m of lifeline to be retracted. The torque of the spring would apply a considerable tension to the lifeline, especially when fully extracted, which would be felt by the climber. This tension would reduce gradually as the climber got nearer to the lifeline housing.*

[10] *Probably a requirement for an arresting device which, after the arrest, automatically lowers the worker to a safe area.*

- have a connection between the sliding arrest device and the point of attachment on the harness not exceeding 9 inches (23 cm) in length;

- for rail-based FAS, to have mountings at each end of the rail, with intermediate mountings as necessary, spaced along the entire length of the rail, to provide the strength necessary to stop employee's falls;

- for cable-based FAS, to have mountings at each end of the cable, and when the cable is exposed to wind, to have cable guides at a minimum spacing of 25 feet (7.6 m) and maximum spacing of 40 feet (12.2 m) along the entire length of the cable, to prevent wind damage;

- have the mountings and cable guides so designed and installed so not to reduce the design strength of the ladder.

In the specification for the ladder, impact loads resulting from the use of ladder safety devices have to be taken into account in the design.

In summary, ladder safety devices have ergonomic, fall-arresting performance and strength requirements in this CFR. Caged ladders do not.

2.2.3 CFR 29 Part 1910.131

In Federal Register (1990) a notice of proposed rulemaking was presented, in which the U.S. Occupational Safety and Health Administration (OSHA) proposed to amend the Code of Federal Regulations 29 Part 1910, in regard to "personal protective equipment (fall protection systems)". This was intended to be under part 1910.131, which was to cover "personal fall protection systems for climbing activities".

This proposal states that: "existing standards[11] in CFR 1910.27 ***require the use of ladder cages and wells for employee protection, and do not allow employers sufficient flexibility to use other available methods or criteria for providing protection to employees during climbing activities. OSHA believes that the equipment[12] covered by the proposed standard can provide employees who are climbing with protection equivalent to or superior to that provided by cages or wells".***

This seems to indicate a suspicion that ladder cages do not afford the same level of fall protection compared to the proposed fall protection systems.

It is interesting to note that a number of proposed requirements come directly from a voluntary American Standard, ANSI A14.3 (1984). Also that the maximum of length of the connection, between the rail or cable element of a ladder mounted FAS and the point of attachment on the body being limited to 9 inches (23 cm), is based on ergonomic work in Chaffin and Stobbe (1979). Both of these documents are reviewed later on in this report.

2.2.4 CFR 29 Part 1917.118

In later legislation, Code of Federal Regulations Part 1917.118 (1999), fixed ladders at marine terminals (ports) are specified.

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[11] *Standards in this case referring to the text within a Code of Federal Regulation which is a legal document*

[12] *Ladder safety devices, limited velocity descent devices, automatic pay-out and self-retracting lifelines*

A ladder cage or basket guard is defined as a: "barrier enclosing or nearly enclosing a ladder's climbing space and fastened to one or both of the ladders side rails or to another structure".

This is in contrast to a ladder safety device (FAS), being defined as a: "support system limiting an employee's drop or fall from the ladder, and which may incorporate friction brakes, lifelines and lanyards, or sliding attachments". ***Again the FAS is defined in terms of positively stopping a fall, whereas the hoops are defined in terms of a barrier enclosing a space.*** Interestingly, cages in this document do have a newer requirement in that they: "shall be of rigid construction that allows unobstructed use ***but prevents an employee from falling through or dislodging the cage by falling against it".***

This recognises the risk of falling through the cage, but not the risk of falling down it.

2.3 CANADIAN LEGISLATION

The Canada Occupational Safety and Health Regulations (1996) make important statements about fixed ladders in Part II "Building Safety": (excepting fixed ladders that are used with fall protection systems), "a fixed ladder that is more than 6 m in length shall be fitted with a cage for that portion of its length that is more than 2 m above the base level of the ladder ***in such a manner that it will catch an employee who loses his grip and falls backwards or sideways off the ladder".***

This is an explicit mention of the fact that cages are expected to arrest the fall of a worker from a fixed ladder. Not only that, but there is specific mention that the cage should perform this protective role irrespective of the direction of the falling-off motion, whether in a backwards or sideways direction. No fall-arrest test method is stipulated or referred to for the cage, but such methods are referred to for FAS, which are mentioned later on in those particular regulations

Furthermore: "a fixed ladder that is more than 9 m in length shall have, at intervals of not more than 6 m, a landing or platform that is not less than 0.36 m^2 in area and is fitted at its outer edges with a guardrail. A fixed ladder, cage, landing or platform shall be designed and constructed to withstand all loads that may be imposed on it."

2.4 OFFICIAL GUIDANCE AND STANDARDS

2.4.1 United Kingdom

HSE guidance note GS12

In Guidance Note GS 12 (1981), which is now out of print, the risks of effluent storage on farms is described. The Note mentions that: "platforms and ladders fixed externally to effluent stores must comply with the Agriculture (Safeguarding of Workplaces) Regulations (1959) (which is also now out of print). These regulations use the term "stairway" to denote not only a permanent staircase but also: "a permanently fixed ladder…which is either within a building or gives access to a building or to part of a building". Reading on, the requirements state that: "every stairway shall be fitted with a handrail or handrails". Also: "a handrail shall extend the whole length of the stairway provided that if it is impossible for a handrail to extend the whole length of the stairway without obstructing access thereto the handrail need not extend so as to obstruct access to the stairway". This seems to indicate that a fixed vertical ladder required handrails and so the logical deduction is that safety hoops could have been fitted to act as guardrails. Such "handrails" would not have to extend to ground level so to allow access to the ladder.

Although this is a deduction, it is supported by reference to a diagram in Guidance Note GS 12 (1981), see Figure 14. This diagram, entitled: “safe access to above ground structure”, depicts a storage tank with a short hooped ladder fixed to the upper part of the tank, which in turn is accessed by a removable, portable ladder.

Guidance Note GS 12 (1981) recommends that: “when in position, the lowest part of any fixed ladder should not be less than 2.4 m and not more than 3.0 m above ground level. If access to a store involves the use of a portable ladder……in conjunction with a fixed ladder, it must comply with the Agriculture (Ladders) Regulations, (1957)”. Note that the scope of these particular regulations cover portable ladders only.

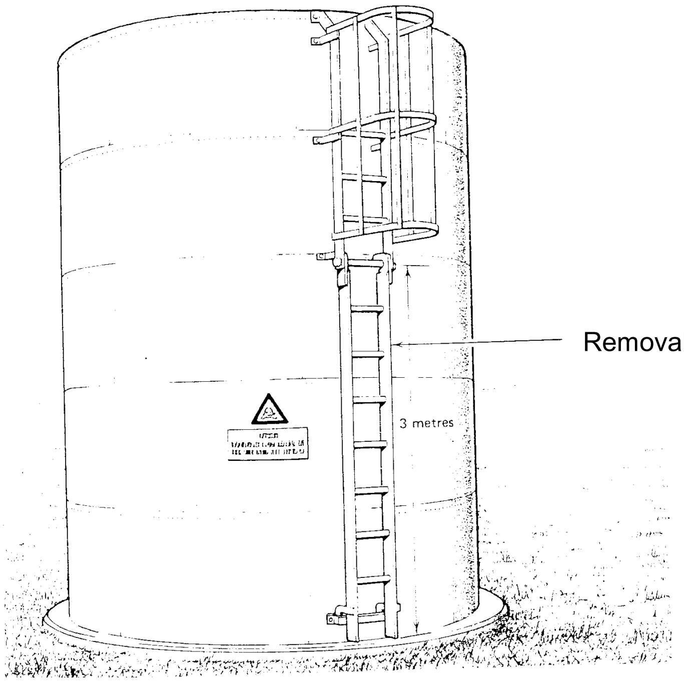


Figure 14 Safe access to above ground structure after Guidance Note GS 12 (1981)

British Standard BS 4211

This standard deals with fixed ladders and was first published as BS 4211 (1967), and was subsequently revised in 1987 and 1994. In BS 4211 (1967) a safety hoop is described as: ***“a bar fixed to both stringers[13] to enclose the path of persons climbing the ladder, to prevent them falling outwards”.*** This definition was maintained in the 1987 and 1994 versions. The question is immediately raised as to ***what will happen if a person falls downwards?***

In regard to defining rest platforms: “a platform provided to enable the person climbing the ladder to rest”.

Under provision of hoops: “all ladders rising 7 ft 6 in (2.3 m) or more from the lower platform or ground level to the top rung shall be fitted with safety hoops, the spacing of which shall be uniform and at intervals not exceeding 3ft (0.91 m). The lowermost hoop shall be fitted to the stringers at a height of 8 ft (2.4 m) from the lower platform or ground in order to give sufficient overhead clearance when getting on to the ladder”.

[13] *The side members of a ladder to which the rungs are fitted, more commonly known as the stiles*

“The uppermost hoop shall be fixed in line with any guard rail to the upper platform…..”. This information is more or less the same as that identified in documents previously reviewed.

The standard stipulates an interesting requirement in respect of ladders that rise less than 2.3 m, giving access to a platform from which it is possible to fall more than 6 ft 6 in (2 m). In this respect the ladder “shall be provided with a single safety hoop at a height of 3ft 6 in (1.07 m) above the platform level”, (i.e. to integrate into the guard rails on the platform, as per Figure 7). This, as mentioned previously in clause 2.1 of this report, gives rise to the idea that a single hoop can possibly restrict the backwards or sideways fall of a worker, if they fell during the vulnerable action of exiting the ladder onto the platform, or possibly more vulnerable action of exiting platform onto ladder.

BS 4211 (1967) then goes on to describe design and manufacture details for making the hoops. Dimensions are specified for a “circular pattern” of hoops and a “rectangular pattern”, Figure 15. No explanation is given as to why there are two different patterns.

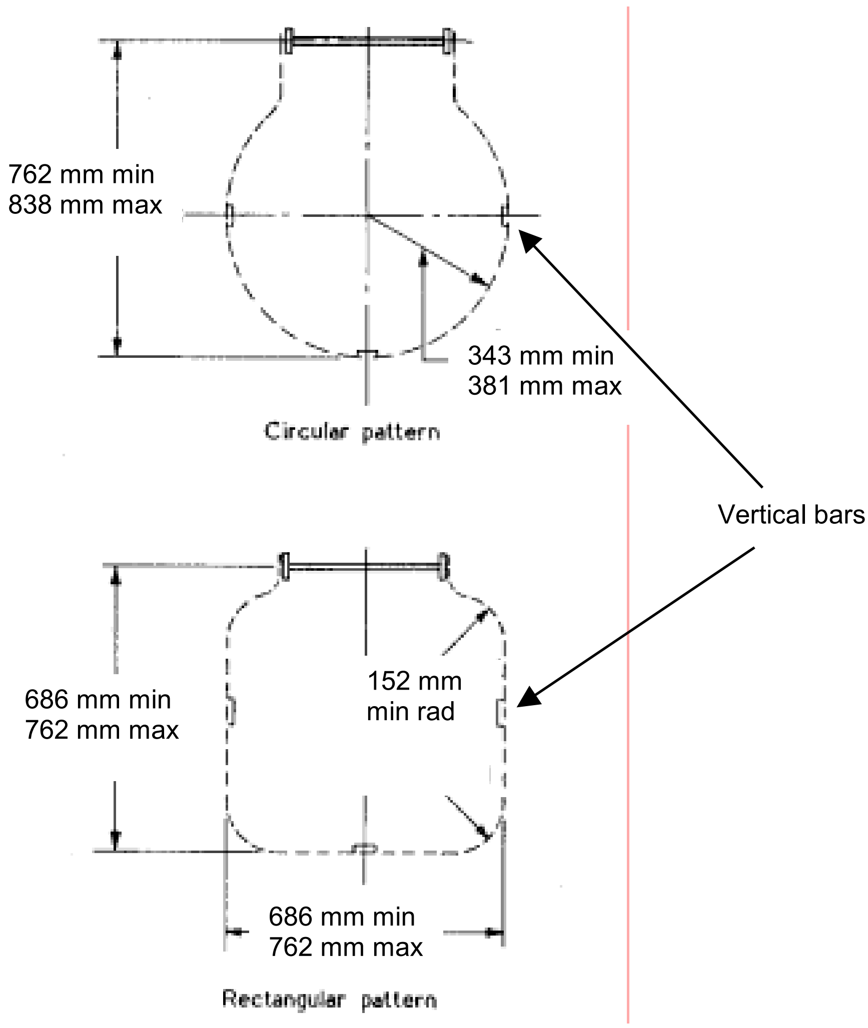


Figure 15 Safety hoop dimensions after BS 4211 (1967)

In regard to the vertical bars: “At least three vertical straps shall be fitted internally to ***brace the hoops***; one of these straps shall be at the centre back of the hoop, and the others spaced evenly between the centre back of the hoop and the ladder stringers.” It is worth considering the question: ***were the vertical bars introduced at a later stage in safety hoop development for bracing, or were they intended as part of the original protective arrangements?***

The question is raised, since as part of the survey, (the results of which are described in Section 3), fixed ladders were discovered with hoops but without vertical bars, Figure 16.

Figure 16 Safety hoops without vertical bars

This in contrast with the American requirement, Figure 11, which specifies 7 vertical bars.

Further information in BS 4211 (1967) is given about landing places which may be provided as rest platforms: “landing spaces shall be provided at intervals of not greater than 30 ft (9.15 m)”.

Also in regard to the ladder: “the ladder shall be vertical or shall be inclined towards the structure to which it is fixed at an angle not exceeding 15° from the vertical, which is the preferred angle.”

Some interesting information can also be found in the appendix on “recommendations for use”: “the ladders covered by this standard are not intended to accommodate, in any one section, loads exceeding that of one person and ***care should be taken to ensure that neither ladders, safety hoops or straps are used to support additional loads such as lifting appliances, scaffolding, etc, for which they are not designed***.”

Also: “***The provision of safety hoops may be a temptation to experienced operatives to mount the ladder by means of the hoops instead of the rungs. This should be prohibited***”.

In the revision, BS 4211 (1987), FAS are also introduced: “All fixed ladders rising 2.5 m or more above ground level or a lower platform shall be fitted with either safety hoops or a permanent FAS in accordance with British Standard BS 5062”. Slightly differing hoop sizes are specified, and these included in Table 2, which compares sizes between the various documents reviewed.

The further revision, BS 4211 (1994) adds no new information in regard to ladder safety hoops.

British Standard BS 5395 Part 3

In British Standard BS 5395 Part 3 (1985), a code of practice gives recommendations for the design of fixed ladders and other industrial access systems. The code defines a ladder as a: “ladder having a pitch greater than 75°” and states that: “a sloping ladder is generally easier and safer to use than a vertical ladder”.

In regard to distances between landings and fall protection, the code recommends: “the height of a ladder should not exceed 6 m without an intermediate landing[14], preferably breaking the line of the ladder”. (This in contrast to BS 4211 which specifies 9 m). “If a user could fall 2 m or more……. the ladders should be fitted with safety equipment”. This statement refers to the use of safety cages or vertical FAS: “It is essential to fit a safety cage, or a fixed vertical rail or wire cable for use with a sliding FAS and harness, whenever a user could otherwise fall 2 m or more or come into contact with dangerous equipment. Cages should be constructed of components robust enough to minimise flexing”.

This code also introduces the idea of hoops with extra protection: “where maximum enclosure is desirable because of an elevated position or other hazard, one half of the hoop structure may be extended down to near floor level. ***In particularly hazardous and exposed situations, mesh panels may be used to cover the ladder cage***”, see Figure 17.

[14] *Except on chimneys*

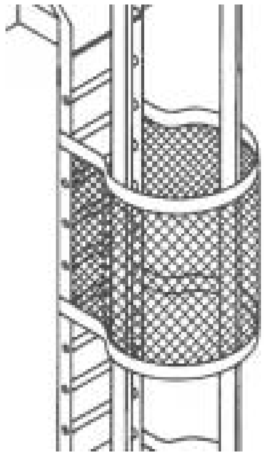


Figure 17 Mesh panelling on hoops after BS 5395 part 3 (1985)

In regard to dimensions, the code links the variation in rung-to-hoop dimensions allowed in other documents to the pitch of the ladder, i.e. in the other documents so far mentioned, the variation seems to indicate a manufacturing tolerance, whereas in BS 5395 Pt 3 (1985) the variation is attributable to pitch, see Table 2. For example, with the round pattern of hoop, the dimension between the ladder rung and back of hoop: “varies from 760 mm, for a vertical ladder, to 840 mm, for a ladder having a pitch of 75°”. This seems to be sensible, and from the caption in Figure 13, the Code of Federal Regulations 29 Part 1910.27 (1996) also seems to allow a greater dimension when the ladder is inclined. One assumes this is to cater for body attitude when climbing a slightly inclined ladder. But this approach differs from that laid down in BS 4211.

2.4.2 USA

National Safety Council Data Sheet 1-606-Rev. 83

In National Safety Council (1983), an official U.S. safety data sheet describes fixed ladders and climbing devices. It mentions the main hazard of free fall, and others including falls from carrying loads, running up and down ladders, jumping from a ladder, and reaching too far out to the side while working. Climbing devices (FAS): “are intended to prevent the free fall of a ladder user if, for any reason, the climber should lose his grip or footing, or both”. Caged ladders are given a relatively brief description, but the document is silent in regard to a cage’s ability to stop the fall of a worker.

ANSI A14.3

Two versions of the American National Standard for fixed ladders were reviewed, namely ANSI A14.3 (1984) and the later ANSI A14.3 (1992). This standard has a long lineage, having been originally established in 1923. Subsequent revisions were published in 1935, 1948, 1952, 1956, 1974, 1984 and 1992. Attempts were made to locate these earlier versions, because it was felt that these documents might determine the inception date for caged ladders in the U.S.A. These documents could not be obtained in the available project time, but their acquisition would be important in any further work subsequent to this research.[15]

[15] *See Section 8*

Upon review, it became clear that the work in ANSI A14.3 was the basis for the Code of Federal Regulations 29 Part 1910.27 (1996). In fact in Best (1978) the following is stated on page 704: "…fixed ladders CFR 1910.27 – this OSHA standard is based on ANSI A14.3-1956, the safety code for fixed ladders. The regulations cover………ladders with cages or baskets….. ladder safety devices". This information, combined with the history of the standard as described in the foreword to ANSI A14.3 (1992), makes it certain that ladder safety hoops were described in a standard as early as 1956, but it is possible that they may have also been described in the 1935 version.

In both ANSI A14.3 (1984) and (1992), a cage is defined as: "***a barrier, which may be referred to as a cage guard or basket guard, that is an enclosure mounted on the side rails of the fixed ladder or fastened to the structure to enclose the climbing space of the ladder in order to safeguard the employee climbing the ladder***". A ladder safety system is defined as: "***an assembly of components whose function is to arrest the fall of a user***……". Again, there is a clear distinction between the levels of safety attributable to hoops and FAS. ***The phrase "safeguard the employee" is very ambiguous, whereas "arrest the fall of a user" is very definite and clear.***

In ANSI A14.3 (1992), the following general design points are of interest:

- Where cages are used, the ladder shall consist of multiple sections, each section horizontally offset from adjacent sections, with a maximum climbing length of 50 ft (15.2 m) between which landing platforms are to be provided;

- Where ladder safety systems (FAS) are used, the length of climb may be continuous, but rest platforms shall be provided at maximum intervals of 150 ft (45.7 m);

- A ladder safety system may be used in combination with a cage.

After considering the above, the question is again raised as to why caged ladders need a platform every 15.2 m, compared to 45.7 m for the FAS. Does this mean that a worker climbing a caged ladder requires more effort, and is more likely to become tired, per metre of climb? It is difficult to imagine that this is the case. In fact it would be more likely to be the reverse – a worker climbing a caged ladder has no impediment when climbing because there is no connection between the worker and the cage. Indeed, a worker may rest at any point within the cage, by keeping the legs straight and leaning back against the upright bars, (see Figure 33 later in the report). In the case of FAS however, the worker is connected to a rail- or cable-based member via a sliding arrest device, which has to be pulled up that member in response to body movement, which can cause an impediment over the heights involved.

Note also the use of the phrases "landing platform" for caged ladders and "rest platform" for ladders with FAS. Why are there two different terms for each method? Neither of the terms are defined in the standard, but the use of two different terms suggests two different functions. Also, in the case of a caged ladder, the "landing platforms" are offset, i.e. the climb is interrupted by the platform, so the worker has to negotiate the platform before proceeding with the next part of the climb. With the FAS case, the "rest platforms" are not offset; the worker has the option to "rest" on them if required.

The conclusion drawn from the above is that the "landing platforms" were originally conceived not so much to provide rest areas, but to provide "catch areas" which would probably stop someone falling down a caged ladder. This deduction is supported by the statement: "A ladder safety system (FAS) may be used in combination with a cage". It is difficult to understand why a FAS would want be fitted to a caged ladder, if the caged ladder could arrest a fall. ***It would seem that there is uncertainty in regard to the fall-arresting effectiveness of caged ladders, and that the fitting of FAS in conjunction with a cage gives a greater assurance. However the question remains as to whether both systems are compatible with each other in terms of arresting a fall.***

In regard to cage size and design, given that the standard was used as a basis for the Code of Federal Regulations CFR 1910.27 (1996), it will no surprise to find that requirements are near identical. Dimensions are summarised in Table 2.

In regard to use, a fundamental aspect in regard to climbing a ladder is mentioned: "when ascending/descending a ladder, the user shall face the ladder and maintain a three-point contact at all times. Three point contact consists of two feet and one hand or two hands and one foot which is safely supporting the user's weight…".

Ladder safety system (FAS)

When comparing the ladder safety system (FAS) requirements of ANSI A14.3 (1992) it becomes obvious that they were used a basis to write the Code of Federal Regulations 29 Part 1926.1053 (1996), as both sets of requirements are very similar. The requirements of particular note in ANSI A14.3 (1992) which are not mentioned in the CFR, are:

- The ladder safety system shall allow at least two persons, but not more than four, averaging 250 pounds (113.4 kg) each (including equipment), to ascend or descend simultaneously;
- Only one person at a time (except in rescue operations) shall use the same portion of rail or cable between intermediate mountings for rails or cable guides for cables;
- The system shall be designed to absorb the impact load of a solid object weighing at least 500 pounds (226.8 kg) in a free fall of 18 inches (457.2 mm). The sliding arrest device shall lock onto and stay locked onto the rail/cable within 6 inches (150 mm) of being released.
- Flexible components such as webbing and fabric shall have a safety factor of not less than 5 for the designed static load
- Cables shall have a safety factor of not less than 10 times the designed static load
- Ductile material shall have a safety factor of not less than 5 times the designed static load

There are no fall-arrest requirements for caged ladders.

It is interesting to note that this standard is the first document to be reviewed which mentions the need for rescue operations in the context of FAS requirements. (There is no mention of the need for rescue after a fall in a cage).

After a worker falls and is arrested by a FAS, they need to be recovered or rescued. At this point they will be suspended from the FAS, supported by their harness. They may be in shock and may have suffered some form of injury during the fall. Furthermore, they become subjected to "orthostatic shock", a condition in which motionless suspension can induce a retention of blood volume in the venous system of the legs, which reduces the amount of oxygenated blood available to the brain and other vital organs. Loss of consciousness and death ensue, so an immediate method of rescue is vital, as part of any working at height safety plan. A thorough review of this subject can be found in Seddon (2002).

2.4.3 Later documents

ISO/FDIS 14122-4

More updated requirements for caged ladders and ladder-mounted FAS can be found in ISO/FDIS 14122-4 (1999), a draft standard which may be published this year (2004). The identical European draft is prEN 12437-4.

An "anti-fall device" is defined as: "a technical measure to prevent or reduce the risk of people falling from fixed ladders – commonly used anti-fall devices are safety cages and guided type fall arresters on a rigid anchorage line".

A safety cage is defined as: "an assembly comprising of framework which serves to limit the risk of people falling from the ladder".

Guided type fall arrester on a rigid anchorage line is defined as: "protective equipment fixed to a ladder used in combination with personal protective equipment that everyone has available before being allowed to use the ladder".

These definitions appear to be quite confusing. ***The anti-fall device definition says that both cages and arresters are anti-fall measures. The cage definition then expresses that the cage limits the risk of a fall, but the fall arrester is just described using the ambiguous term of "protective equipment".*** These definitions are not consistent, and discriminate to some extent against fall arresters, i.e. that fall arresters are personal equipment, which "everyone needs before being allowed to climb".

In the requirements section, when safety cages are tested with a vertically applied load of 2.6 kN, any deflection has to be limited to 50 mm, and under a horizontally applied load of 0.5 kN, any deflection has to be limited to 10 mm. The FAS in contrast, with its fittings: "shall withstand the stresses caused by the fall arrester catching the person who falls down".

The way this is worded seems to be an attempt at disguising the fact that the safety cage cannot arrest a fall.

It is interesting to note that the 2.6 kN load applied in the vertical direction on a cage is the same load as that applied in a test to the rungs of a single-stiled ladder. These ladders have a single, central stile from which a pair of rungs emanate on either side (Figure 18). This stile is often utilised as the rail element of a FAS so, in effect, these types have the advantage of offering an integral FAS. In this case the 2.6 kN load represents the load that has to be resisted by the worker's foot during the climbing process. The fact that the same load and orientation is applied to a hoop, seems to anticipate that some workers may climb up hoops in some circumstances (as confirmed in BS 4211 (1967), on page 25 of this report).

ISO/FDIS 14122-4 (1999) proceeds with a description of the height above which protection is required: “the ladder shall be fitted with an anti-fall device when the height of the ladder flight is more than 3 m, or, the height of the ladder is 3 m or less, but at the departure area there is a risk of falling”. A risk of falling is considered to exist when the platform at the base of a ladder is unprotected and the edge of which is less than 3m away from the ladder.

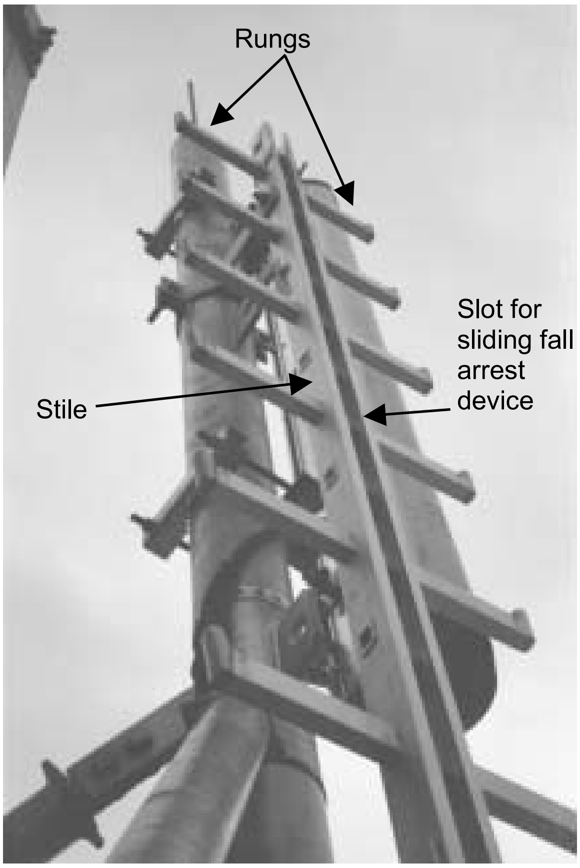


Figure 18 Example of single-stiled ladder with integral slot for sliding fall arrest device

Choice between cage and FAS

Discrimination against FAS and confusion about the fall-arresting effectiveness of cages continues with the “choice of the type of anti-fall device” clause: “Priority shall be given to the choice of the cage, as it is a collective means[16] which is always present and the actual level of safety does not depend on the activity of the operator” and: “if the cage is not possible to use, individual protective equipment shall be used. The guided type fall arrester on a rigid anchorage line is only effective if the user chooses to use it. If a harness with an incompatible sliding system is used with a guided type fall arrester, there will be a risk.” Then the confusion: ***“an appropriate individual anti-fall protection device is able to arrest a fall better than a cage”.***

[16] *Collective protection is for the common use of any worker or workers, who at any particular time enter the work area bounded by the protection; no special training or other equipment is needed, whereas individual protection requires training and other equipment. Also collective protection is fixed to the workplace structure as opposed to being fixed to the worker, which facilitates mobility. However collective protection may not be as effective in protecting workers when compared to individual protection.*

It is true that collective measures in general are the preferred means of protection, but only where the effectiveness of those measures can acceptably lower the risk involved. The phrase: "the actual level of safety does not depend on the activity of the operator" is difficult to comprehend, since body attitude at the onset to a fall in a caged ladder may affect whether a limb or other part of the body catches or jams against a hoop during the fall, or whether the fall continues down to the platform below. This is shown to be the case from the results of the test programme, refer Section 5.

The statement about fall arresters is very obvious: "is only effective if the user chooses to use it". However the next statement about incompatibility is very important, because if one manufacturer's fall arrester is used with another's rail or cable system, the system may not arrest properly in a fall situation.

The advice about collective measures being the preferred means of protection is thrown into confusion by the statement about FAS being able to arrest a fall better than a cage. The greatest risk when climbing a ladder is that of falling-off the ladder, so FAS should be the preferred choice. Some would say it is the only choice, because it would seem that the fall-arresting performance of ladder cages is unknown.

Hoop configuration

In regard to hoop configuration, ISO/FDIS 14122-4 (1999) prescribes a circular hoop (no rectangular shape shown), with a maximum vertical distance between hoops of 1.5 m, and with a maximum distance between vertical bars of 300 mm. This in effect creates 5 bars as opposed to the UK's 3 and the U.S.A.'s 7. Also: "the spacing of safety cages shall be designed so that the empty spaces are not more than 0.4 m^2 ".

"Empty spaces" are the curved, rectangular shaped gaps formed by the framework of the cage. It would seem that either workers have been falling through these gaps or else the perception of that risk has changed and hence the reduction in allowable area to 0.4 m^2.

The diameter of the cage and distance from rung to back of cage is prescribed as 650-800 mm. There is no association with dimension and ladder inclination as with BS 5395 pt 3 (1985). Some of the other dimensions are difficult to interpret as the diagrams and text do not appear to confirm one another.

There is an interesting confirmation of specification of the Code of Federal Regulation 29 Part 1910.27 (1996), see Figure 13, which requires the extension of the bottom of a caged ladder down to meet the guard rail, if the horizontal distance from the ladder to the guard rail is 1.5 m or less. ***This caters for the risk of a worker falling or stumbling down the bottom 3 m of the ladder, where a cage is not fitted, and then impacting the platform in close proximity to the guard rail, such that the momentum of that fall or stumble would otherwise cause a fall over the rail.***

Trap-doors

Trap-doors in platforms are also described. These are openings in platforms, (guarded by doors which hinge upward), to allow access to a ladder below. ***The point of interest is in the statement: "the dimensions of the opening shall be at least equal to the dimensions (diameter) of a safety cage". The reason for the interest is that so far no evidence has been discovered as to why safety hoop dimensions are set as they are***, (see Table 2). Prompted by the above trap-door statement, one theory that can be put forward is that hoop dimensions could have been created from trap-door dimensions.

Holes in platforms are dangerous because of the risk of workers falling through them, so they tend to made as small as possible, whilst allowing a man to pass through. Consequently, anthropometrical data has to be consulted. In Pheasant (1996), the minimum 95th percentile diameter to allow a "heavily clothed person" access through a circular aperture in a horizontal surface is 600 mm, (according to ISO 2860 [17]), and 760 mm, (according to MIL-STD-1472C [18]).

When studying Table 2, a comparison between safety hoop sizes from various documents, it can be seen that the 760 mm dimension is virtually identical to a number of the hoop dimensions quoted. So the trap-door dimension could have automatically led to the setting of the hoop dimensions by certain groups.

Platforms

ISO/FDIS 14122-4 (1999) adopts the stance that if a fixed ladder is to be more than 10 m high then it has to be equipped with one or more platforms. Distance between platforms is 10 m maximum, but "preferably no more than 6 m".

BS 4211 revision

BS 4211 (2002) is a draft standard intended to revise BS 4211 (1994) and is: "to adopt, where appropriate, the requirements of ISO/FDIS 14122-4 (1999)".

One difference is highlighted in a note: "The use of single stile ladders is not recommended in the UK". There is no explanation attached to this note, so it can only be assumed that there is some safety concern, or else some form of discrimination, because these types of ladders, (see Figure 18), are extremely popular on the European mainland. Furthermore, they have the advantage of offering a FAS which is integral to a ladder, so there is no need to purchase and install these items separately.

There is also clear discrimination against the use of FAS in regard to choosing either a cage or FAS for fall protection: "a passive protection system, for example, safety cage, shall be the preferred choice. Where it is not possible to use a cage, individual protective equipment shall be provided. A fall arrester shall be provided only where low frequency and specialised access (e.g. maintenance) is required". It is noted that this draft standard does not include the note from ISO/FDIS 14122-4 (1999): "an appropriate individual anti-fall protection device is able to arrest a fall better than a cage".

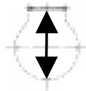
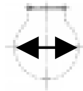
2.4.4 Summary of hoop sizes

A summary of hoop sizes and configurations is shown in Table 2, in respect of documents previously mentioned. Whereas differences may be due to anthropometric variations in different parts of the world, in general it appears that there is not a great deal of difference.

However, from the documents reviewed, this part of the research has not satisfactorily identified the basis for the dimensions themselves.

[17] *An international standard that deals with earth-moving machinery; the dimensions it gives are: "the smallest that will accommodate 95% of the worldwide operator population"*
[18] *An American military standard*

Table 2
Comparison between safety hoop sizes from various documents

Document	***Hoop pattern***	***No. of vertical bars***	***Rung to hoop (mm)*** 	***Hoop width (mm)*** 
CFR 29 pt 1910.27	Circular	7	685 min 711 max	711 min
CFR 29 pt 1926.1053	Circular	7	685 min 762 max	762
BS 4211: 1967	Circular	3	762 min 838 max	687 min 762 max
	Rectangular	3	685 min 762 max	685 min 762 max
BS 4211: 1987 & 1994	Circular	3	760 min 840 max	700 min 760 max
	Rectangular	3	690 min 760 max	690 min 760 max
BS 5395 pt 3: 1985	Circular	3	760 for vertical ladder, to 840 for a pitch of 75°	700 min 760 max
	Rectangular	3	690 for vertical ladder, to 760 for a pitch of 75°	690 min 760 max
A14.3: 1992	Circular	7	685 min 762 max	685 min
ISO/FDIS 14122-4: 1999	Circular	5	650 min 800 max	650 min 800 max

2.5 RESEARCH PAPERS

In Chaffin and Stobbe (1979) a 110 page U.S. document reports on research into the following areas:

- Analysis of scaffold fall injury statistics
- Evaluation of scaffold plank set-away distances from walls and guardrails
- Evaluation of the potential fall protection provided by cross-braces of scaffold
- Factors affecting the maximum dynamic step loading on fixed vertical ladders
- Ladder inclination effects on torso-to-ladder distance.

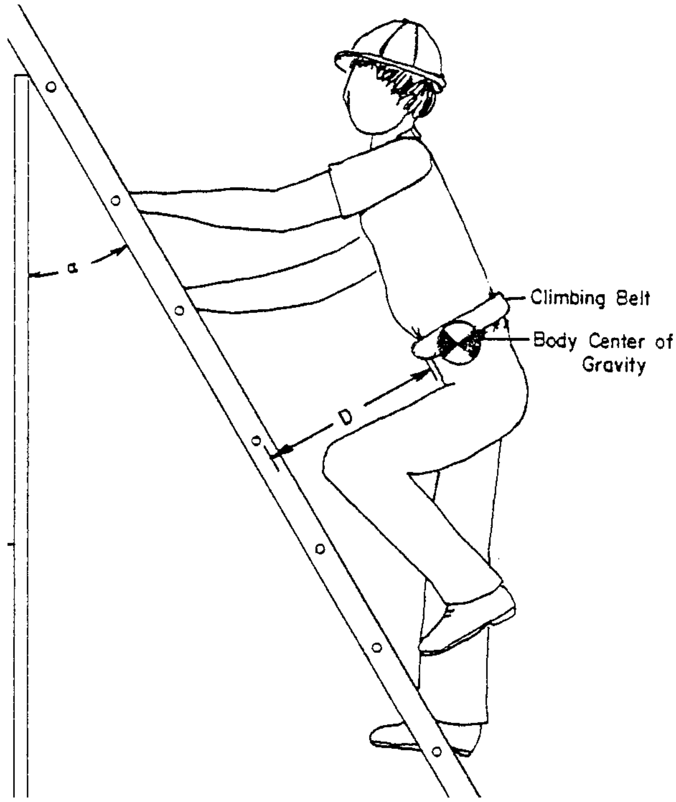
The work was commissioned by OSHA, relating to certain ergonomic considerations pertinent to proposed modifications to Subpart D "Walking-Working Surfaces" of the Code of Federal Regulations 29 Part 1910.

Whilst this work, amongst other things, studies the anthropometric dimensions necessary to prevent falls through and falls over guardrails, it does not study falls in caged ladders. However it did study the problem of using a ladder climbing safety device (FAS) on inclined ladders: "with the advent of more effective ladder climbing safety devices, it has become desirable to use these on inclined ladders more than 15° from the vertical".

In so doing, Chaffin and Stobbe (1979) describe how the lanyard between the climber's belt[19] and the fall-arrest cable or rail must be longer than when used on vertical ladders, to allow a climber to remain in a normal climbing attitude, (to keep the body's centre of gravity over the supporting foot). If a normal, short, lanyard is used, (as in a true, vertically orientated system), "the climber is forced to lean forward in the climb, close to the ladder, placing a fatiguing stress on the arms and shoulders and creating interference with normal leg motions".

The study focuses on the distance normally needed between the anterior portion of the climber's belt and the rungs of a ladder, with the ladder inclined at 10°, 20°, 30° and 40° from the vertical, Figure 19.

[19] *Waist belts would have been the main body containment device for fall-arrest purposes at the time, but are unacceptable for use today*



Notes: Angle α = angle of ladder from vertical

Dimension D = distance from anterior of climber's belt and sliding fall arrest device

Figure 19 Inclined ladder investigation after Chaffin and Stobbe (1979)

Chaffin and Stobbe conclude that a distance "D", see Figure 19, of 12 inches (305 mm), was not sufficient to allow a safe climbing posture at ladder incline angles greater than about 20° from the vertical. In fact: "the distance D necessary for a ladder inclined at 40° from the vertical would probably need to be as large as 20 inches (508 mm) to accommodate a tall, slim 95th percentile male". This would create falls of greater distances. The point is made that: "it may be necessary to require fall safety devices (FAS) on vertical or near vertical ladders deviating less than 20° from the vertical, and require climbing cages on more inclined ladders, unless the climbing safety device manufacturers can provide equipment which will allow a normal climbing attitude"… (without the attendant free fall dangers).

In slightly earlier work, Chaffin et al (1978), a 179 page report similarly used to justify OSHA's regulation making, addresses the following topics:

- Fall injury, severity of falls of varying heights
- Basis for selecting types of fall protection systems
- Stair-railing height specification

- Handrail dimension
- Use of varying size wire rope for fall guarding
- Scaffold cross-bracing for fall guarding
- Fixed ladder dimensions
- Fall warning systems.

Most of these areas are not of interest to the present investigation, but some content is relevant, or is at least of interest. For example, 925 fall accidents are surveyed in respect to heights fallen, and resulting injury. There was a 14% fatality rate for free falls of 4 feet (1.22 m) or less, and a fatality rate of 13% for free falls of 5 to 10 feet, (1.52 to 3.05 m). Fatalities were most often due to head injury, and the remainder to trunk injury. Feet first falls resulted mainly in fractures to the long bones of the legs, or the bones of the feet and generally held no serious consequences.

Chaffin et al (1978), go on to show that the portion of the body that sustains the initial impact, thus absorbing the most energy, after a fall depends on the fall height. Persons who fell less than 20 feet (6.1 m) landed on their heads 74% of the time, while persons who fell more than 20 feet (6.1 m) landed on their feet 63% of the time. This again indicates the high exposure of the head to possible injury in short falls.

Severity indicators for free falls are also discussed, namely: impact velocity, body orientation at impact, portion of the body initially impacted, surface impacted and degree of rigidity, sex and age of subject, impact time, rate of onset of acceleration and deformation distance.

Chaffin et al (1978) concluded that a fall from a 2 ft (0.61 m) high platform would result in only minor injuries to most people so involved, and therefore a fall warning system of signs, floor lines etc, would be adequate protection. A fall from a 4 ft (1.22 m) high platform would result in injuries of a severity to make “guardrails, safety harnesses and safety nets necessary”.

Work is also reported on the likelihood of falling through a guardrail. One specific criterion for the design of guardrails at the time (1976) as an effective fall protection system is the size of openings allowed in the system. This was expressed in the statement: “any opening in the guardrail system shall reject the passage of a spherical object of 19 inches (482.6 mm). This will “inhibit accidental passage of the human body through guardrail openings”. This dimension was based on the shoulder width of the 95th percentile U.S. adult male in 1963.

Further, work is conducted in assessing ladder dimensions. This includes windblast forces and the verification that the human strength could withstand certain loadings whilst gripping the ladder.

This includes a focus on the dimensions of the ladder stiles: “Handrail (stile) dimensions are of major importance when providing fall protection. If designed such that they can be easily grasped and are positioned accordingly, a handrail (stile) can provide the stabilizing forces to prevent a fall. When climbing a ladder, the ability to securely grasp onto the ladder is even more critical than when using stairs, since hand and arm supporting forces are continually required to keep the body from falling backwards or to one side during ascent or descent”.

Observations are that: “the rungs provide a poor substitute for a side rail (stile) for adequate grasping ability, since they are often covered with dirt, grease and other accumulated grime of which a worker would not normally attempt to grasp. Attention should be given to the side rail (stile) dimensions, so as to provide an adequate handrail”.

It can be seen from this part of the report that a great deal of effort was expended in the anthropometric detailing of fixed ladder dimensions, the results of which found their way into the U.S. Code of Federal Regulations, and possibly into Europe and other continents. However, what is quite amazing is that there is no overt mention at all to cages and their dimensions. It may be that cages were assessed in another one of Chaffin and Stobbe’s research investigations, or by their colleagues and scientific community at Michigan University, but given the comprehensive content of the two aforementioned reports, the coverage of those reports, and the total lack of mention of cages in the bibliographies in those reports, it seems difficult to accept that any assessments on cages were ever made.

The only recommendation in fact, to come from the fixed ladder portion of the report with respect to fall protection was, in respect of ladder rung width: “a minimal width between side rails (stiles) shall be 12.7 inches (322.6 mm) for all fixed ladders. If a ladder is exposed to wind gusts over 40 mph (64.4 km/h) while in use, the minimum width shall be increased to 16 inches (406.4 mm) and a rigid centre rail safety climbing device (FAS) shall be provided”.

In Dewar (1977) a detailed investigation is made of body movements when climbing a ladder. It was thought that this paper may cast some light on how hoop measurements were arrived at. Descriptions are given of (i) the displacement and rotation of the pelvic girdle and trunk and (ii) rotation of the knee and hip joints. The descriptions are derived from cine film of a laboratory experiment in which 35 male subjects climbed a ladder set at 70.4° and 75.2° inclinations. The results indicated that, at the steeper ladder angle, the hands play a greater part in maintaining the balance of the body and there are greater differences between the movement patterns of tall and short subjects. These, in turn, suggest a decreased stability of the body and was thought to have a bearing on the kind of ladder accidents in which the worker slips or misses his footing. However no references to caged ladders could be found in this document.

2.6 MISCELLANEOUS DOCUMENTS

This is a summary of literature found in sources other than legislation, official guidance and standards, and research papers. It includes items from engineering hand books and manufacturer’s literature

2.6.1 Safety engineering

In Marshall (1982), a U.S. book on safety engineering refers to the features of fixed, vertical ladders. Of special note is that when a person is climbing such a ladder, “their centre of gravity is outside the ladder itself”. If that person loses control on the ladder, there is a greater likelihood, claims Marshall, that he or she will fall off the ladder rather than onto it, as with, say an inclined ladder. Marshall goes on to claim that it is for this very reason that a cage, or ladder safety device (meaning FAS), is required on vertical ladders more than 6.1 metres in height. Also of importance: “***If a cage is fitted, then it must permit easy movement on the ladder but restrict how far away from the ladder the body can move***”.

This seems to confirm that the cage dimensions are crucial, anthropometrically.

In EEMUA (1996), the Engineering Equipment and Materials Users Association handbook specifies requirements for fixed ladders. This follows much of that contained in BS 4211 (1987). EEMUA (1996) itself was utilised in the production of BS 5395 part 3 (1985). Many of the requirements contained are therefore the same as already mentioned under standards BS 4211 and 5395, so are not repeated here. The following however, are notable points of interest to this research.

The handbook claims to have taken the definition of safety hoops from BS 4211 and BS 5395 part 3 as: "a bar fixed to both stiles to enclose the path of the person climbing the ladder". However the handbook has been careful to miss off the last part of the BS 4211 definition, which says: "a bar fixed to both stiles to enclose the path of the person climbing the ladder, ***to prevent them falling outwards***". BS 5395 part 3 itself has no definition.

In regard to application: "fixed ladders should be installed only where occasional access is required and where the provision of a stairway is impracticable", and: "adequate clearance should be provided around the ladder to ensure safe use".

In regard to heights: "ladders should not rise more than 6 m without the provision of an intermediate landing; this should preferably break the line of the ladder…….. ***and will prevent a fall to a lower level***………………although this need not apply to access ladders on chimneys and similar high structures", and: "safety hoops should be provided where there is a risk of the user falling from a height of 2.0 m or more, or where there is a risk of coming into contact with dangerous equipment".

This is an overt mention of the fact that intermediate landings were obviously intended as catch platforms to stop the fall of a worker, in case the safety hoops didn't. What is of concern is that the advice effectively allows a worker to fall down a hooped ladder for a potential 6 m. But the same statement seems to be saying that hoops can offer some form of protection against falls from a height, i.e. "they should be provided where there is a risk of the user falling from a height of 2.0 m or more". These statements seem to be in conflict with each other, and, to the reader the situation is quite confusing.

It is interesting that hoops are also to be used as a sort of guard, to prevent contact "with dangerous equipment".

Later on, under "safety equipment", FAS are also specified for ladders, which is rather confusing after stating that safety hoops are the only means of protection, earlier in the document. Safety equipment, as before: "should be provided where there is a risk of the user falling from a height of 2.0 m or more, or where there is a risk of coming into contact with dangerous equipment. This may take the form of safety cage and hoops, or a fixed vertical rail or wire designed to be used in conjunction with a harness and sliding fall arrest equipment".

In regard to safety hoops themselves: "hoops should be connected by at least 2 vertical straps with additional bracing as required to support their weight. A third strap to support the back of the hoops is strongly advised and preferred for the majority of applications". This seems to indicate that some safety hoop installations did in fact only have 2 vertical bars, which would have greatly increased the possibility of someone falling through the cage to the ground or other substantial platform.

Hoop dimension are identical to those in BS 5395 (1985), see Table 2.

Under "ladders for access to high structures", Type "A" ladders as described in BS 4211 (1987) are excluded from EEMUA (1996).

Type “A” ladders are described as: “steel ladders with single bar rungs intended to be fixed to chimneys and other high structures to provide means of access. They are also specified to be used in other locations where corrosive conditions may exist. Where ladders are used on chimneys, provision of rest platforms may present design problems and a continuous length of ladder may be used. Safety hoops or other approved form of fall arrester (see BS 5062) should be incorporated”.

EEMUA (1996) again seems to be indicating that the safety hoops are an approved form of fall arrest protection.

There is again the statement that intermediate platforms are in effect catch platforms: “the line of a ladder should be broken at landings in order to limit the free fall distance of any one who may be using the ladder.” This distance may be an incredible 9 m: “for ladders used for occasional access the maximum distance between platforms is increased from that given in BS 5395 of 6 m to 9 m”.

2.6.2 Trade publications

An interesting assertion is made by J.N. Ellis, writing in the notable U.S. Best’s Safety Directory, Best (1978): “Fixed ladder climbers need suitable fall protection systems. Basket cage protection consists of metal hoops installed around fixed ladders according to an OSHA requirement. ***This arrangement has the advantage of being a one-time installation for the employer with low maintenance and little or no training procedure for safe climbing. In chemical process work with many operators this has a decided advantage. However caging gives low personal protection. At most it gives psychological protection and serves as grab bars for a falling worker***”.

This emphasises the benefits of caged ladders in terms of their simplicity and their collective method of protection, but it questions what form of protection is actually given. In contrast: “***Climbing safety devices (FAS) offer a personal safety system which positively limits a worker’s fall***. On tall ladders they are especially needed if only for economical reasons.”

In regard to the offset platform rule: “OSHA requires protection of all fixed ladders more than 20 ft (6.1 m) high. If caging is used however, then a maximum 30 ft length (9.15 m) is specified and landing platforms must be provided. Ladder safety devices however, if used in lieu of caging or wells, require no offsetting landing platforms and the ladder climbing safety system may extend the entire length of the ladder. Since OSHA’s standard on fixed ladders is under revision, the OSHA Program Directive #200-36 makes ladder safety devices essentially an equal alternative to caging for all fixed ladders and not just those on chimneys, towers and water tanks”.

Although the reasoning above is quite sound, there is a bias towards FAS manufacturers – an advert in Best (1978) sums up the commercial competition between hoop and FAS manufacturers, Figure 20. Note the claims: “regardless of the length of climb….the device...does not require offsetting platforms as required by OSHA for cages and can be installed for one-third the cost of a cage”. Also: “a…..fall prevention system can upgrade your existing cage to comply with OSHA standards without expensive modifications”.

Furthermore in Ellis (1993), reference is made to more contemporary proposed changes to U.S. legislation: “since OSHA’s standard on fixed ladders, in 1910 subpart D has been proposed for revision, OSHA program directive 100-57 makes ladder safety devices (FAS) essentially an equal alternative to caging for all fixed ladders and not just those on chimneys, towers and water tanks. ***Cages are recognized by safety professionals as failing to provide positive fall protection. They provide at best, perhaps, psychological comfort and resting points***. Therefore, climbing protection systems (FAS) should be used in addition to cages for effective personal protection”. Also: “ANSI A14.3-1992 permits ladder FAS to be used with cages for more safety”. This indicates a clear trend away from relying on safety hoops for fall protection.

2.6.3 OSHA interpretations

In Kurtzer (1997) questions about fixed ladders are put to OSHA for interpretation in regard to Code of Federal Regulations Part 1910.27 (1996). OSHA’s answers are tabled under each question. One of the questions concerns when ladder cages were first introduced. According to OSHA, the Code was first introduced in 1971, and since then the ladder cage requirements for fixed ladders have remained unchanged.

In another question, the height to which a ladder can rise without the need for fall protection is questioned. OSHA replies using a proposed rulemaking, but also goes to talk about cages: ***“questions have arisen regarding the effectiveness of cages in protecting employees and OSHA by this notice solicits comments, supported by information and data, regarding the extent to which reliance on cages either protects or endangers employees”***. It would seem that OSHA themselves do not know what ladder cages actually do in the event of a fall.

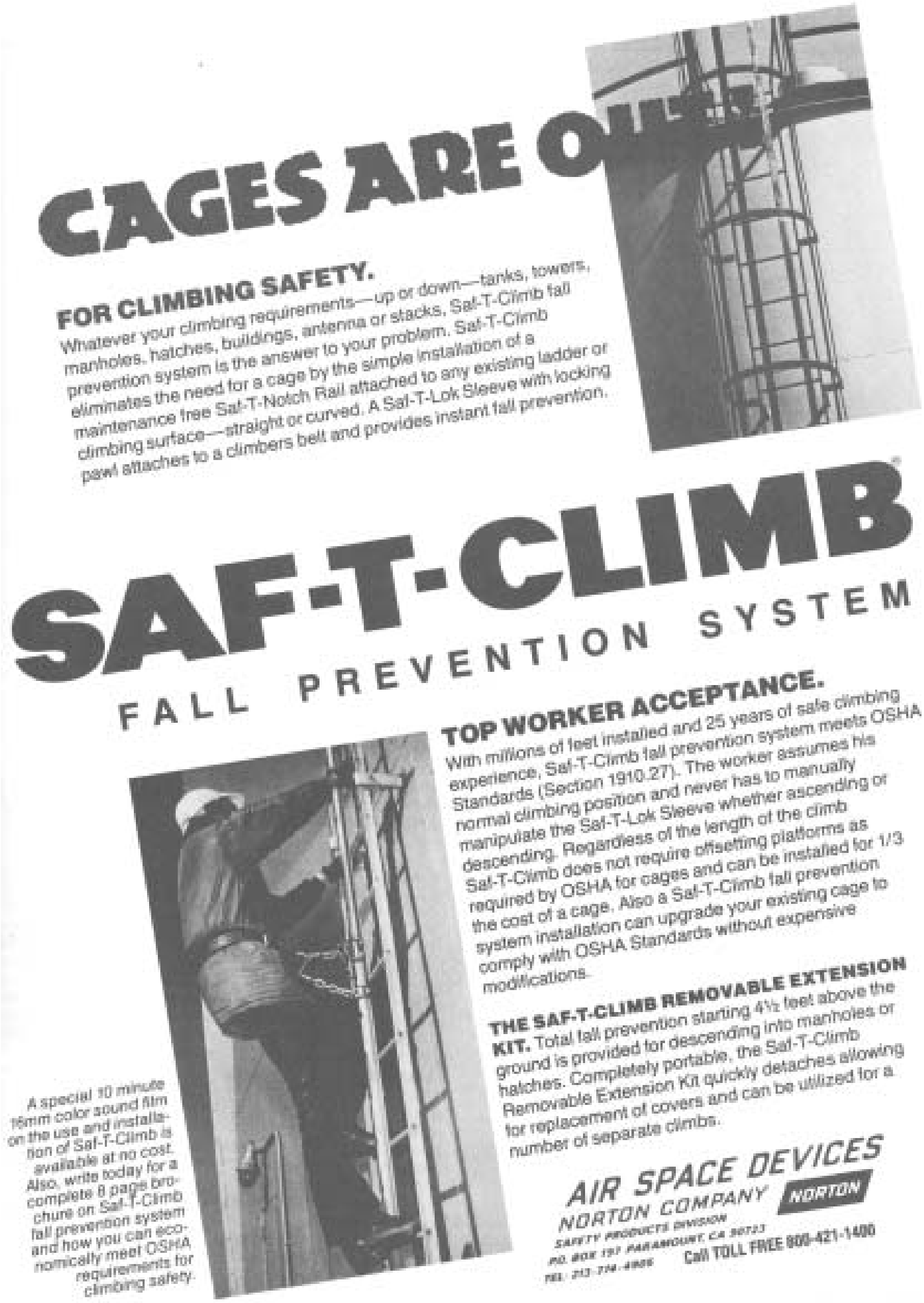
In Berry (1999), the U.S. National Ski Areas Association put questions to OSHA in regard to ladder cages on fixed ladders that are installed onto ski lift towers. Berry argues that the presence of cages presents a significant hazard to riders using the ski-lifts, as their skis are likely to become entangled in the cage structure. In addition, in bad weather, the possibility of ice accumulation on the cage creates an unacceptable potential for structural failure. OSHA accepts with this assessment that such conditions create situations where using cages may prove infeasible or may create a greater hazard. FAS are proposed for use instead.

In Ellis (1999), questions are put to OSHA about working off fixed ladders as opposed to using them for climbing activity. Particularly, can a worker lean out from a ladder while working by using the ladder safety system for support? (That is, by leaning back against a cage with the feet still on the rungs, but hands off the stiles). As part of the reply, OSHA states that: “***a cage is usually designed to provide fall protection while moving up or down the ladder – not while working with both hands off the ladder***”. This seems a strange reply – but perhaps it indicates that if both feet were to slip off the rung, then the worker would probably fall down the cage[20].

OSHA goes on to say in respect of the same question when applied to FAS: “Most ladder safety systems (vertical lifeline type systems) are not designed to support a worker leaning out from the ladder; they are usually designed to protect a worker while fully on the ladder. ***Also, a cage is not designed to provide fall protection for a worker using the cage for support, or working with both hands off the ladder”. This appears to be saying that cages cannot provide fall protection when the body is in certain postures.*** And: “using ladder safety systems (FAS) or cages for support would violate Code of Federal Regulations 29 Part 1926.1053 (1996)”.

This would appear to negate the school of thought that cages were provided as a back-supporting means.

[20] *Assessed for in the testing phase, see Section 5*



Note: the worker in the photograph at the time is wearing a waist belt for fall-arrest purposes. This is not an acceptable practice today.

Figure 20 Example of 1978 advert summing up competition between U.S. caged ladder and FAS manufacturers after Best (1978)

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3. SURVEY

3.1 INTRODUCTION

A small-scale survey of fixed ladder suppliers and users was undertaken. This took the form of an informal search and enquiry for information rather than a structured survey. It attempted to establish reliable historical, technical and accident information by way of telephonic and internet enquiry. Twelve supplier and user organisations were contacted who were most likely to be able to contribute some level of knowledge. No interviews or group discussions were conducted. Questions were limited in number and complexity in order to reduce the burden on respondents. Best survey practice was employed.

Questions asked were:

- What are ladder safety hoops?
- What do they do?
- What is their historical background and development?
- What is their fall-arrest capability?
- Has any research been conducted?
- What documents, currently available, contain any information on ladder safety hoops?
- Are ladder safety hoops fitted in preference to a ladder-mounted FAS as the preferred protection method or vice versa? Why?

Various on-site studies were made to supplement the above. National and European standards-making committees were also contacted.

3.2 SURVEY RESULTS

Disappointingly, the ladder manufacturers and steel fabricators contacted knew little about caged ladders. Most were simply producing them to BS 4211 (1994), and could readily quote dimensions and materials, but very little information could be elicited in regard to whether hoops could arrest the fall of a worker or not. There was no knowledge as to when hoops were introduced and how they were developed.

When asked about whether there was a preference for hoops or for FAS, most said that they would fit both systems. This included a manufacturer who specialised in glass-fibre ladders.

Some mentioned the cost of transporting sections of hoops to site, which made them too expensive compared to installing a FAS, especially over a long ladder run.

In one case a German ladder manufacturer was contacted for information. This manufacturer referred to the German standard, DIN 18799 Part 3 (1999), which details “rűckenschutzkorb” (ladder safety hoops) for chimneys. ***This standard apparently states that, due to the corrosive effects of the gas stream from chimneys, hoops are to be preferred over FAS in that circumstance.*** (There is a concern that the sliding fall arrest device would not work properly). This manufacturer also claimed that the ***DIN standard mentions the lack of protection afforded by hoops***. DIN 18799 Part 3 (1999) was not obtainable during the timeframe of the project, but would be a key document to obtain in future research.

In regard to the background of cages, the same manufacturer thought that they were originally intended as back-rests, and had been developed from the marine industry. They thought that the typical ship’s lookout platform cage had been developed downwards in order to prevent a fall outwards. Also that a caged ladder might afford good protection whilst on-board a ship. The swaying motion of a ship could throw a worker off the ladder, whereas the hoops would provide a steadying measure and would act as grab-bars.

One of the main problems arising from the users of caged ladders in this enquiry and that from previous work when caged ladders were encountered was that of uncertainty. Personnel who conduct risk assessments on work at height in the course of their duties cannot say with any degree of certainty whether safety hoops reduce the risk of falling or not. This is because there are no known test methods which subject the apparatus to a simulated fall as with FAS. There was also concern expressed that a falling worker may severely injure themselves on the hoops as a result of limb entanglement or localised impact. All this leads to some companies installing FAS within cages which can make climbing up the ladder very difficult. There is also the question whether the impacts against the cage during a fall would interfere with the locking action of the sliding fall arrest device.

There were comments about the potential difficulty arising if a rescue was required to recover a worker who had fallen whilst within a cage. The perceived entanglement of limbs would be a concern – how would the worker be lifted in order to disentangle the limbs from the apertures formed by the hoops and vertical bars, so that they then could be lowered.

3.3 ON-SITE INVESTIGATIONS

As part of other work, various opportunities arose to study ladder safety hoops on site:

- On a railway bridge which spanned a large river, a slightly inclined, fixed hooped ladder was studied, which had its rectangular apertures meshed-in along the lines of BS 5395 part 3 (1985), refer Figure 17. The reason for the meshing was that the ladder was on the side of the bridge and any fall through the cage’s apertures would have meant a fall into the river, with almost certain fatal consequences. The company concerned had identified this to be a significant risk and had specified hoops with in-fill.

- A Norwegian crane (Figure 21), had an access ladder running up to a platform on top of a central tower structure. As it can be seen from Figure 21, although a cage is fitted, it would appear to have only two uprights. It is extremely unlikely that this arrangement would stop the fall of a worker down or through the hoops.

- A mooring point (Figure 22), had a two-hooped caged ladder for access to and from a mooring point. This was an example of the idea (page 31) that a single hoop can possibly restrict a worker falling backwards or sideways (into the sea in this instance) when moving from the horizontal to vertical planes or vice versa.

Figure 21 Caged ladder with two uprights

Figure 22 Caged ladder at mooring point

- A crane tower in Brussels had an internal access ladder up to the control cabin, but the run of the ladder was broken into several inclined short flights, Figure 23. A worker climbing up/down would adopt a zigzag motion between each flight. A three-bar cage was fitted to each flight, and the thinking behind this approach appeared to be that the cage could prevent a fall outwards, but if a worker fell down the cage, then it might be relatively short. Note also the guardrails at the bottom of each flight in Figure 23.

Figure 23 Caged ladder on crane tower with zigzag run

- A number of fixed ladders giving access to signalling posts were studied on the UK rail network. Most of these either had a single or double hoop arrangement at the top of the ladder. In the case of the single hoop arrangement, Figure 24, the hoop was formed by an extension to the top of the stiles. However the dimensions of the hoop were smaller than in the case of conventional hooped ladders, and it appeared that these were designed not just to prevent an erect worker from falling backwards, but more so to allow an erect worker to lean back against the hoop, in a work-positioning stance, to allow both hands to be free for attending to the task in hand.

Also in Figure 24 a mesh screen can be seen, which is probably a guard to prevent a sideways fall off the ladder, although guarding against coming into contact with electrified lines is equally possible.

Figure 24 Single hoop formed by extension to top of ladder used for work positioning purposes

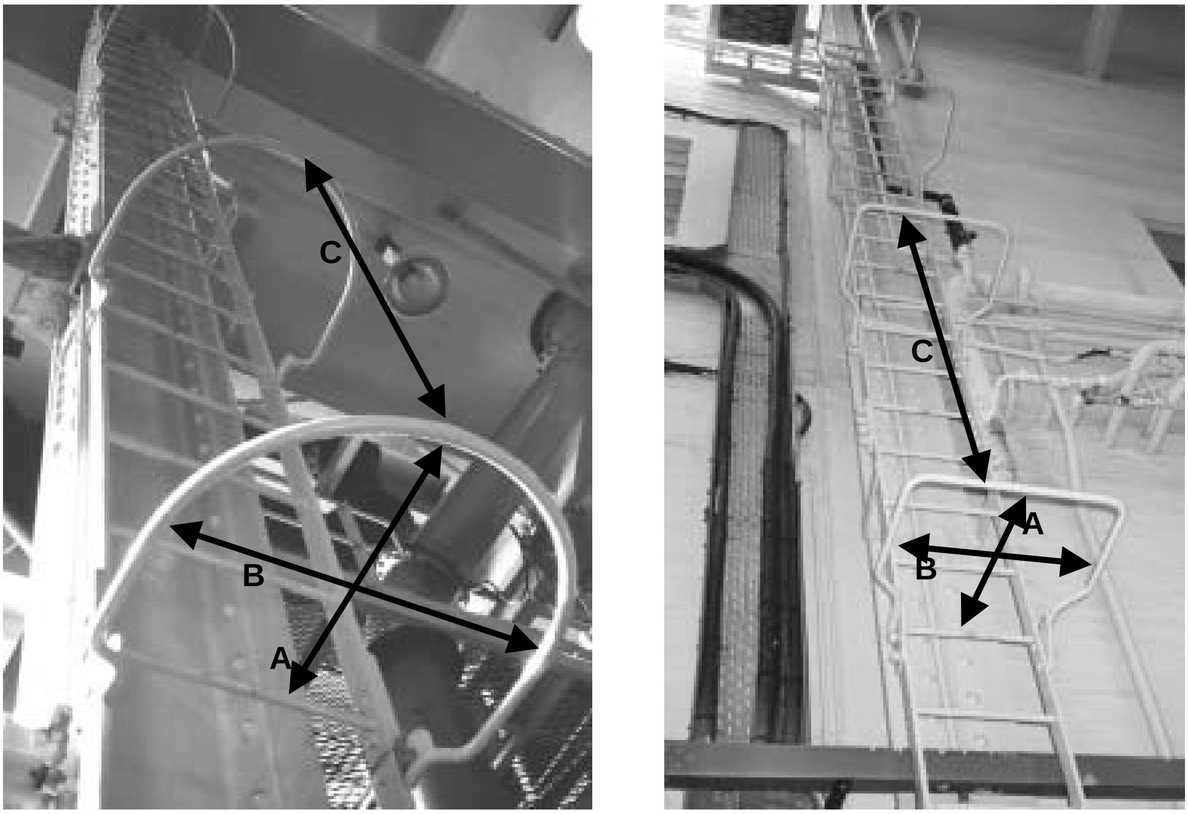
This work-positioning theme is continued in Figure 25, which shows another access ladder attached to a signalling post, but this time to a platform rather than the post itself, and also with two hoops of unequal size. It would appear that the lower hoop is of the traditional size, the intention of which would be to restrain the back of a worker if they fell whilst either ascending onto or descending from the platform, whereas the smaller upper hoop provides the same work-positioning function when the worker is standing erect as that shown in Figure 24.

Figure 25 Two hoops of unequal size on top of signalling work platform

- Two ladders of special interest were studied, Figure 26. These were hooped ladders without vertical bars, one having a circular pattern, the other, rectangular. The hoops themselves were made of solid bar as opposed to steel strap, and were welded to a ladder bracket. This gave them sufficient rigidity on their own, without the need for bracing from vertical bars. The dimensions were also very different to the corresponding dimensions as laid down in BS 4211 (1994), see Table 3 for comparison.

  It can be seen from Table 3 that the dimension for these hoops are somewhat smaller than conventional BS 4211 hoops. It can also be seen from Figure 27 that climbing through these hoops was quite difficult as when compared to a conventional BS 4211 caged ladder, but that once through, they were ideally sized for work-positioning purposes. A worker could lean back and have both hands free for work, Figure 28, in a similar manner to using a pole-rope or –strap with a safety harness.

  These items were clearly not designed for fall protection purposes either when in the hoop or between hoops, as, if a fall occurred, the hoops would not arrest a fall at all. ***This leads to the hypothesis that perhaps originally, hoops were for work positioning purposes, and they were developed with vertical braces so as to guard the path of a worker from falling outwards from the ladder.***



Note: see Table 3 for dimensions A, B and C

Figure 26 Hooped ladders without vertical bars

Table 3

Comparison between safety hoop sizes of Figure 26 and BS 4211 (1994)

Subject	***Dimension "A" (mm)***	***Dimension "B" (mm)***	***Dimension "C" (mm)***
Circular hoops in Figure 26	500 (760-840)	500 (700-760)	1200 (900)
Rectangular hoops in Figure 26	500 (690-760)	530 (690-760)	1500 (900)

Note: Corresponding dimensions from BS 4211 (1994) in brackets

Figure 27 Comparison of climbing through hoops from Figure 26 (left and centre views) compared to BS 4211 hoops (right hand view)

Figure 28 Working hands-free on ladders from Figure 26
whilst leaning back against hoops

3.4 STANDARD-WRITING COMMITTEES

As part of the enquiry process, the standard-writing committees responsible for the various UK and European fixed ladder standards were contacted, to determine if any person on those committees would be willing to provide information about ladder safety hoops.

In earlier research, Riches (1999), the British Standards Institution (BSI) Technical Committee B/542 were contacted for specific guidance on the specification of ladder safety hoops as shown in BS 4211 (1994). This document had been prepared by subcommittee B/542/9. A letter was written, Riches (1995), asking if the experts of B/542 could confirm the purpose of safety cages on fixed ladders, especially from a risk assessment[21] perspective. In this letter the author explained his understanding that the purpose of a caged ladder was to prevent a climber from falling off the ladder in a backwards direction. Given that the human skeleton can be modelled as a system of levers and joints, it could, during the action of a fall, lock by wedge action of the back against the cage, and knees against the rungs of the ladder, to prevent a fall to the ground. However this view had been challenged by other schools of thought which had said that the caged ladder idea had never intended to stop a fall by "body lock" but was simply intended as a psychological gesture to give assurance to a prospective climber.

A letter, BSI (1995), was received in reply stating that the above letter had been circulated to all members of the committee, along with a request to confirm the purpose of a ladder safety cage as shown in BS 4211 (1994). B/542/9 were also requested to send in comments if they felt that the standard should be amended. No information was ever received on either count by the author.

In the present research, the British Standards technical committee B/208, who are responsible for BS 4211, and the European Standards committee CEN/TC 114 WG 17, who are responsible for pr EN 14122-4, were contacted. The same questions as listed in clause 3.1 were asked, but not all were answered.

In the case of CEN/TC 114 WG 17, information was very limited. Emphasis was placed on the need for 5 vertical bands to be on a cage, and that hoops without these are not acceptable.

Apparently the dimensions of the hoops were the result of test methods, but no references to these test methods were forthcoming.

In regard to fall protection the statement was made that: ***"safety cages do not prevent downward falls, but they can stop falls with a backwards-motion of the user's body. Therefore this kind of protection is only permitted up to a falling height of 10 m; but with ISO 14122-4 this is reduced to 6m, if there are broken flights".***

There was no information available as to how safety cages can stop a backwards fall; no test data could be offered.

This again raises the question: is it safe to allow a person to fall down a cage either 6 or 10 m, as the case may be?

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[21] *Required under the Management of Health and Safety at Work Regulations (1999) in order for employers and self employed people to assess health and safety risks to workers and others who may be affected by their work or business. This enables them to identify the measures they need to take to comply with health and safety law.*

In the case of B/208, more detailed information was received, but it still did not answer all of the questions posed in clause 3.1.

In Stewart (2004a) a fixed ladder accident was described, (the same one as described in Safteng (2003), see Section 4). As part of the resulting accident investigation it was decided to obtain accident data pertaining to fall accidents on fixed ladders. None could be obtained from within the UK, but a study had been made in France, a summary of which was obtained, Stewart (2004b).

The summary mentions the first French standard written about fixed ladders which concerned "fixed ladders on tower cranes". Within this standard, the maximum height of an individual flight was specified as 12 m. At that time there were no other standards for fixed ladders in France, so this standard was used by other industries, including those who required to gain access to machinery and to plant.

Statistics recorded by CNAM (the National Health and Safety Fund) and OPPBTP (The Occupational Accident Prevention Organisation for the Construction and Civil Engineering Industries) were still recording serious injuries and fatalities, so a new standard was produced and issued in 1974, French standard NF E 85-010. This specified improved safety requirements that included a reduced maximum flight height of 9 m and a safety cage design that included five vertical bars.

Analysing the statistics of accidents resulting from falls from fixed ladders, the French national organisations involved in the prevention of occupational accidents, INRS (The National Research and Safety Institute) and OPPBTP, made the following conclusions:

- No fatal accidents were recorded where safety cages were provided with 5 vertical bands and the ladder flights were under 6 m in height;
- There were only a small number of accidents on fixed ladders with flights between 6 and 9 m in height;
- Fatalities were recorded where fixed ladders had flight heights in excess of 9 m;
- Fatalities were recorded where the free spaces between safety cage vertical bars were considered excessive, i.e. where safety cages were provided with 3 vertical bars.

The French experts concluded that there should be an immediate reduction in the flight height of all fixed ladders and requested immediate action to be taken in order to reduce flight heights of all existing fixed ladders to improve their level of safety. This was implemented by the Tower Cranes Programme by CRAMIF (The Regional Health and Safety Insurance Fund) and OPPBTP.

The reduction in the maximum flight height of fixed ladders had two positive results:

- The ***reduction in the maximum height of a fall***;
- The reduction in pressure on the heart and tiredness of the climbing worker.

The first item above indicates clearly that flight height is linked directly to falling distance.

Despite the French findings, in writing pr EN 14122-4, CEN/TC 114 WG 17 specified a maximum flight height of 10 m for a single ladder and 6 m for a multi-flight ladder, whereas the French delegation continued to argue for a maximum flight height of 6 m for all fixed ladders.

In Stewart (2004a) further information is given to supplement the French research. The French had recognised that a fall through the gaps created by the use of a cage with only three vertical bars was possible, so a five vertical bar specification had superseded the three bar one, with a maximum aperture area specified as 0.4 m^2.

In regard to fall-arresting effectiveness, the understanding was that the arrest of a backwards fall was supposed in a caged ladder, but that if both feet came off a rung, resulting in a fall downwards, then there would be no guarantee of arrest.

4. UK FALL ACCIDENTS IN HOOPED LADDERS

4.1 ANECDOTAL EVIDENCE

There is various anecdotal evidence which suggests that hooped ladders do little if anything when called upon to arrest the fall of a worker from a ladder. Various near-accidents or accidents have been relayed to the author by word of mouth, but documented evidence is not readily available and therefore these accounts are difficult to substantiate. Examples are as follows:

- In Dennis (1997), an account is given of two riggers who were gaining access to the top of a communications tower via a hooped ladder. Whilst climbing, the leading rigger suddenly fell backwards and out of the cage, through one of the rectangular-shaped apertures, (see Figure 29 which portrays similar circumstances[22]). Whilst falling, a hoop caught the inside of his legs, causing him to pivot into an inverted posture. The rigger following managed to push him back into the cage of the ladder. His opinion was that if the leading rigger had not caught the hoop by the inside of his legs, then he would have plummeted to the ground.

- In Williams (1998), an account is given of an utility worker who fell down a hooped ladder, broke his back, and died.

- In Mould (1998), an account is given of a worker who fell down a hooped ladder on a new building. He dropped his tools and his arms and armpits caught some hoops, which saved him. He was severely bruised and shaken. He was 20 m above ground level when the fall occurred. He came to rest "a few metres above a rest platform".

[22] *During the testing phase, it was discovered that it was possible for the test dummy to fall outside of the cage. Although this did not actually occur during the tests, there was one occasion in which there was a near miss (test No 3, Section 5 refers). To model the motion of the dummy falling outside the cage, the dummy was lowered slowly, starting with the same body attitude at the end of test No 3. The results are shown in Figure 29, where it can be seen that the body of the dummy could pass through the aperture.*

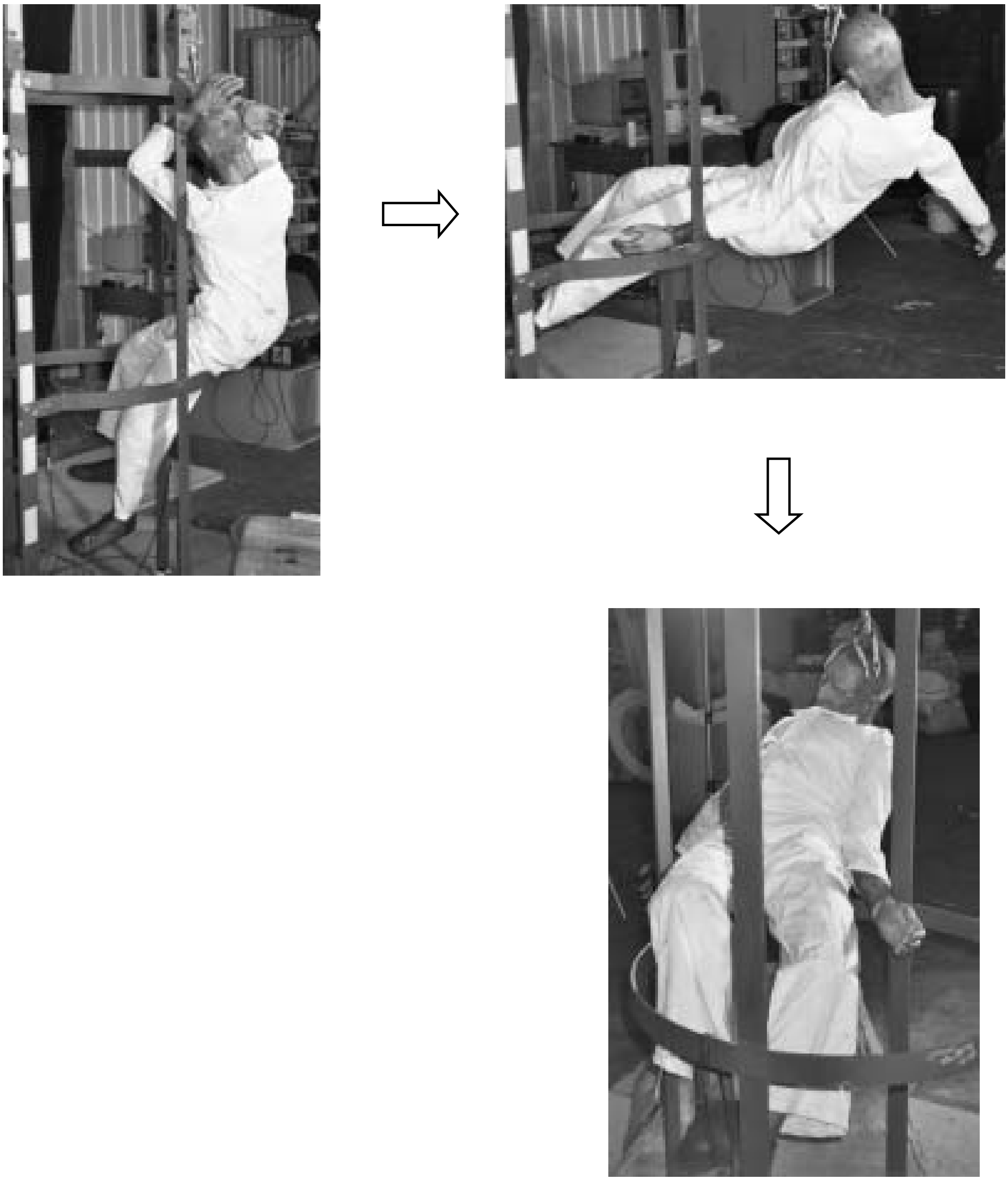


Figure 29 Three views of test dummy being slowly lowered to simulate fall through cage aperture

4.2 DOCUMENTED EVIDENCE

4.2.1 HSE Database

In order to try and obtain more substantial accident evidence, permission was obtained to study cases recorded in the HSE Field Operations Directorate (FOD) database. The search used the keywords and phrases: “HOOPED LADDERS” “PERMANENT / FIXED ACCESS LADDERS” “LIFELINES” “FALL-ARREST” and “LANYARDS”. The search revealed that 270 accidents contained one or more of the keywords, occurring between April 2001 - June 2003.

The accidents involving hooped ladders are as follows:

- Event No. 01A058660 June 2001. An inspection of a crane was being undertaken. The injured party (IP) climbed up the access route to the level of the operator’s cab to inspect that area of the crane. As the IP proceeded around the platform, he fell through the access hatchway and down the hooped ladder to the next platform below. The access hatch had been left open. Injuries were shock, bruising of the whole body, fractured ribs and little finger. There is no record as to how far the IP fell.

- Event No. 01A073374 January 2002. The IP was climbing a “fixed cage hooped ladder” on the side of a building. The IP was carrying a laptop computer and the bag got caught on one of the hoops (about 6 metres above ground level). The IP attempted to unhook the bag, whereupon he lost his footing and fell to the bottom. The IP was taken to hospital and later released. The diagnosis was a cracked vertebra (one of the bones of the spine).

- Event No. 01A094109 October 2002. The IP had climbed up a hooped ladder (approximately 2.5 metres); as he stepped onto the landing he struck his head on the frame causing him to fall down the ladder to the ground. The IP sustained a head injury resulting in a visit to the local hospital. The IP also sustained bruising to his body.

- Event No. 02A076320 October 2002. The IP was going into the basement of a machinery building to carry out some maintenance work. Access to the basement was by a vertical ladder with hooped back support. The IP said he must have missed his footing and slipped off the ladder. He fell to the ground and damaged his ankle. No height of fall mentioned.

- Event No. 05A038263 November 2001. The IP was descending a fixed ladder in the de-aerator at the sewage works. He lost footing, slipped and fell back. As he fell, his left elbow hit ladder protection, causing severe bruising. The IP tried to grab the ladder to regain his balance but failed and fell approximately one metre to the floor. The IP attended hospital, where examination of the elbow confirmed severe bruising; no other injuries were sustained in the fall.

- Event No. 19A052677 August 2001. The IP was involved in routine checks of a dry powder silo. As he descended the fixed, hooped ladder from the silo he lost his footing and fell approximately 1.6 metres onto the landing directly below that ladder. It is possible that his foot slipped due to some powder on a rung of the ladder. He suffered scratches and bruising to his left and right arms and lower back.

- Event No. 23A000395 April 2002. IP was climbing up a hooped ladder. IP got to the top of the ladder, missed the rung and fell down, hurting his back on the hoops. No record of height of fall.

In a further case, Event No. 18A046458 November 2001, there was a fatality recorded, but whilst it is clear from the report that hoops were fitted at the top of the ladder, it is not clear whether the deceased fell from the hooped or un-hooped portion of the ladder (no witnesses).

There are also some further 20 accidents where the injured party fell down a fixed ladder to the next level. Although in these instances most of the ladders would probably be hooped, the investigating officer did not confirm this. Accordingly, these cases are not mentioned since it is disputable whether the injuries recorded can be attributed to the influence of hoops or not.

4.2.2 Publications

In Health and Safety Executive (1985), a study of fatal accidents at work is compiled. Under accident outline No. 2, a fatal accident is described in which: “a maintenance supervisor who was carrying equipment fell from a vertical ladder below the level of the steel hoops”. This accident cannot therefore be fully attributable to hoops.

In a safety professionals association report, Safteng (2003) a fatal accident is described when a worker fell over 9 m to the ground whilst descending from a hooped ladder. An eyewitness reported that the worker lost contact with the ladder, fell backwards through an unprotected section of the ladder, hit the handrail on the platform below, and the momentum of the fall carried the worker over the rail. There was no guarding between the bottom of the ladder safety hoops and the top of the handrails, which were in close proximity to the ladder, and so the platform was of insufficient area to contain the backwards fall of the worker from the ladder. Recourse to the type of approach as shown in Figure 13 would have prevented this type of fall.

5. DROP-TEST PROGRAMME

5.1 GENERAL

This part of the research involved full scale physical testing, intended to simulate what might happen when a person falls off a caged ladder. Falls were simulated by using an anthropomorphic test dummy (ATD) in place of a human being. The ATD was released in various pre-fall climbing postures. This kind of dynamic simulation testing is commonly termed as: “drop testing”.

For comparison purposes, various ladder-mounted FAS which were currently available on the UK market were subjected to the same method of test, again to see what might happen when a person falls off.

5.2 DROP-TEST PREPARATION

5.2.1 Test rig

Testing was to be performed at the National Engineering Laboratory (NEL), using a 3-legged drop-test rig, Figure 30. This rig meets the requirements of EN 364 (1992)[23].

Figure 30 Drop-test rig

[23] *That is the rig’s natural frequency of vibration in the vertical axis is not less than 100 Hz, and a force of 20 kN at an anchoring point will not cause a deflection greater than 1.0 mm. This is to ensure that any mechanical flexibility of the rig is insufficient to affect electronic measurements. (Natural frequency refers to the mechanical response of a system to vibration; if subjected to sustained vibration at the natural frequency the system will respond at that frequency with increasing amplitude until mechanical failure occurs).*

5.2.2 Test ladder

A test ladder was manufactured in accordance with BS 4211 (1994) with a rung width of 350 mm and with a safety hoop arrangement as shown in Figure 31. The ladder was made in 3 mating sections for ease of transportation and installation. Three vertical bars braced and were welded to the eight hoops; the hoops were bolted to the ladder stiles so that they could be removed for the second phase of testing, which involved the evaluation of the FAS[24].

An overall length of 6.3 m was specified, equating to the ladder flight height between platforms of 6.1 m, as advised in the Workplace (Health, Safety and Welfare) Regulations (1992), see Section 2. In effect, the test ladder represented one flight of a staggered ladder run.

The dimensions and details of the stiles, rungs, hoops and vertical bars were all checked to ensure that they complied with BS 4211 (1994). Each of the eight hoop to rung dimensions (Figure 32) were within a 830-840 mm band, meaning that some were on the upper limit of the 760-840 mm tolerance. Each of the eight hoop width dimensions (Figure 32) were within a 740-750 mm band, meaning that some were approaching the upper limit of the 700-760 mm tolerance. Obtaining a test ladder with some of the safety hoops at the maximum permitted dimension was not intentional – the ladder was simply specified as one that would meet the requirements of BS 4211 (1994).

The total mass of the ladder and safety hoops was 215 kg.

Purely out of interest rather than for scientific reason, two members of the testing staff, one of medium build and one of tall build, assessed the caged ladder for size, in particular to see how easy it would be to lean back and rest. As seen in Figure 33, it was easier for the taller person to do this and, in this case, it might be argued that a taller person may have a greater possibility of wedging against the safety hoops if they lost the grip of both hands at this point.

The test ladder was secured to one of the columns of the test rig using five pairs of brackets to ensure sufficient connection rigidity in accordance with BS 4211 (1994).

[24] *It was decided to test the FAS on their own without the influence of the safety hoops*

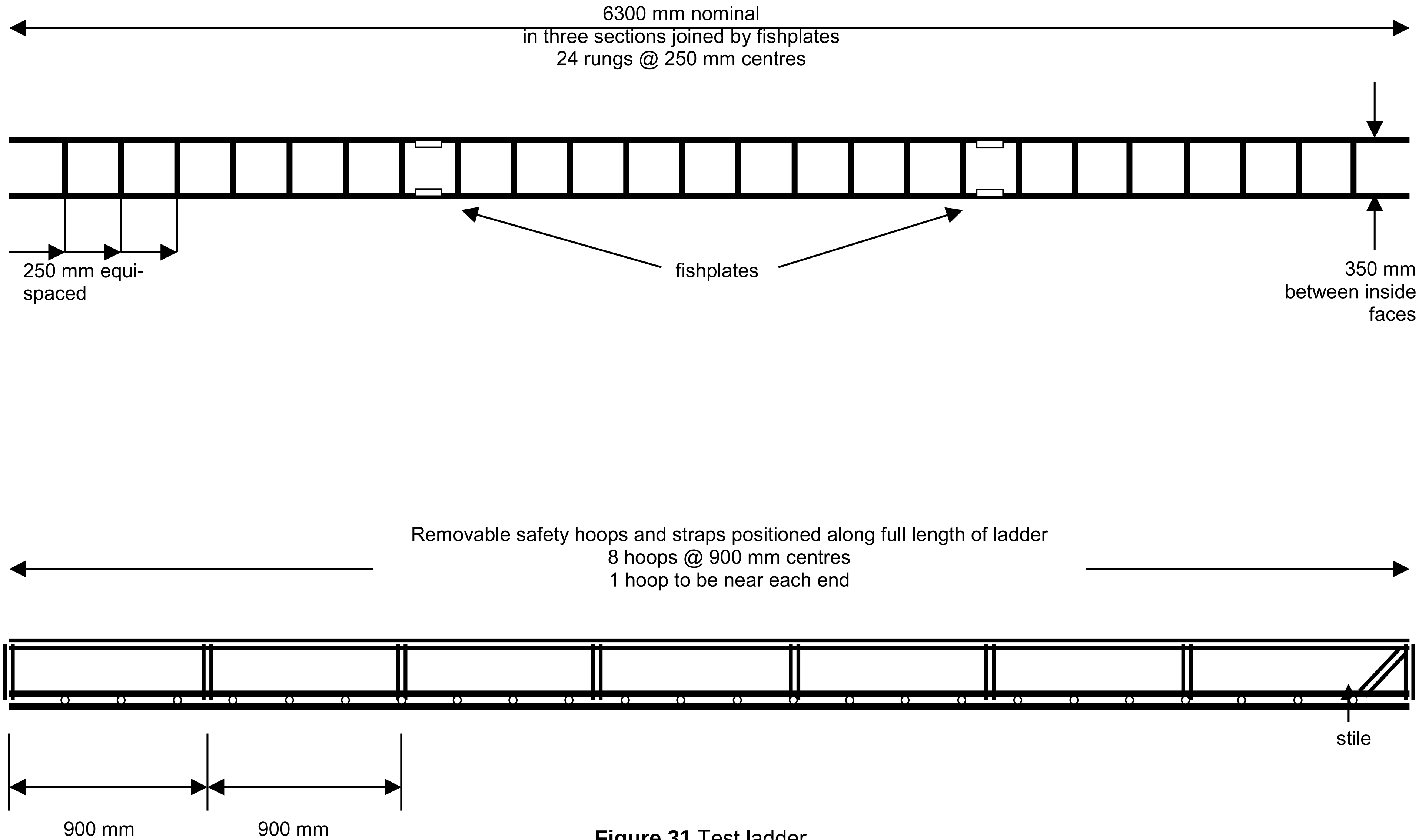


Figure 31 Test ladder

Figure 32 Rung to hoop dimension (left hand view) and
hoop width dimension (right hand view)

Figure 33 Example of how taller person with relatively long reach and leg length (right hand view) can lean back against cage with grip maintained as compared to smaller person (left hand view)

5.2.3 Ladder-mounted FAS

Five different kinds of ladder-mounted FAS from UK and European mainland manufacturers were selected for testing. Test specimens were prepared accordingly, together with full body harnesses that would be typically used in conjunction with these systems. All of the equipment had been tested previously and was certified either to EN 353-1 (1993) in the case of the FAS or EN 361 (1993) in the case of harnesses.

As per Figure 4, each of the FAS tested consisted of a rail and a sliding arrest device.

Each of the rails were designed to be made up from a number of sections bolted together by joining plates, and to be fixed by brackets onto vertical, fixed ladders.

Each of the sliding arrest devices were designed to:

- engage into or onto their respective rail, depending on the rail profile;
- be connected to a worker's harness;
- slide up and down the rail, in response to climbing movements;
- lock onto the rail in response to the sudden jerk of a fall.

Each of the sliding arrest devices were supplied with a connection to link the device to the harness. This was either a simple connector, certified to EN 362 (1993), or a short energy-absorbing lanyard with a connector.

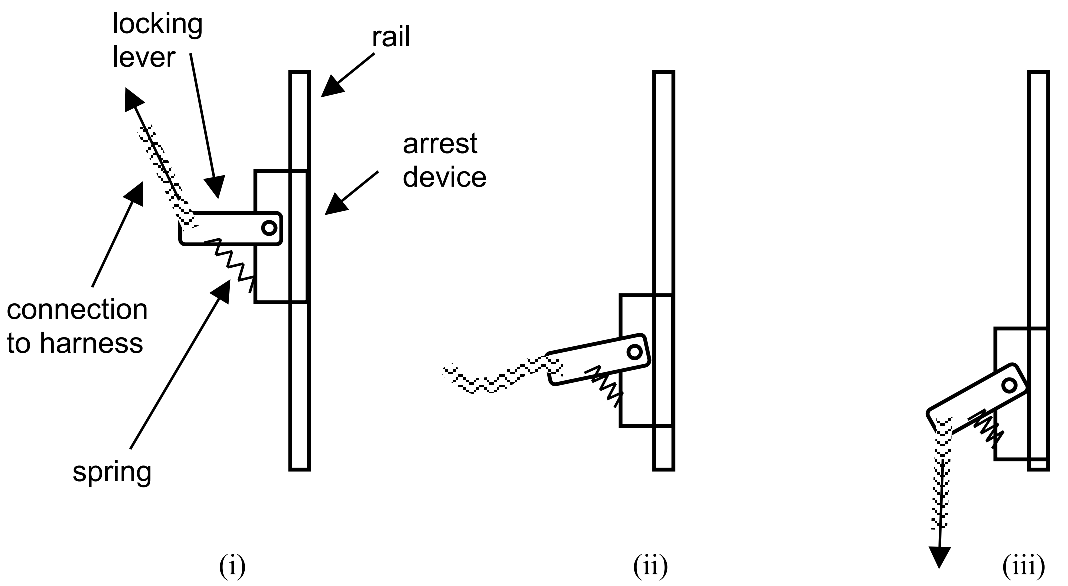
The arresting function of each of the sliding arrest devices was provided by the locking action of a spring loaded lever bearing upon the rail, or by engaging into one of a series of preformed slots in the rail. The springs were arranged to constantly bias the lever towards its locked-onto-the-rail position, (similar to a "dead-man's handle").

The designer's aim is that during normal climbing movements the spring bias is overcome by tension in the connection between device and harness, allowing the device to slide on the rail. Under the action of a fall, the connection goes slack initially, allowing the spring loaded lever to lock onto the rail, and the arrest device then becomes a fixed anchor point, see Figure 34. This decelerates the worker over a short distance. The aim is to ensure that the braking force imposed on the worker is kept below 6 kN [25]. The worker is brought to a complete stop and remains suspended in mid-air whilst awaiting rescue[26], Figure 35.

The overall intention behind this approach is to minimise the otherwise harmful effects of fall-arrest loading and distance by (i) minimising free fall at the onset, and by (ii) dissipating kinetic energy which the attached worker would otherwise have to bear.

[25] *This figure is measured during laboratory testing in accordance with EN 353-1 (2002) which simulates a fall by dropping a steel weight of 100 kg mass in place of a human being. No harness is used.*

[26] *Ladder mounted FAS are in close proximity to the ladder, which means that workers in post-fall arrest suspension will probably be able to recover to a safe position if conscious after the fall.*



Key:

(i) tension in the connection line to harness pulls against spring and keeps locking lever away from rail, allowing arrest device to slide unhindered during normal climbing movements

(ii) when worker falls, tension in the connection decays and spring pulls locking lever towards rail; arrest device falls down rail

(iii) spring pulls locking lever fully against rail which locks arrest device to rail; worker falls past locked arrest device, which then acts as anchor to stop fall motion

Figure 34 Normal sequence of locking operation of sliding arrest device on rail

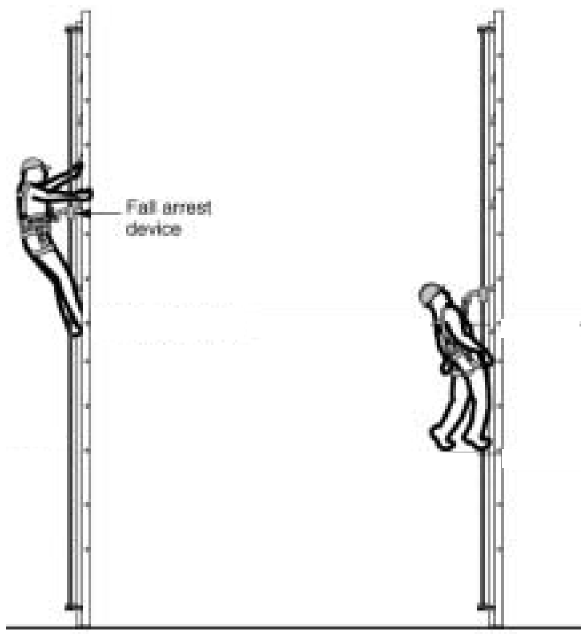


Figure 35 Before and after a fall when attached to a ladder-mounted FAS

5.2.4 Test instrumentation

Deceleration of the ATD with respect to time was to be measured in the three principal body axes, i.e. in three mutually perpendicular directions, see Figure 5 and Table 1[27]. This was to be achieved by using a piezoelectric tri-axis accelerometer, (Type B&K 4321 delta shear), mounted to the thoracic area of the ATD's spine, (Figure 36).

Microdot cables were connected to the accelerometer and were routed inside the ATD to emerge at the posterior. Care was taken to prevent the cables from being snagged by moving parts within the ATD. The cables were then allowed to hang freely from the ATD during testing, preventing interference with the motion of the fall, (Figure 37).

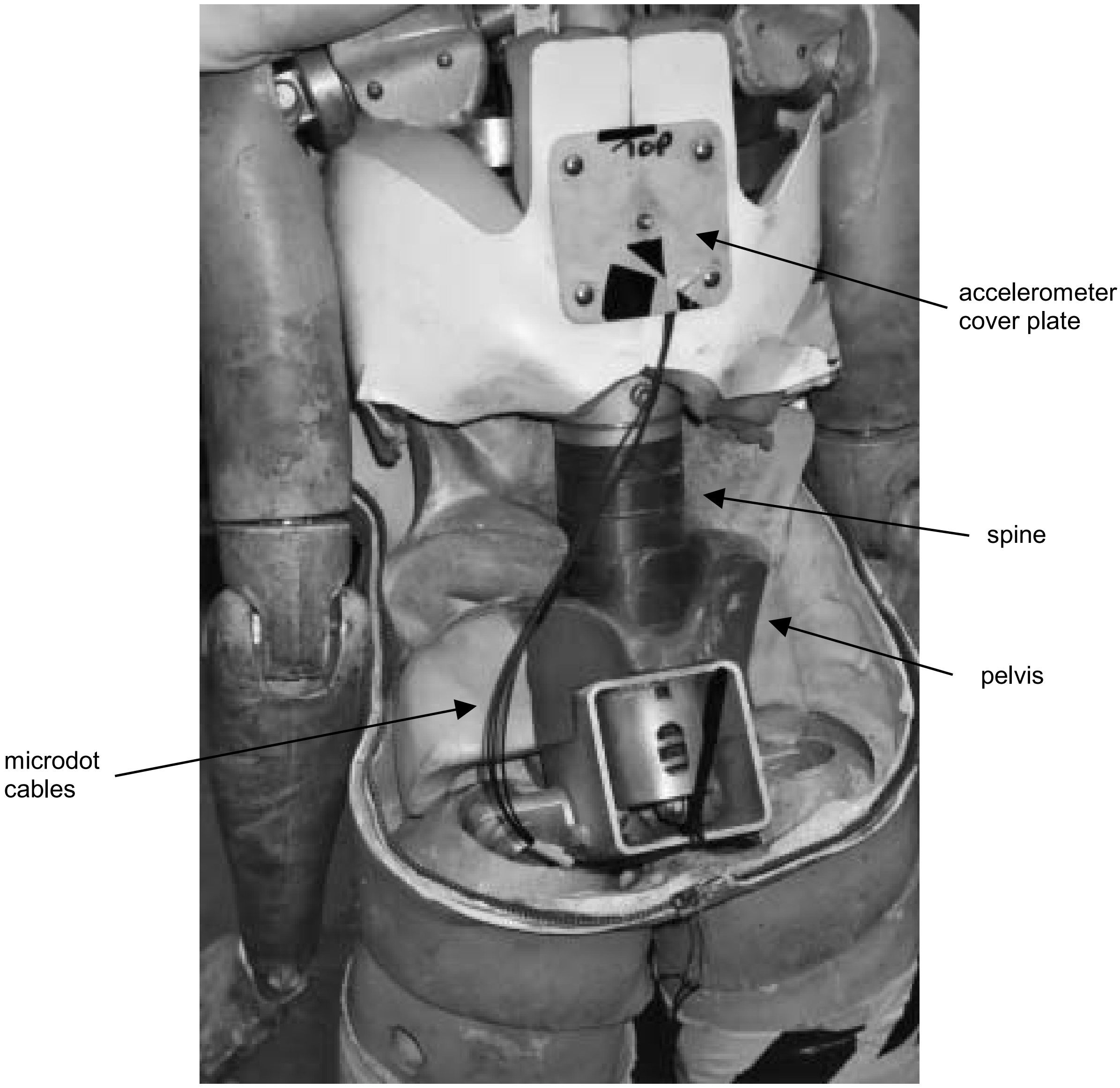


Figure 36 Inside of ATD, looking from the rear, showing accelerometer cover plate and microdot cables

[27] *Note that for test numbers 15-18 the accelerometer polarity in the z axis was reversed. This does not affect actual results and details can be found in Appendix 1 and 2.*

Figure 37 ATD in pre-release position inside caged ladder; accelerometer cables can be seen hanging from ATD's posterior

Charge amplifiers, (Type B&K 2635), were used to condition and amplify the accelerometer signals, which were then low pass filtered using a Butterworth type Kemo filter to allow only frequencies within the range 1 - 60 Hz [28] to be measured.

The An Omnilight 837 high-speed acquisition system was used to collect the test data at a sampling rate of 10 kHz. [29] The test data was finally post processed in Microsoft Excel and presented in graphical acceleration-time history format. Figure 38 shows the measurement chain used.

[28] *In accordance with EN 364 (1992). See Appendix 4 for further details.*

[29] *The minimum sampling rate (the number of measurements taken per second) agreed by most authorities when reconstructing events in the time domain is typically 10 times that of the highest frequency. EN 364 (1992) requires a sampling rate of 1000 times per second (1000 Hz); the sampling for this research was done at 10,000 times per second (10 kHz). Sampling at a higher rate ensures that maximum values are more readily detected.*

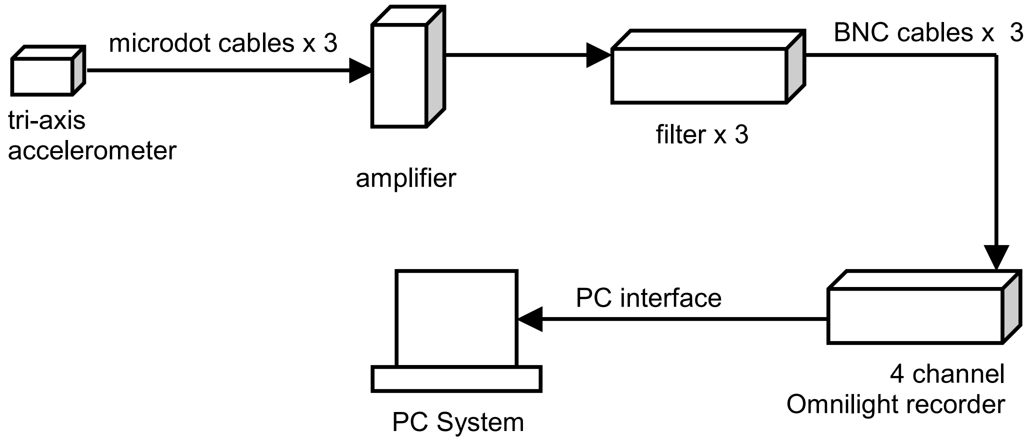


Figure 38 Dynamic measurement chain

When conducting tests simulating humans it is important to measure those frequencies that have a detrimental effect on the body. The chosen frequency range or bandwidth provides a force- or acceleration-time trace containing all events occurring at these frequencies. The test trace is vital in the measurement of peak forces/accelerations at different frequency events and in determining how long the body remains above certain force/acceleration or pain thresholds. It should be recognised, however, that the higher the frequency the greater risk of other external interferences corrupting the test data. This can include noise and vibration from other external electrical and mechanical sources within the vicinity, such as plant, machinery and general background noise. For this study a frequency bandwidth of 60Hz was used, which is that used in harmonised European test standards when measuring fall arrest forces using test dummies[30].

5.2.5 High Speed Video Recording

High speed video was used to capture to motion of the ATD during test. The equipment used was a Photron Ultima 1024 High-Speed Colour Digital System. This system was capable of recording and displaying events at up to 500 pictures per second (PPS) at a resolution of 1024 x 1024 pixels, or up to 16000 PPS at reduced resolution. For the tests a frame rate of 250 PPS was selected at a resolution of 1024 x 1024 pixels.

The system was positioned to give a clear field of view and in order to capture the whole event of each individual test.

The camera head was fitted with a Cosmicar 25 mm prime lens. For the tests the lens aperture was set to f2.8 and +2Db electronic gain was selected to increase brightness. Frame shutter speed was 1/250th of a second.

Illumination was provided by a number of infinitely variable 5-2000 kW “Blonde” and 2-800 W “Redhead” tungsten lamps, which could direct a total of 11.6 kW towards the test area.

[30] *See Appendix 4 for further details.*

To facilitate the high speed filming and to achieve appropriate contrasts, the test ladder was painted in a colour approximating to shade No. 1797 of the Pantone Colour Matching Standard, commonly known as “red-lead”. The ATD wore white overalls and a black “Calico” backdrop was suspended behind the test area.

The ladder stile facing the camera had scale markings taped on it at 100 mm intervals, for displacement analysis during slow motion playback.

After each drop-test, the recorded images were transferred from the camera memory to S-VHS tape. This provided a permanent master record of the tests. Each test was transferred to the tape at playback rates of 25, 12, 8 and 4 PPS for post-test analysis. The display featured information such as elapsed time and recording rate.

Selected sequences were also transferred to CD-ROM.

Photographic stills were taken throughout the test programme.

5.2.6 “Sierra Stan” ATD

An ATD was used in place of a human being[31] or cadaver[32] as the test surrogate. This was the “Sierra Stan” model, part number 292-850. Sierra Stan is an anthropomorphic, anthropometric, fully articulated[33] test dummy of 71 kg mass and of 50th percentile major dimensions. The use of Sierra Stan would allow realistic fall simulations within the caged test ladder and when testing the ladder-mounted FAS. The key factors in the choice of using Sierra Stan as the test surrogate, were:

- A number of researchers have used the Sierra Stan ATD previously, for example:
    - Reader (1970) - parachute opening shock research at the Royal Air Force Institute of Aviation Medicine at Farnborough, UK
    - Armstrong and Waters (1969) - vehicle occupant restraint research
    - Sulowski (1978) - fall-arrest research which compared the drop-test results of using a steel weight as the test surrogate to that of the Sierra Stan ATD

[31] *Various researchers have used live human being volunteers in experimental fall-arrest drop-testing previously, e.g. Reader et al (1969) and Mattern and Reibold (1994). However those tests were conducted feet-first into free space, (i.e. the body was erect and there was no possibility of the subject colliding with any structure), and anticipated deceleration levels were lower than those known to cause certain likelihood of injury. In the present case, it was anticipated at the outset that using live human volunteers for simulating falls within a caged ladder would be extremely dangerous, since parts of the body would almost certainly strike the cage in the fall, and there was the uncertainty of whether the cage would stop the fall at all.*

[32] *Impact tests which can produce significant injury cannot be conducted on human volunteers, so a number of researchers have used human cadavers instead, especially in the vehicle crash protection industry, King (1993), but also in the fall-arrest field, Blake et al (1952). However there are the problems of large variations amongst cadaver subjects, impracticality of use in test laboratories, limited availability, and whether such methods are ethical, to consider. Consequently, one of the main uses of cadavers has been to develop realistic ATDs, and so using such an ATD for the tests in this research was considered to be the best option available.*

[33] *A dummy that is anthropomorphic (resembling the human form), anthropometric (of a set size and with set proportions relating to a statistical population), and with articulating joints, similarly disposed as with the human body and with anthropometric ranges of movement.*

- Marsh (1974) – fall-arrest research, part of which included the fitting of two accelerometers in the head to allow the measurement of acceleration of the head in two mutually perpendicular planes, (a_z and a_x), and also included the measurement of whiplash angles of the head.

- Availability for fall-arrest use

- Technical specification. One of the technical manuals, Sierra (1967a), states that the ATD is: "extremely rugged in all details of construction……and that the general construction withstands test loads of 100g disruptive forces", making it ideal for testing the fall-arresting effectiveness of caged ladders, where before the testing their fall-arresting capability was unknown

- The ATD's ability to accept instrumentation in the head, chest, spine, pelvic area and leg

- The extent to which the design and engineering detail of the ATD's anatomy models the human being. The ATD was dismantled as part of the pre-test preparation, and the internal parts were studied. This is reported more fully in Appendix 3. Of particular note was the ATD's degree of joint articulation and friction adjustment, and the degree of neck and spine articulation which had adjustable damping. Some ATDs which are available for fall-arrest test purposes only have a hinge to model the bending of the back, which can be very restrictive in terms of replicating the jackknifing[34] motion of the body.

  Sierra Stan was first produced in 1967, Smrcka (2002), and whilst it may be virtually obsolete in terms of today's state-of-the-art car crash test dummies, it nevertheless provides a good choice of surrogate for drop-testing purposes.

- The 50th percentile anthropometry, having a stature height[35] of 1.74 m and a mass of 71 kg [36]. Using an ATD of 50th percentile major dimensions was considered to be more representative of the UK working at height population than some of the larger ATDs available whose dimensions correspond to the 95th percentile. These ATDs tend to have a stature height of 1.85 m and a mass of around 95-100 kg. 50th percentile values correspond to the median value, i.e. the middle value in a frequency distribution, below and above which lie 50% of the values.

  The usual mass for Sierra Stan is 74.5 kg, but in the actual model used, the chest deflection device[37] which is normally mounted in the chest cavity, was not fitted, (see Appendix 3). This allowed the mounting of a tri-axial accelerometer instead.

[34] *The folding motion of the body about the waist with the head coming forward to meet the feet*
[35] *Height from the bottom of the foot to the top of the head with the ATD standing erect*
[36] *With the ATD clothed*
[37] *A device used for measuring shoulder strap forces in vehicle occupant restraint tests*

Anthropometry

Sierra Stan's anthropometry was based on data from a U.S. Government survey - U.S. Department of Health, Education and Welfare (1966), and to a lesser extent on a U.S. Air Force survey - Hertzberg et al (1954). One of the drawbacks of using Sierra Stan was the 74.5 kg mass figure, which may have been representative of the 50th percentile when the ATD was first produced in 1967, but which may be considered to be too light in terms of today's 50th percentile working at height population. The surveys on which Sierra Stan was designed were based mainly on 1966 data, and it is reported that there is a trend of increasing population size over the decades. For example in Diffrient et al (1983), 8 mm in U.S. stature height increase per decade is recorded, and in Pheasant (1996), 10 mm in UK stature height increase per decade is recorded. Pheasant (1996) also records a 2 kg mass increase per decade in UK adolescents. It is interesting to compare the above U.S. data sources for mass – the data in Hertzberg et al (1954) records a 50th percentile mass of 73.5 kg whereas the data in U.S. Department of Health, Education and Welfare (1966) has a figure of 73.9 kg. The difference is negligible, but like all statistics, the sources and population size measured may explain much.

In terms of actual comparable figures, Diffrient et al (1983) records U.S. male 50th percentile stature height as 1.75 m and mass as 78 kg (originally published in 1974). Bolton et al (1971) records U.K. Royal Air Force aircrew 50th percentile stature height as 1.77 m and mass as 74.5 kg. Pheasant (1996) records U.K. male 50th percentile stature height as 1.74 m and mass as 75 kg, (based on a 1981 survey).

Increasing the mass of the ATD slightly to allow for say two decades' increase would have a slight affect in the outcome of the results, particularly in regard to measured forces and decelerations. This was not done, partly because the exact 50th percentile figure was not known and partly because the U.K working population may have different percentile values to that, say, of a military or civilian population from which anthropometrical surveys are typically taken[38]. In this research, a slightly greater importance was placed on kinematics, i.e. to determine how effective both caged ladders and FAS were at retarding the motion of a fall. In this respect the ATD's degree of accuracy in modelling the human being and the degree of joint articulation were seen as being of more importance than it's total mass.

Performance

Whereas ATDs are designed to perform in a manner which approaches human behaviour under deceleration, usually based on cadaver data, it must be recognised that they cannot be fully representative. The main uncertainties and usual criticisms associated with the use of ATDs, are: (i) to what degree recorded forces and decelerations correspond to that of a human being in identical circumstances (bio-fidelity), (ii) the degree of likeness to a human being and modelling accuracy, especially joint articulation, and (iii) lack of muscular response.

No attempt was made to determine Sierra Stan's degree of bio-fidelity, or as demonstrated in Guignard (1961), the natural frequency. It is likely that deceleration values would be slightly higher when testing with the ATD than with a human being of the same mass in identical circumstances, Riches (2002). Impacts upon locations on the human body tend to crush the flesh and cause lesions which dissipate energy, the remainder of which is transmitted through the skeletal frame and more compliant structures, such as internal organs, muscles and tissue support systems.

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[38] *Another HSE research project is currently surveying anthropometric details of persons who work at height in the UK*

This energy dissipation happens but to a much lesser extent with an ATD, the internal structures of which are much more rigid. However, the effectiveness of arresting the motion of the fall was seen to be of more importance than measured values, and, as the title of this report describes, the research was preliminary in nature. Also it was envisaged that the values from the caged ladder testing could be used to directly compare with those from the FAS testing without the need to take account of a bio-fidelity factor. It may be that in future research assessing the degree of bio-fidelity may be investigated.

In regard to the degree of likeness to a human being and modelling accuracy, especially joint articulation, a more detailed account of the ATD can be found in Appendix 3.

Whilst it is admitted that the main deficiency with using ATDs is the lack of muscular response and tone, (a similar criticism often made of using cadavers), the brevity of the impact duration renders muscular response virtually irrelevant in terms of its ability to modify body kinematics. It is not a predominant factor in most cases because the muscular effort that can be mustered in the short time interval of the impact is minimal, King (1993). The exception is the neck, because of the large muscles surrounding a relatively small structure. Muscular tone can have a significant effect on the kinematics of head and neck, and so neck responses in vehicle crash biomechanical studies for instance, are often obtained from human subjects.

Some muscle tone can be simulated by applying clamping, torque and support devices to critical joints that can affect body kinematics. In Sierra Stan’s case, muscle tone could be simulated by altering the resistance to movement of each of the joints by setting a frictional adjustment.

Prior to the testing, each of the joints were set at 1g. This meant, for example with the arms, that the friction setting would be increased until the joint was locked, and then would be slowly decreased until the arm just fell under the influence of gravity. This is a standard adjustment to give a representation of muscle tone and in order to achieve reproducible results, used for example in Armstrong and Waters (1969), and in Council Directive (1977), the latter document being a European Directive in regard to testing vehicle occupant restraint systems.

5.3 DROP-TEST METHOD FOR CAGED LADDER

An eyebolt on the ATD's head was used to connect a quick release mechanism, which was in turn connected to the chain of an electric hoist, Figures 39 and 40. With the ATD raised to the required height, the function of the quick release mechanism was to allow the remote release of the ATD without imparting any motion to it except that caused by falling under its own weight, thus creating the circumstances of a fall as accurately as possible[39].

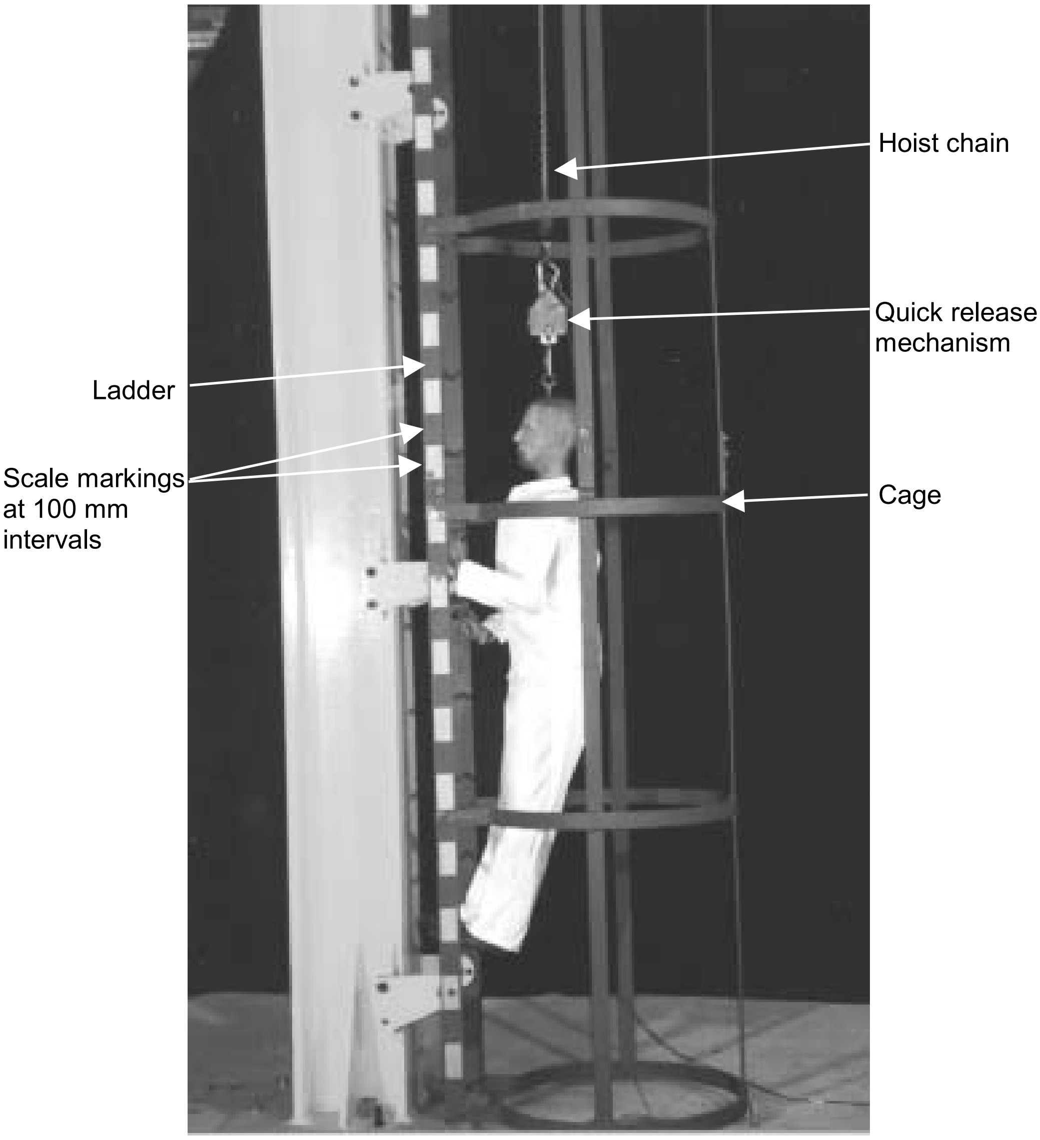

Figure 39 General arrangement of drop-test preparation

[39] *Note that the hoist was also centrally positioned about the cage's centre line so that no sideways motion could be imparted to the ATD (in the "y" direction) at release.*

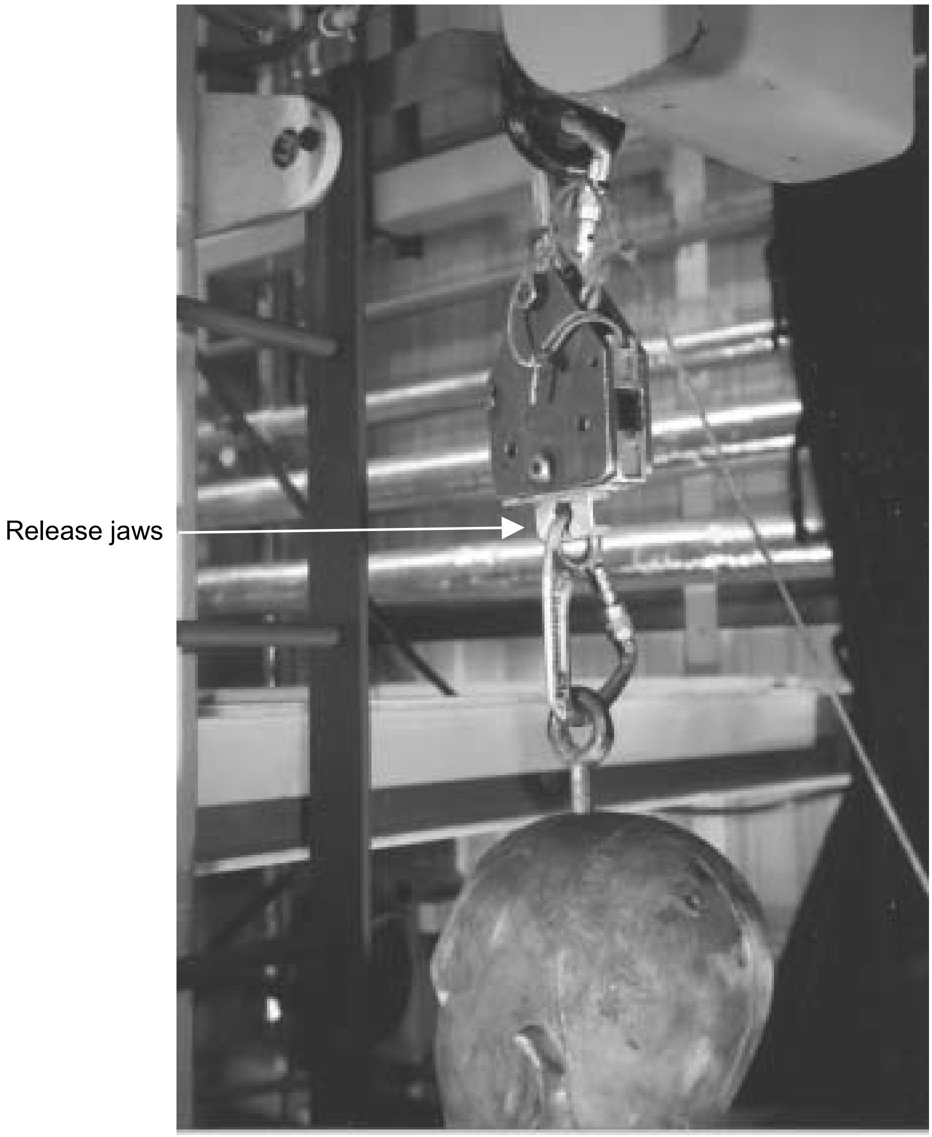

Figure 40 Close-up view of quick release mechanism

With the ATD raised to the highest point within the cage, the limbs and posture could be set to simulate climbing attitude prior to release. The degree of articulation and general geometrical disposition of the ATD, (as detailed in Appendix 3), were utilised to reproduce a number of realistic pre-release body attitudes.

A number of possible situations were considered in which a fall was likely to result, as opposed to temporary loss of control or stability which could be recoverable. The conclusion was that a fall was most likely to occur when a loss of grip from both hands occurred in a non-recoverable manner, with the body falling away from the ladder, as supported in other research, e.g. Clark (1985) and Dewar (1977). The loss of contact by one or both feet was thought unlikely to result in a non-recoverable situation, provided that one or both hands retained a grip, (likened to a slip from a rung).

Various hand- and foot-holds could be simulated, e.g. Figure 41.

Figure 41 Example of ATD's rung-holding capability

The situation where the ATD might crash down the cage to the test house floor was considered. In one respect it was felt that if this should occur, the decelerations should be measured as these would serve as realistic indications of what a person would experience in a real-life situation, (i.e. a fall through 6 m onto a platform). It was known from the ATD's documentation, Sierra (1967a), that the ATD was: "extremely rugged in all details of construction……and that the general construction withstands test loads of 100g disruptive forces". So in theory, the ATD should have been strong enough to withstand such a situation. In another respect it was felt that any damage to the ATD would jeopardise the test programme, and spare parts were not available. After discussion, thick padding was placed at the bottom of the cage to minimise any impact, should the ATD strike the test floor.

With the ATD in the desired pre-release attitude and with the accelerometer cables hanging freely beneath, the measuring electronics were set. The triggering level for the tri-axis accelerometer was set to 2g.

The pre-release posture of the ATD and the shortest distance from the back of the ATD to the inside back surface of the cage was measured prior to release, dimension "B" in Figure 42. Any distance the ATD fell through was to be measured by analysis of the slow motion playback of the high speed film.

The quick release mechanism was manually activated by pulling a cord, allowing the ATD to fall freely within the cage. The high speed video started recording the fall motion at the instant before release.

Figure 42 ATD in a typical pre-release position showing dimension "B"

5.4 DROP-TEST RESULTS FOR CAGED LADDER

5.4.1 General

Seven drop-tests were conducted with the caged ladder, the results of which are summarised in Table 4. This table records:

- dimension B (Figure 42)
- ATD limb position at the point of release
- maximum deceleration and direction in each of the three principle axes of the ATD
- fall distance (from release to the point at which ATD came to rest).

It should be noted that the "equivalent force" category in Table 4 is a simple, crude conversion of the maximum acceleration measurement, using the formula derived from Newton's second law, Force = Mass x Acceleration. Hence the equivalent force is the product of the ATD's mass (71 kg) and acceleration (the "g" figure multiplied by 9.81m/s²). However, due the distributed mass of the ATD and the ATD's mechanical interconnections used to model the body of a human, the effective mass for such a calculation is unknown; also the site of the accelerometer was not at the centre of gravity of the ATD.

Impact investigations in the past have shown that acceleration measurements change from point to point on any distributed body element unless it is rigid and moving in only one linear direction without rotation, Snyder (1973). Thus, one acceleration measure, even if properly made, is not representative of the acceleration distribution over the body. "Equivalent force" has been shown purely to give an ***indication*** for a reader familiar with fall-arrest parameters[40], therefore it should not be relied upon as an accurate value.

Hence in this research, the measurement of falling motion as it is retarded has been given more prominence than inertial forces. The reader should therefore focus on deceleration rather than force in this instance.

A kinematic sequence of the ATD's fall trajectory is presented for each of the drop-tests. This is a sequence of photographic snapshots in time which describes the motion of the ATD during the test. The snapshots are displayed at random time intervals to reflect significant events in the test.

The individual acceleration-time history graphs can be found in Appendix 1. Note that test numbers 2 and 5 have no graph since the accelerometer was not triggered in these tests; it therefore can be assumed that deceleration levels did not exceed a 2g threshold[41]. This can be corroborated when examining the fall trajectories of test numbers 2 and 5.

[40] *In fall-arrest quarters, one would expect to see maximum fall-arrest force shown in test results. This is due to the intrinsic feature of FAS, in that an ATD is physically connected to the test structure, and hence it is relatively easy to insert a load cell to measure the reactive forces in such a connection. When considering a caged ladder, there is no such physical connection. In a fall situation the ATD falls into space and reacts against the cage at random. Therefore a load cell cannot be used in the same way.*
[41] *Instrumentation was checked after each test to make sure accelerometer was registering correctly.*

Table 4
Summary of caged ladder drop-test results

Test No.	***Dimension B (mm) and ATD limb position at release***	***Maximum deceleration, direction applied and equivalent force****						***Fall Distance (m)***	***Remarks***
		z axis		***y axis***		***x axis***			
		deceleration (g)	***force (kN)***	***deceleration (g)***	***force (kN)***	***deceleration (g)***	***force (kN)***		
1	B = 330 Hands on same rung, arms bent Feet on same rung, legs straight	18 headwards	12.54	8.34 sidewards to right	5.80	12.66 backwards	8.82	4.7	ATD fell to floor
2	B = 150 Hands on adjacent rungs, arms straight Feet on same rung, legs straight	no trigger	-	no trigger	-	no trigger	-	0.7	ATD wedged against upright and hoop
3	B = 95 Right hand on rung, arm slightly bent Feet on adjacent rungs, left leg bent, right leg straight	17.88 headwards	12.45	4.92 sidewards to right	3.43	7.37 backwards	5.13	1.0	ATD buttocks fell onto hoop edge
4	B = 300 Both hands off rungs Feet on adjacent rungs, left leg straight, right leg bent	23.42 headwards	15.3	11.11 sidewards to left	7.74	7.85 frontwards	5.47	4.1	ATD fell to floor
5	B = 330 Both hands off rungs Feet on adjacent rungs, left leg bent, right leg straight	no trigger	-	no trigger	-	no trigger	-	1.6	ATD armpit caught on hoop
6	B = 340 Both hands off rungs Feet on adjacent rungs, left leg straight, right leg bent	4.58 headwards	3.19	4.06 sidewards to right	2.83	6.5 frontwards	4.53	2.3	ATD armpit caught on hoop
7	B = 320 Hands on same rung, arms bent Both feet off, legs straight	11.98 headwards	8.34	4.3 sidewards to right	2.99	3.39 backwards	2.36	4.2	ATD fell to floor

** see clause 5.4.1*

5.4.2 Drop-Test No. 1

The position of the ATD just before release is shown in Figure 43.

Figure 43 ATD just before release

Upon release, the ATD fell a distance of 4.7 m to the test house floor, registering deceleration maxima of 18g headwards in the z axis, 8.34g sidewards to the right in the y axis, and 12.66g backwards in the x axis.

The 18g headward deceleration was applied in 0.01s, giving a jolt of 1800g/s. The 12.66g backward deceleration was applied in 0.01s, giving a jolt of 1266 g/s. Both jolt figures were measured from the slope of the graph in Figure 100, (Appendix 1).

The kinematic sequence of the fall trajectory is shown in Figure 44. Initially, the ATD fell away from the ladder with the arms extending and the body becoming more erect. The hand- and footholds were then lost and the ATD fell in an erect posture with the hands in the air over some 3.5 m. The feet then caught the ladder causing the body to jackknife[42] violently. This caused the buttocks to strike the hoop approximately 0.9 m above the test house floor and the ATD rotated forwards towards the ladder. The impact deceleration maxima all occurred simultaneously and were due to the ATD striking the bottom hoop towards the end of the fall.

[42] *The folding motion of the body about the waist with the head coming forward to meet the feet*

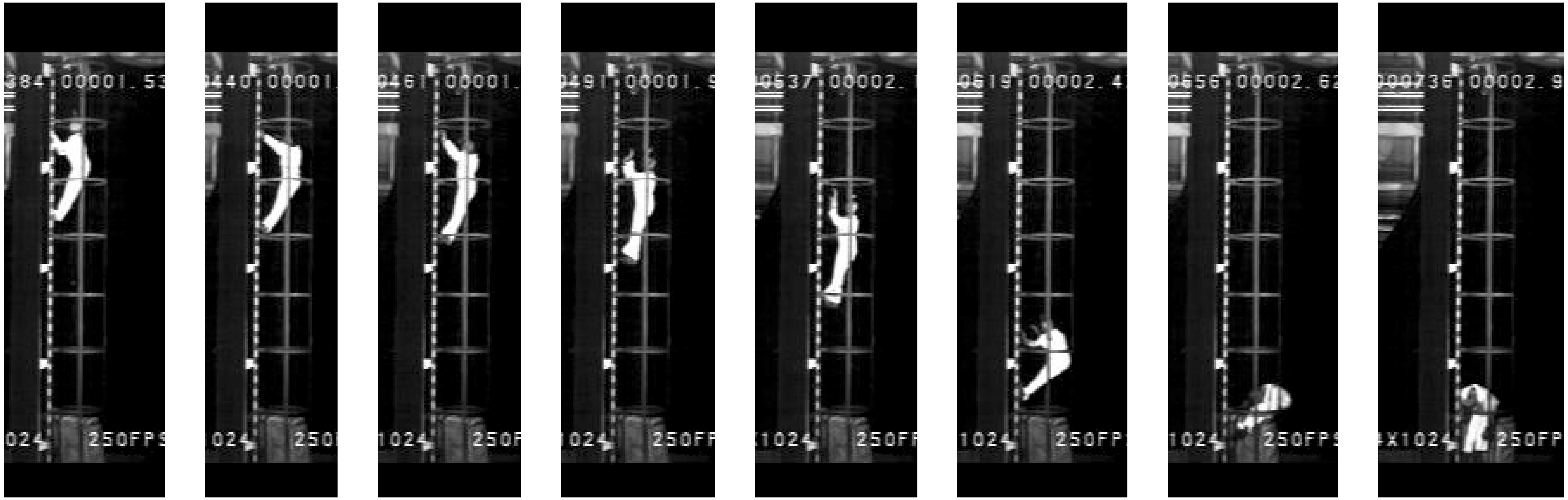

Figure 44 Kinematic sequence of ATD fall trajectory from test 1 (caged ladder)

5.4.3 Drop-Test No. 2

The position of the ATD just before and after release is shown in Figures 45 and 46.

Figure 45 ATD before release

Figure 46 ATD after release

Upon release, the ATD fell a distance of 0.7 m before wedging itself against an upright and hoop of the cage. This explains why the accelerometer was not triggered in this test - deceleration levels did not exceed the 2g triggering threshold.

The kinematic sequence of the fall trajectory is shown in Figure 47. In this test, the ATD was nearer to the back of the cage than in test No. 1. Initially, the ATD fell away from the ladder with the arms extending but with the body adopting a jackknifing posture. The right hand lost grip followed by the left. Both footholds were maintained. The buttocks and lower back of the ATD then wedged against the nearest hoop and the torso slumped forward, the whole ATD coming to rest. Pressure on the buttocks, preventing slippage of the ATD into a further fall, was maintained by the legs of the ATD acting as a strut between the ladder rungs and the cage (Figure 46).

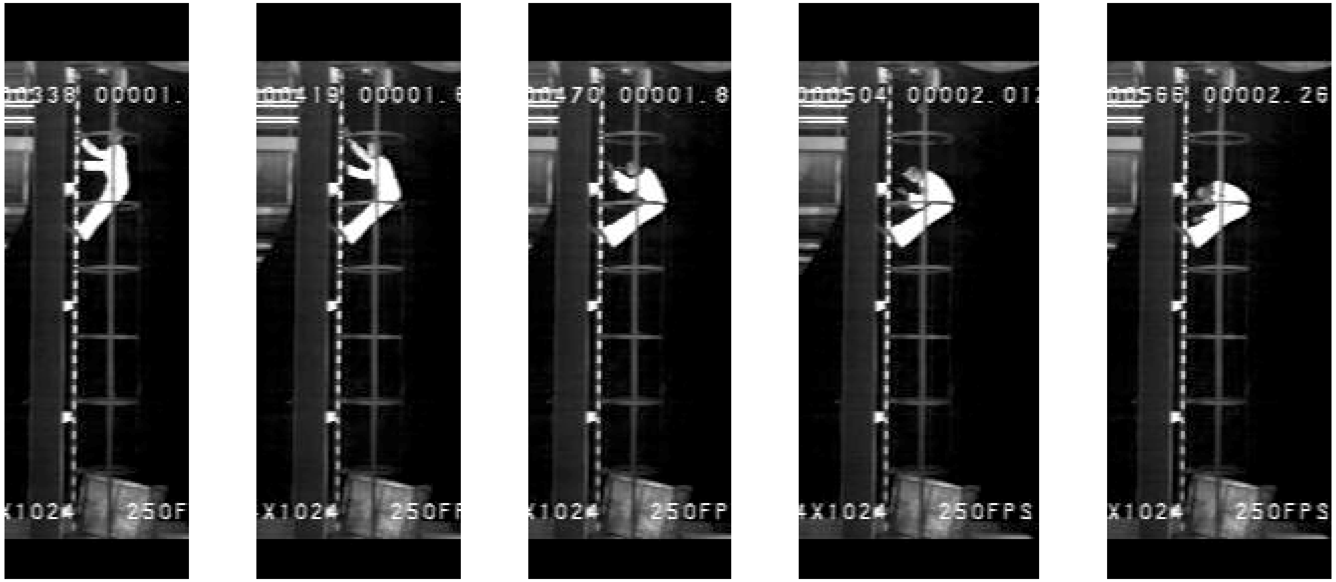

Figure 47 Kinematic sequence of ATD fall trajectory from test 2 (caged ladder)

5.4.4 Drop-Test No. 3

The position of the ATD just before and after release is shown in Figures 48 and 49.

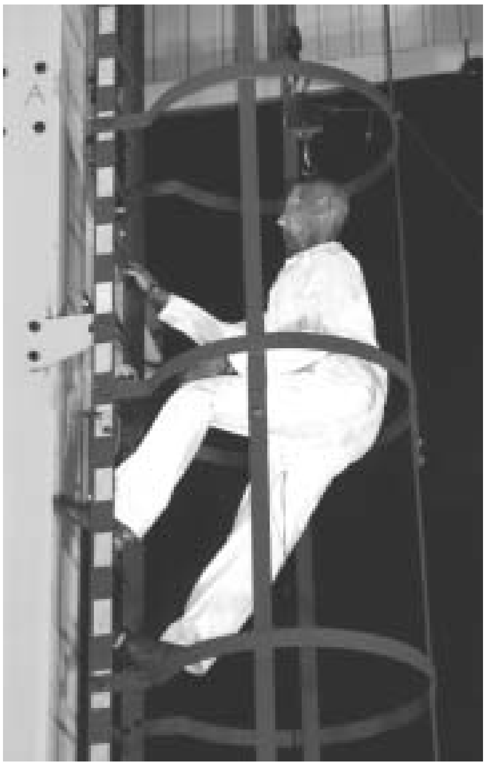

Figure 48 ATD before release

Figure 49 ATD after release

Upon release, the ATD fell a distance of 1.0 m before coming to rest by falling onto a hoop, registering deceleration maxima of 17.88g headwards in the z axis, 4.92g sidewards to the right in the y axis, and 7.37g backwards in the x axis.

The 17.88g headward deceleration was applied in 0.02s, giving a jolt of 894g/s. The 7.37g backward deceleration was applied in 0.02s, giving a jolt of 368.5 g/s. Both jolt figures were measured from the slope of the graph in Figure 101, (Appendix 1).

The kinematic sequence of the fall trajectory is shown in Figure 50. In this test, the ATD was nearer to the back of the cage than in test Nos. 1 and 2 and was in a more "climbing-the-ladder" type posture. Initially, the ATD fell away from the ladder and the right handhold was lost. The footholds were maintained causing the body to pivot about the rungs. With right and left legs in a horizontal, straight posture, the ATD's buttocks struck the next hoop down and to one side of the upright.

For an instant the ATD remained balanced on the hoop and looked like it would fall out of the cage, but the upper torso eventually tilted inwards and the ATD came to rest. Figure 51 shows how close the ATD came to falling out of the cage.

The impact deceleration maxima all occurred simultaneously and were due to the ATD's buttocks striking the hoop towards the end of the fall.

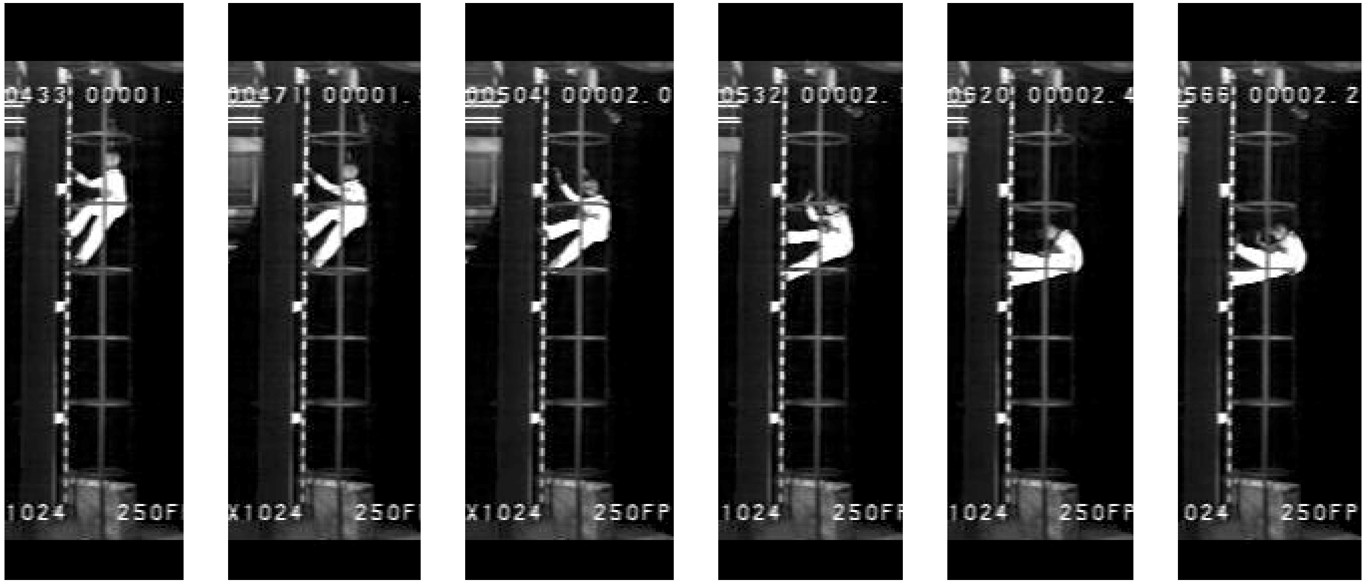

Figure 50 Kinematic sequence of ATD fall trajectory from test 3 (caged ladder)

Figure 51 ATD balanced on hoop after drop

5.4.5 Drop-Test No. 4

The position of the ATD just before release is shown in Figure 52.

Figure 52 ATD just before release

Upon release, the ATD fell a distance of 4.1 m to the test house floor, registering deceleration maxima of 23.42g headwards in the z axis. A second deceleration was immediately applied footwards in the same axis of 21.95g. An 11.11g deceleration was applied sidewards to the left in the y axis, and 7.85g frontwards in the x axis.

The 23.42g headward deceleration was applied in 0.01s, giving a jolt of 2342 g/s. The 21.95g footward deceleration was applied in 0.01s, giving a jolt of 2195 g/s. Both jolt figures were measured from the slope of the graph in Figure 102, (Appendix 1).

The kinematic sequence of the fall trajectory is shown in Figure 53. In this test, the ATD was 300 mm from the back of the cage; the feet were in a climbing posture with the hands off simulating the loss of both handholds. Initially, the ATD fell away from the ladder and the back struck the back of the cage. At this point a deceleration of 12.5g was registered headwards in the z axis and a 7.5g deceleration sidewards to the right in the y axis. Then both feet came off the rungs allowing the ATD to rotate forwards, causing the head to strike the ladder[43]. The left arm was then caught by a hoop and thrown upwards, followed by the left leg, causing the chest to scrape down the ladder. The ATD was rapidly stopped towards the bottom of the cage, which was probably responsible for the 23.42g headwards deceleration in the z axis. The head struck the ladder a second time, followed by the chin hitting the top surface of a hoop; this was probably responsible for the 21.95g footwards deceleration in the z axis. The ATD then came to rest.

[43] *In retrospect, it would have been prudent to have fitted a tri-axial accelerometer inside the ATD's skull to record impact decelerations to the head; this would be a requirement in future research and is commented on in Section 8.*

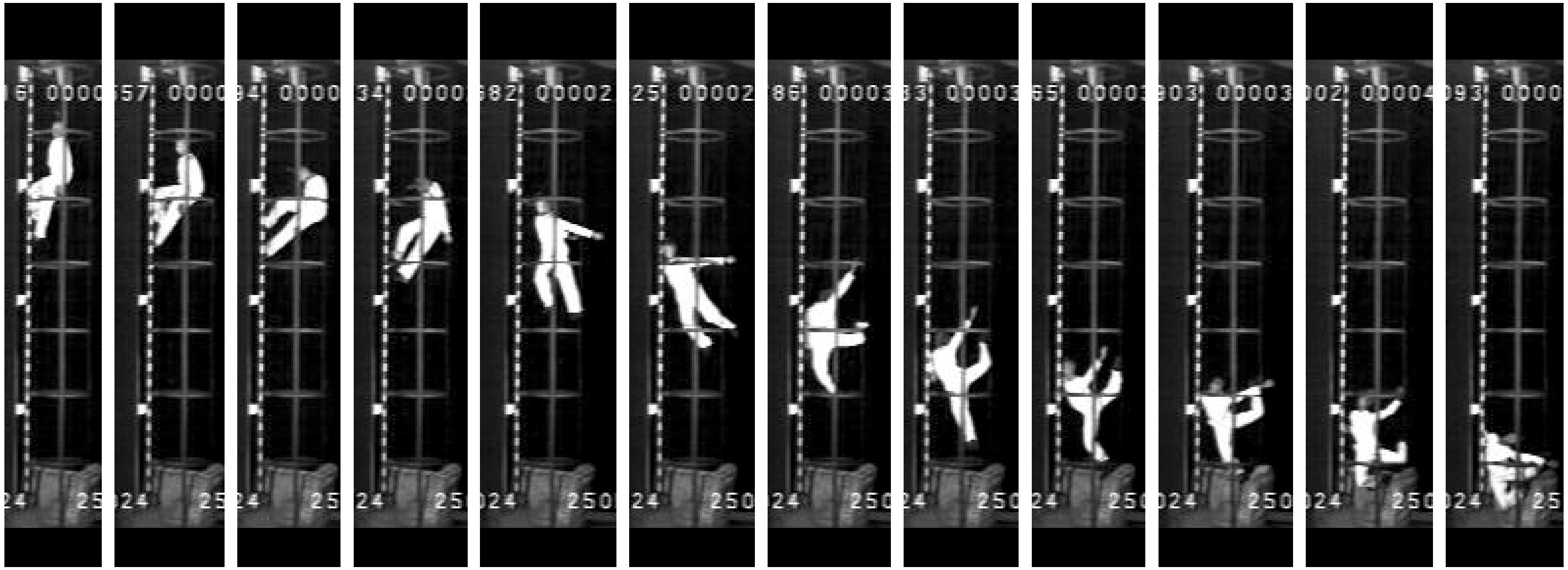

Figure 53 Kinematic sequence of ATD fall trajectory from test 4 (caged ladder)

5.4.6 Drop-Test No. 5

The position of the ATD just before release is shown in Figure 54.

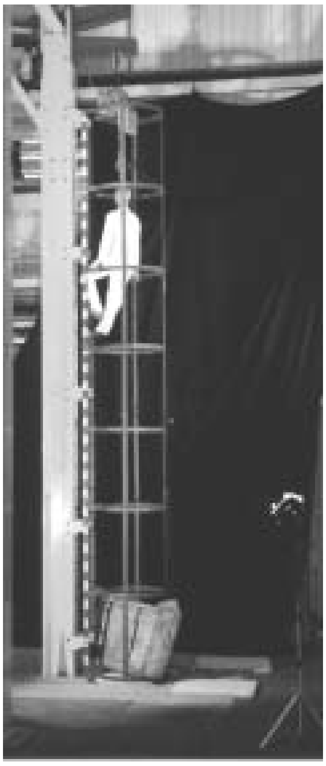

Figure 54 ATD just before release

Upon release, the ATD fell a distance of 1.6 m before catching a hoop by the armpits. The accelerometer was not triggered in this test – it is assumed that deceleration levels did not exceed the 2g triggering threshold.

The kinematic sequence of the fall trajectory is shown in Figure 55. The ATD had a release position similar to that in Test No. 4, and again the feet were in a climbing posture with the hands off simulating the loss of both handholds. Initially, the ATD fell away from the ladder, pivoting about the feet, with the back striking the back of the cage. With the legs in the horizontal, providing a reaction against the ladder, the ATD’s back slid down the inside face of the cage. The left leg then came off the ladder and the ATD’s left armpit caught one of the hoops. This caused the left arm to rise, but nevertheless stopped the ATD’s fall. The right leg was stuck in the ladder, forced slightly upwards, and the right armpit got caught in the same hoop as the left. In effect the hoop acted as a stop under the armpits, Figure 56 refers.

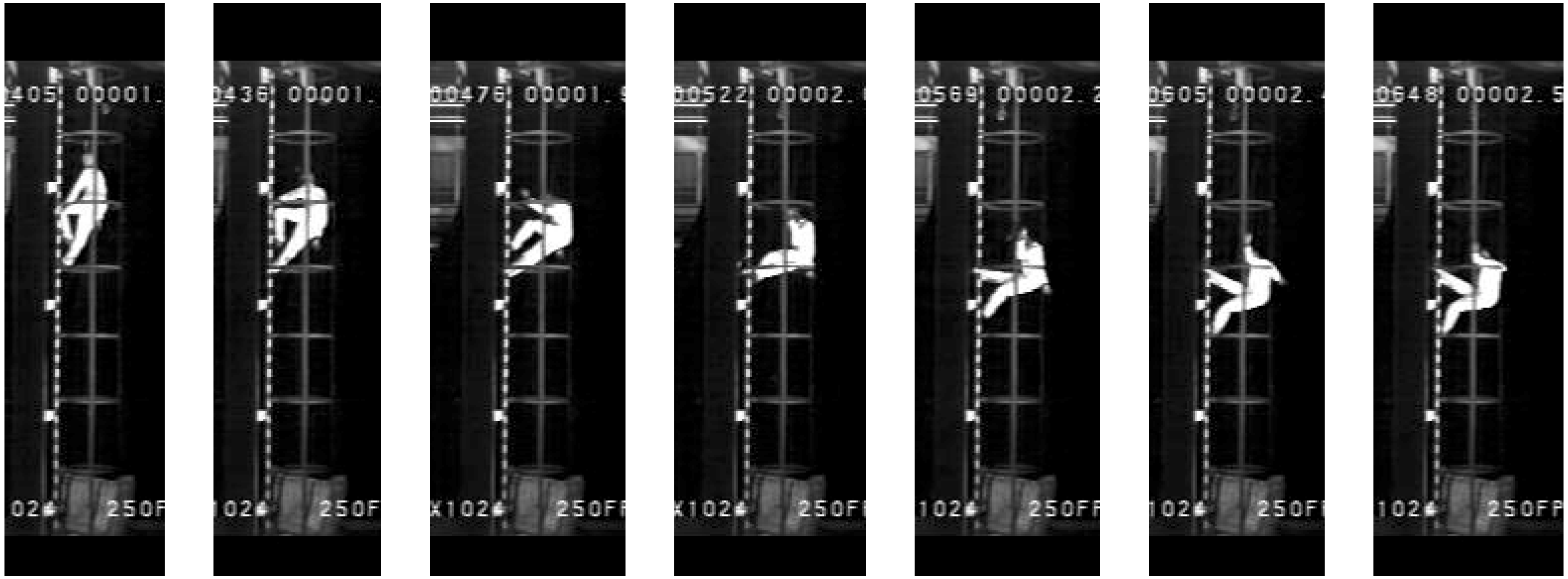

Figure 55 Kinematic sequence of ATD fall trajectory from test 5 (caged ladder)

Figure 56 ATD armpits caught on hoop

5.4.7 Drop-Test No. 6

The position of the ATD just before and after release is shown in Figures 57 and 58 respectively.

Figure 57 ATD just before release

Figure 58 ATD caught by armpit

Upon release, the ATD fell a distance of 2.3 m before catching a hoop by the armpit, registering a series of four headward and two footward deceleration peaks of around 4g in the z axis, (maximum 4.58g), a 4.06g maximum deceleration sidewards to the right in the y axis, and 6.5g frontwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 59. The ATD had a release position similar to that in Test No. 5. Initially, the ATD fell away from the ladder, pivoting about the feet. The back of the ATD fell against the back of the cage and the left foot came off the rungs. With the right foot still on the ladder and the leg horizontal, the ATD continued to fall down the cage guided by the back upright. The right arm was struck by a hoop causing it to rise upwards. The right leg became more upright, and the left armpit caught another hoop which helped to retard the ATD's momentum. The left leg got caught in the ladder again and the ATD came to rest being supported by the left armpit around a hoop, Figure 58 refers.

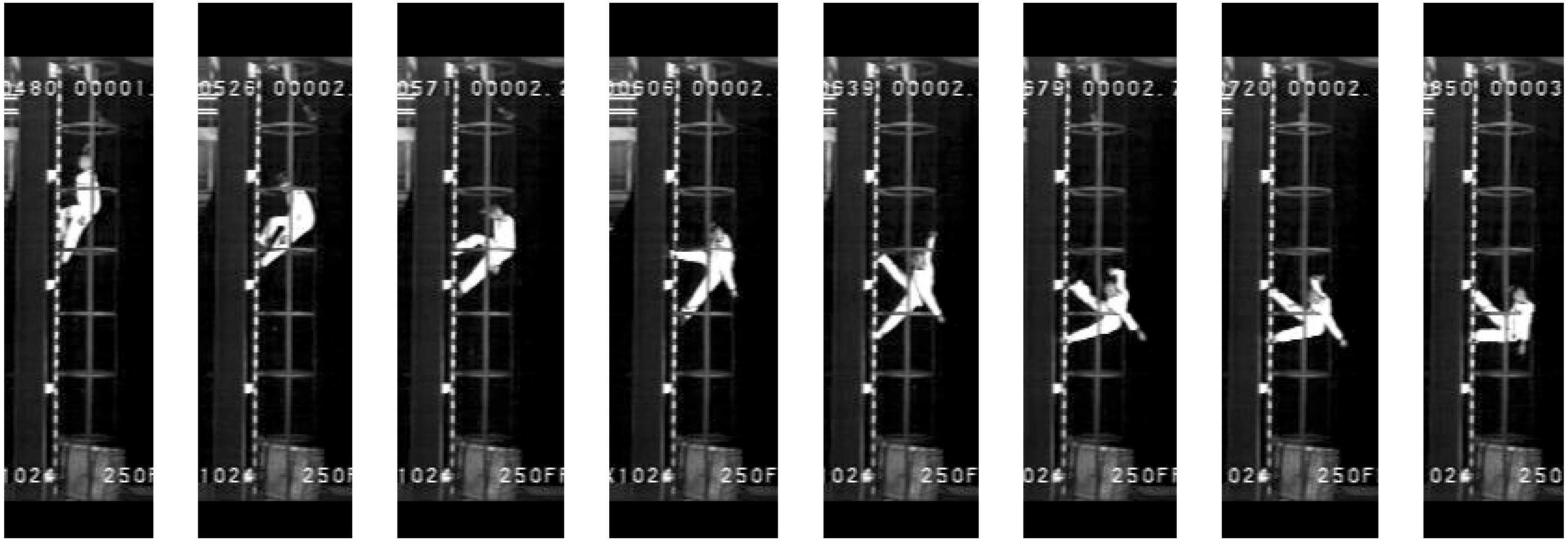

Figure 59 Kinematic sequence of ATD fall trajectory from test 6 (caged ladder)

5.4.8 Drop-Test No. 7

The position of the ATD just before release is shown in Figure 60.

Figure 60 ATD just before release

Upon release, the ATD fell a distance of 4.2 m to the test house floor, registering a maximum deceleration of 11.98g headwards in the z axis, 4.3g deceleration sidewards to the right in the y axis, and 3.39g backwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 61. In this test, the ATD was arranged to simulate the loss of both footholds followed by the hands. Initially, the ATD fell wholly downwards and the arms extended. Both handholds were lost and the arms were raised as the ATD fell. The chest struck the ladder which registered a headward deceleration of 8g in the z axis and a backward deceleration of 3g in the x axis. The ATD continued to fall erect with the knees rubbing the ladder rungs on the way down before the ATD struck the padding at the bottom of the cage, recording deceleration levels which were much lower than those when the ATD struck the cage (Test Nos. 1, 3 and 4).

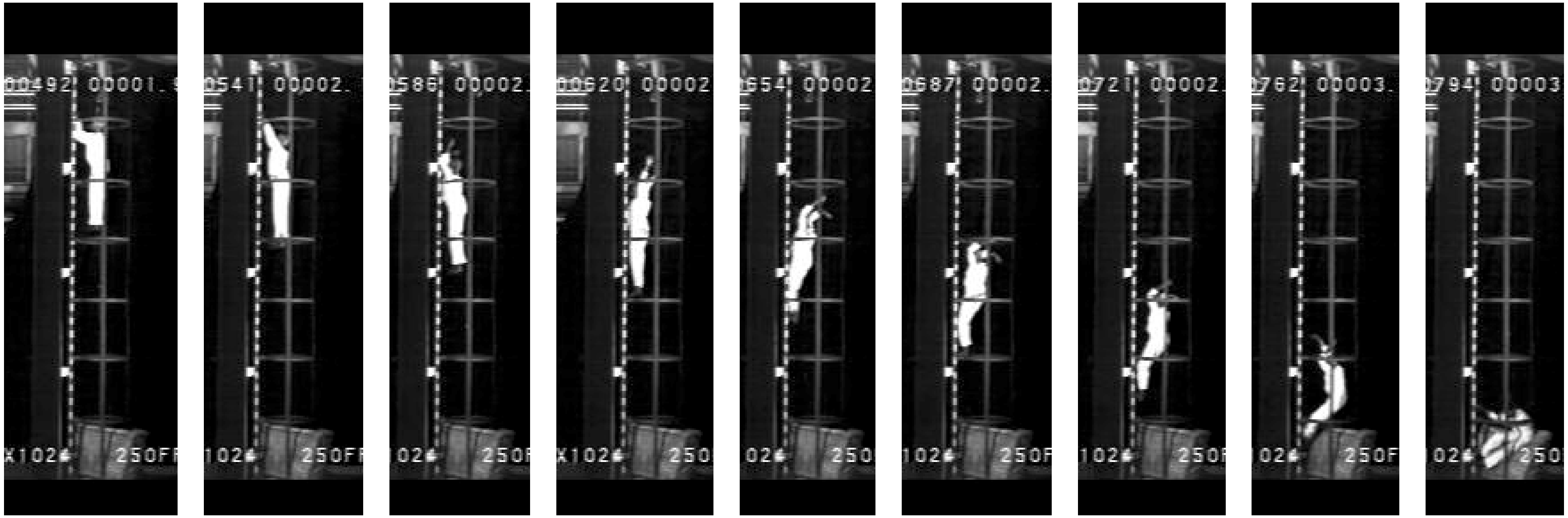

Figure 61 Kinematic sequence of ATD fall trajectory from test 7 (caged ladder)

5.5 DROP-TEST METHOD FOR LADDER MOUNTED FAS

After completion of the caged ladder drop-tests, the hoops and uprights were removed to leave a clean ladder fixed into place on the drop-test rig.

For each of the test specimens in turn, a section of rail was centrally attached to the test ladder and the matching sliding arrest device was engaged onto/into the rail in accordance with manufacturer's instructions.

A full body harness of the type typically used with the FAS concerned, was fitted to the ATD in accordance with the manufacturer's instructions, which in turn was attached to the sliding arrest device using the connection as supplied by the manufacturer. The overall length of this connection was not altered in any way. Attachment was via the sternal attachment point on the harness[44].

The drop-test procedure was almost identical to that used with the caged ladder testing as described in clause 5.3. An eyebolt on the ATD's head was used to connect a quick release mechanism, which was in turn connected to the chain of an electric hoist, Figure 62 refers. With the ATD raised to the required height, the function of the quick release mechanism was to allow the remote release of the ATD without imparting any motion to it except that caused by falling under its own weight, thus creating the circumstances of a fall as accurately as possible[45].

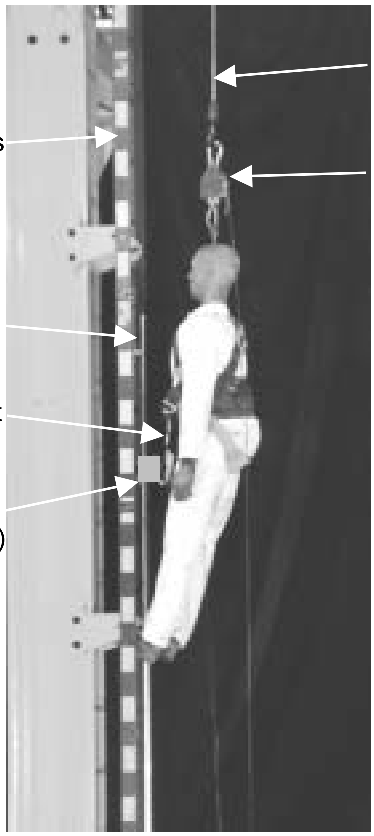

Figure 62 General arrangement of drop-test preparation

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[44] *A designated fall-arrest equipment attachment point which lies at the front and centre of the harness, so disposed to lie at the bottom of the sternum (breast bone) where the lower ribs meet.*

[45] *Note that the hoist was also positioned over the rail so that no sideways motion could be imparted to the ATD (in the "y" direction) at release.*

With the ATD raised to a high point, the limbs and posture could be set to simulate climbing attitude prior to release. The degree of articulation and general geometrical disposition of the ATD, (see Appendix 3), were utilised to reproduce a number of pre-release body attitudes.

A number of possible situations were considered in which a fall was likely to result, as opposed to temporary loss of control or stability which could be recoverable. The conclusion was that a fall was most likely to occur when a loss of grip from both hands occurred in a non-recoverable manner, with the body falling away from the ladder and pivoting about the feet, as supported in other research, e.g. Clark (1985) and Dewar (1977). The loss of contact by one or both feet was thought unlikely to result in a non-recoverable situation, provided that one or both hands retained a grip, (likened to a slip from a rung).

Prior to each test the sliding arrest device was positioned on the rail to provide the worst release circumstances, i.e. to reproduce the worst falling-off circumstances. This entailed:

(i) ensuring that the device was in its fully unlocked position;

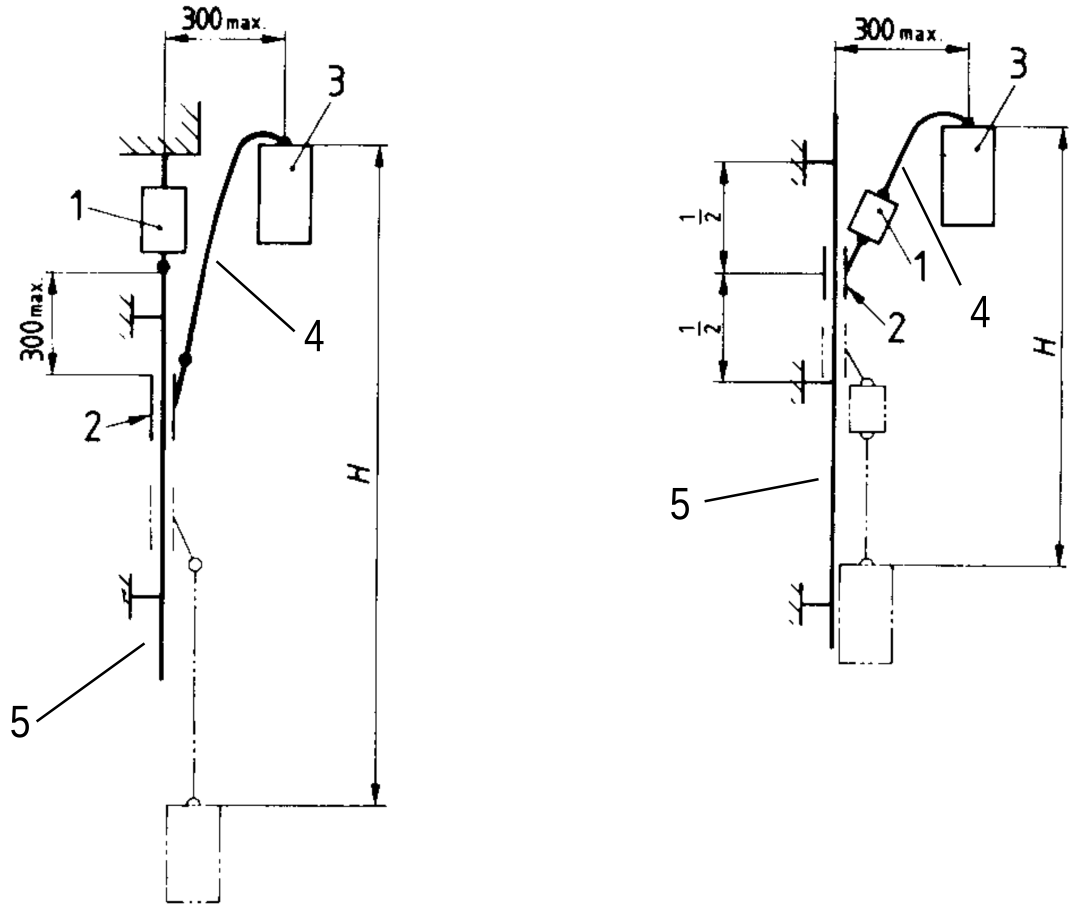
(ii) in addition to (i), ensuring that the device was at its lowest possible position below the harness attachment point, i.e. with the connection as taut as possible, so that upon release, the ATD would fall the furthest possible distance;

(iii) in the case of the rails with preformed slots, in addition to (i) and (ii), positioning the device at the furthest possible distance above the next available rail slot, so that upon release, the device would slip down the rail the furthest possible distance before encountering a slot.

With the ATD in the desired pre-release attitude and with the accelerometer cables hanging freely beneath, the measuring electronics were set. The triggering level for the tri-axis accelerometer was set to 2g.

Whilst conducting drop-tests on ladder-mounted FAS in accordance with EN 364 (1992), it is a requirement to insert a load cell for measuring dynamic forces, either between the test rig and the rail, (the rail being suspended and guided in this case), or between the test weight and safety-line connection, see Figure 63.

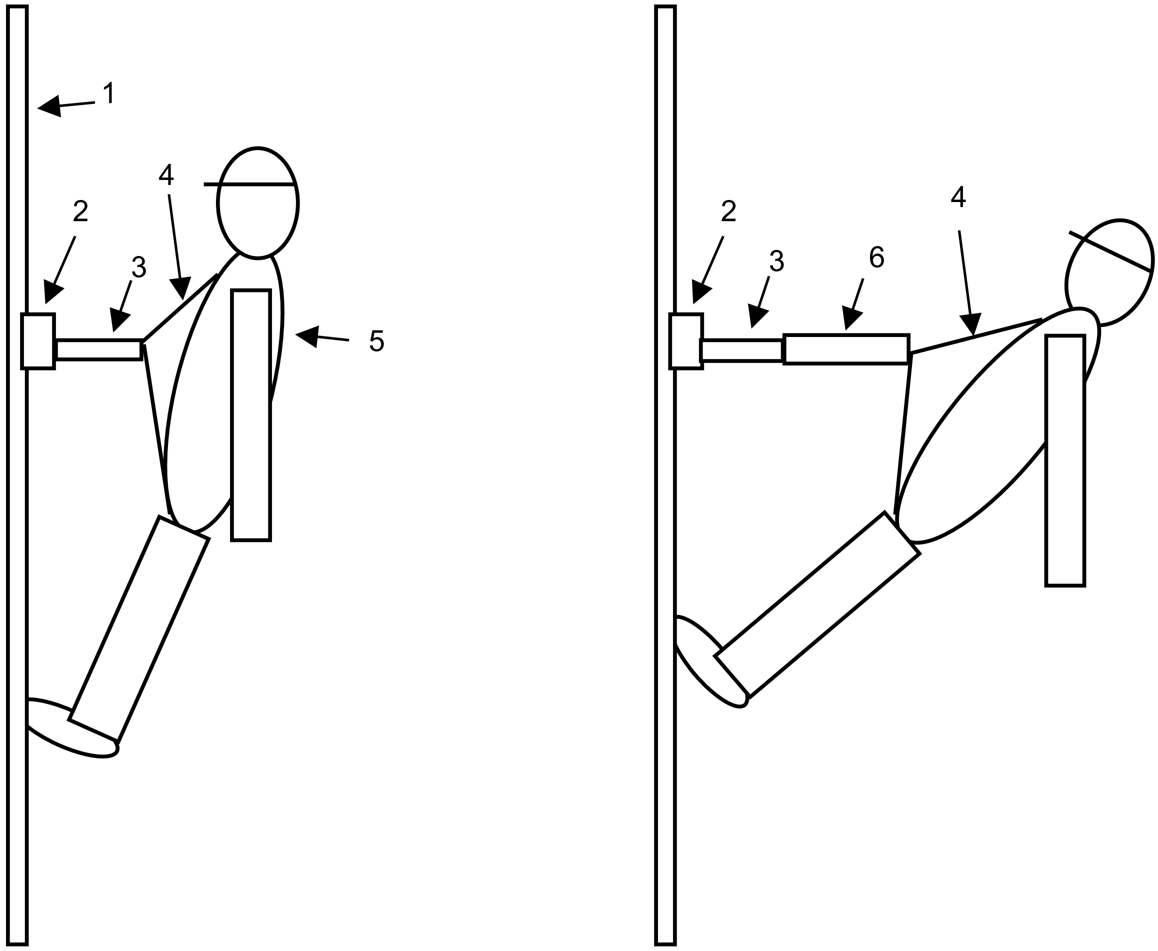
In the second case, (the right hand view in Figure 63), the load cell can be arranged so that it's length does not contribute to the overall fall distance. In this research, the fitting of a load cell between the safety-line connection and the ATD was considered, as this would have given useful corroborative information between arrest forces and the internal accelerometer measurements. However, it was discounted after considering the fall simulation when a worker could fall back away from the ladder, pivoting about the feet, as simulated previously in the caged ladder testing. In this case the length of the load cell would have contributed to the safety-line connection length in a way which could have adversely affected fall-arrest performance, and would not be representative of a real-life situation, Figure 64 refers. Hence a load cell was not fitted in this position.



Key:

1 = load cell
2 = sliding arrest device
3 = test mass
4 = safety-line connection
5 = rail
H = total fall distance (displacement from onset of fall to end of fall)

Figure 63 Alternative methods for drop-testing ladder mounted rail and sliding arrest device based FAS after EN 364 (1992) with some additions



Key:

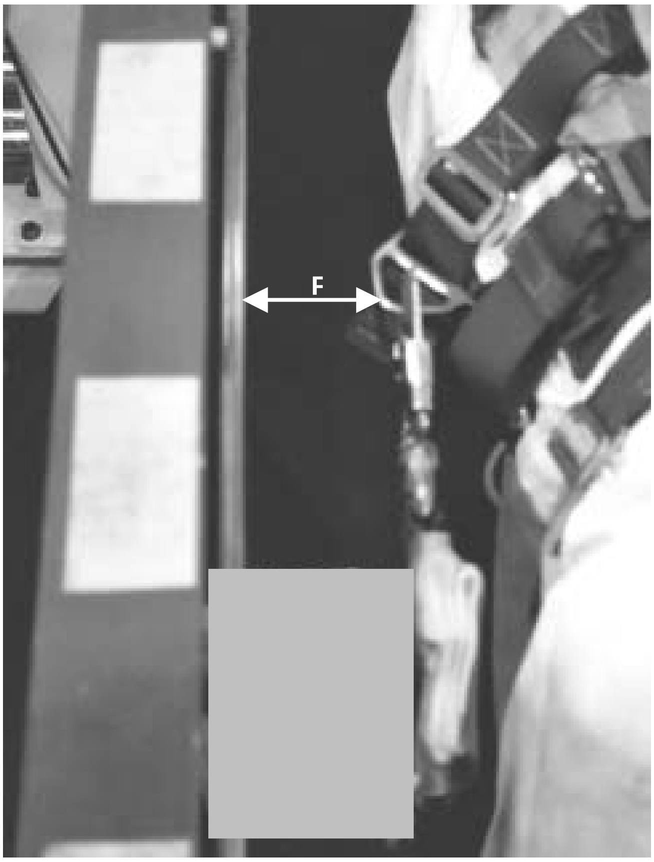
1 = rail attached to ladder
2 = sliding arrest device
3 = safety-line connection
4 = harness strap stretch as ATD leans/falls away from ladder
5 = ATD
6 = load cell

Figure 64 Comparison of pre-release positions of ATD without a load cell inserted (left hand view) and with a load cell inserted (right hand view) showing a greater "fall back" position away from the ladder

The pre-release posture of the ATD and the distance from the harness attachment point to the rail was measured prior to release, dimension “F” in Figure 65. The starting position of the ATD and sliding arrest device were also marked on the ladder in order to measure their displacement after the arrest event, Figure 66.

The quick release mechanism was manually activated by pulling a cord, allowing the ATD to fall freely. The high speed video started recording the fall motion at the instant before release.

New sliding fall arrest devices were used for each test. Rails were examined in between tests and were only replaced if damaged.



Note: arrest device deliberately obscured

Figure 65 ATD in a typical pre-release position showing dimension “F”

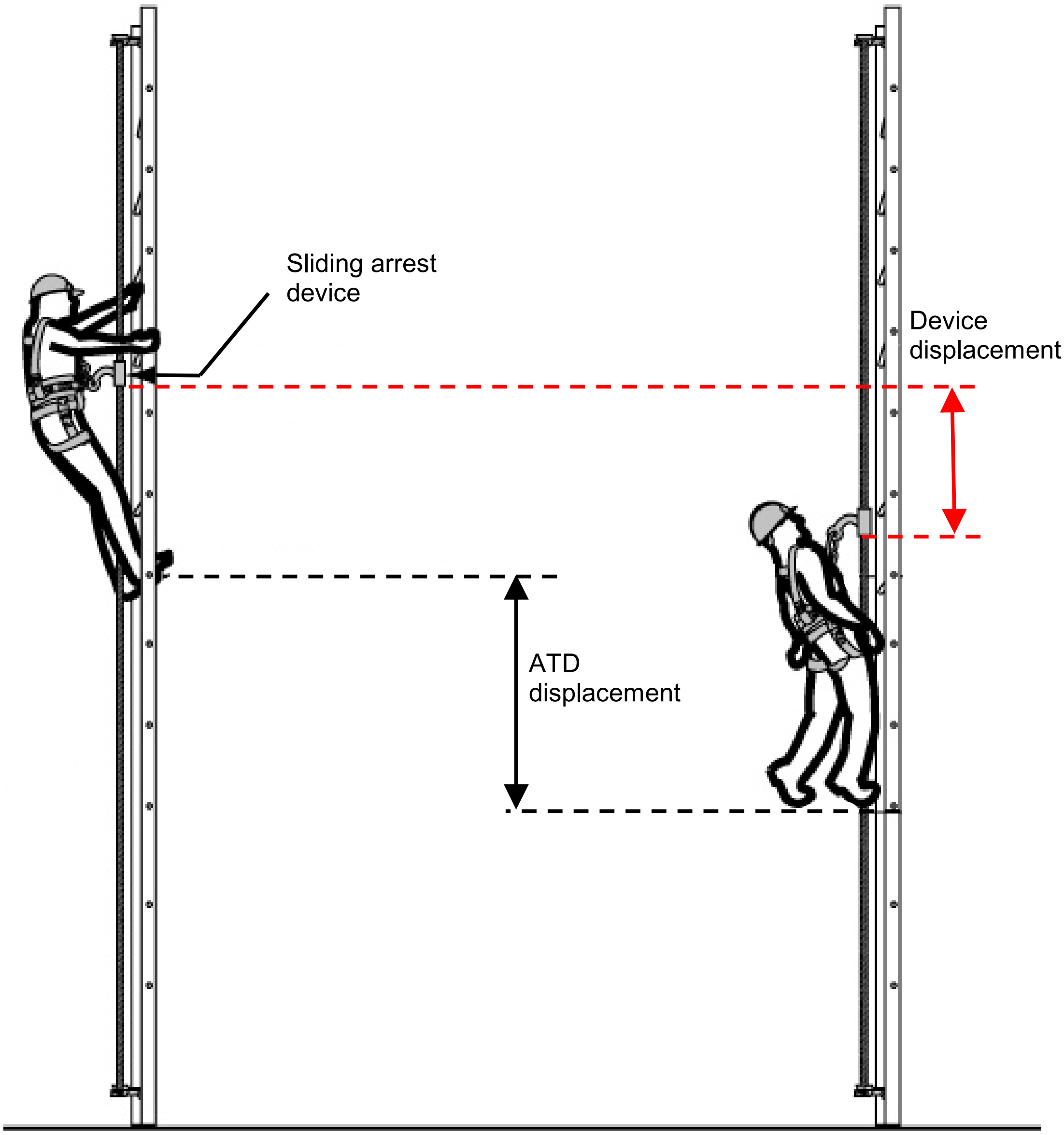


Figure 66 Before release and post-drop test positions of arrest device and ATD showing method of measuring of displacement

5.6 DROP-TEST RESULTS FOR LADDER MOUNTED FAS

5.6.1 General

Eleven drop-tests were conducted with five different kinds of ladder mounted FAS, the results of which are summarised in Tables 5-7. These tables record:

- test numbers 8-19, (numbered sequentially from caged ladder tests), and the five different FAS specimens tested, differentiated by the numbers FAS 1, FAS 2, FAS 3, FAS 4 and FAS 5
- dimension F (Figure 65)
- ATD limb position at the point of release
- maximum deceleration and direction in each of the three principle axes of the ATD
- device locking distance (the distance the sliding arrest device took from release to finally locking onto the rail)
- fall distance (from release to the point at which the ATD came to rest).

It should be noted that the "equivalent force" category in Tables 5-7 is a simple, crude conversion of the maximum acceleration measurement, using the formula derived from Newton's second law, Force = Mass x Acceleration. Hence the equivalent force is the product of the ATD's mass (71 kg) and acceleration (the "g" figure multiplied by 9.81m/s²). However, due the distributed mass of the ATD and the ATD's mechanical interconnections used to model the body of a human, the effective mass for such a calculation is unknown; also the site of the accelerometer was not at the centre of gravity of the ATD.

Impact investigations in the past have shown that acceleration measurements change from point to point on any distributed body element unless it is rigid and moving in only one linear direction without rotation, Snyder (1973). Thus, one acceleration measure, even if properly made, is not representative of the acceleration distribution over the body. "Equivalent force" has been shown purely to give an ***indication*** for a reader familiar with fall-arrest parameters[46], therefore it should not be relied upon as an accurate value.

In this research, the measurement of falling motion as it is retarded has been given more prominence than inertial forces. The reader should therefore focus on deceleration rather than force in this instance.

A kinematic sequence of the ATD's fall trajectory is presented for each of the drop-tests. This is a sequence of photographic snapshots in time which describes the motion of the ATD during the test. The snapshots are displayed at random time intervals to reflect significant events in the test.

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[46] In fall-arrest quarters, one would expect to see maximum fall-arrest force shown in test results. This is due to the intrinsic feature of FAS in that they have a physical connection to the test structure, and hence it is relatively easy to insert a load cell to measure the reactive forces in such a connection. However as explained in clause 5.5, a load cell was not used in this instance as the length of the load cell would have contributed to the connection length in a way which could have adversely affected fall-arrest performance, and would not be representative of a real-life situation.

The individual acceleration-time history graphs can be found in Appendix 2. Note that test number 11 has no graph since the accelerometer was not triggered in this test; it therefore can be assumed that deceleration levels did not exceed 2g [47]. This can be corroborated when examining the fall trajectory of test number 11.

[47] *Instrumentation was checked after each test to make sure accelerometer was registering correctly.*

Table 5
Summary of ladder-mounted FAS drop-test results for test numbers 8 - 10

Test/ FAS No.	*Dimension F (mm) and ATD limb position at release*	*Maximum deceleration, direction applied and equivalent force**						*Energy absorber extension (m)*	*Device locking distance (m)*	*Fall distance (m)*	*Remarks*
		z axis		*y axis*		*x axis*					
		deceleration (g)	*force (kN)*	*deceleration (g)*	*force (kN)*	*deceleration (g)*	*force (kN)*				
8/1	F = 90 Both hands off rungs Feet on same rung, legs straight	3.84 headwards	2.67	3.49 sidewards to right	2.43	5.57 backwards	3.88	0.26	1.16	2.69	Device locked at first, then unlocked, and then locked again resulting in excessive fall distance
9/1	F = 90 Both hands off rungs Feet on same rung, legs straight	4.65 headwards	3.24	2.66 sidewards to left	1.85	5.2 backwards	3.62	0.17	0.605	1.98	Device locked at first, then unlocked, and then locked again resulting in excessive fall distance, but not as great as in test No. 8
10/1	F = 120 Both hands and feet off rungs	4.03 headwards	2.81	2.48 sidewards to left	1.73	5.62 frontwards	3.91	0	0.1	1.3	ATD was lowered at hoist speed (0.145 m/s) before release, to simulate man descending ladder; lock-on occurred quickly, energy absorber did not operate

** see clause 5.6.1*

Table 6
Summary of ladder-mounted FAS drop-test results for test numbers 11-14

Test/ FAS No.	*Dimension F (mm) and ATD limb position at release*	*Maximum deceleration, direction applied and equivalent force**						*Energy absorber extension (m)*	*Device locking distance (m)*	*Fall distance (m)*	*Remarks*
		z axis		*y axis*		*x axis*					
		deceleration (g)	*force (kN)*	*deceleration (g)*	*force (kN)*	*deceleration (g)*	*force (kN)*				
11/2	F = 150 Both hands off rungs Feet on same rung, legs straight	no trigger	-	no trigger	-	no trigger	-	n/a	0.04	0.5	
12/2	F = 180 Both hands off rungs Feet on same rung, legs straight	10.51 footwards	7.32	23.85 sidewards to left	16.6	22.21 frontwards	15.47	n/a	-	4.0	Device and ATD disengaged from rail-end; ATD impacted test house floor
13/3	F = 170 Both hands off rungs Feet on same rung, legs straight	7.45 headwards	5.19	13.87 sidewards to right	9.66	12.72 backwards	8.86	n/a	1.65	2.16	
14/3	F = 180 Both hands off rungs Feet on same rung, legs bent	1.73 headwards	1.20	0.3 sidewards to left	0.21	1.1 frontwards	0.77	n/a	0.76#	0.9^	Locking ability of device prevented by outward pushing action of ATD's folded legs wedged between chest and ladder

** see clause 5.6.1*
n/a "not applicable"
 # device did not lock but was stopped by motion of ATD
^ ATD feet did not come off rung so this dimension refers to the distance through which the ATD's head fell

Table 7
Summary of ladder-mounted FAS drop-test results for test numbers 15-18

Test/ FAS No.	*Dimension F (mm) and ATD limb position at release*	*Maximum deceleration, direction applied and equivalent force**						*Energy absorber extension (m)*	*Device locking distance (m)*	*Fall distance (m)*	*Remarks*
		z axis		*y axis*		*x axis*					
		deceleration (g)	*force (kN)*	*deceleration (g)*	*force (kN)*	*deceleration (g)*	*force (kN)*				
15/4	F = 180 Both hands off rungs Feet on same rung, legs straight	2.12 headwards	1.48	1.12 sidewards to right	0.78	2.1 backwards	1.46	0	0.035	0.73	
16/4	F = 240 Both hands off rungs Feet on same rung, legs bent	2.67 headwards	1.86	1.68 sidewards to right	1.17	2.86 backwards	1.99	0	0.03	0.6^	ATD was arrested in a sitting position as feet did not fall off ladder rung
17/5	F = 150 Both hands off rungs Feet on same rung, legs straight	2.67 headwards	1.86	1.3 sidewards to left	0.91	1.62 backwards	1.13	n/a	0.022	0.48	
18/5	F = 185 Both hands off rungs Feet on same rung, legs bent	3.10 headwards	2.16	0.69 sidewards to right	0.48	1.68 backwards	1.17	n/a	0.255	0.65^	ATD was arrested in a sitting position as feet did not fall off ladder rung

**see clause 5.6.1*
n/a “not applicable”
^ ATD feet did not come off rung so this dimension refers to the distance through which the ATD’s head fell

5.6.2 Drop-Test No. 8

FAS 1 was used in this test. The sliding arrest device had an integral short energy-absorbing lanyard and connector of 0.33m overall length for connecting to the harness. The position of the ATD just before release is shown in Figure 67.

Figure 67 ATD just before release

Upon release, the ATD fell a distance of 2.69m before being brought to a complete stop. The sliding arrest device skidded 1.16 m down the rail before finally locking onto it. Energy absorber extension was 0.26m.

The following deceleration maxima were registered: 3.84g headwards in the z axis, 3.49g sidewards to the right in the y axis, and 5.57g backwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 68. Initially, the ATD fell away from the ladder, pivoting about the feet, with the body folding about the waist. Both sliding arrest device and ATD fell together whilst the device to harness connection remained taut, and when the device had fallen 400 mm the feet came off the rung, and the ATD continued to fall in a slightly jackknifed attitude.

After the device had fallen 600 mm, the motion of the ATD was such as to allow the device to harness connection to go slack, enabling the device to lock onto the rail[48]. At this point the ATD could fall past the device, and then the connection became taut again as it reacted the load of the falling ATD.

[48] *After the test, the locking marks on the rail showed that the first lock-on attempt was at a distance of 600 mm from the release point, also verified by playback of the high speed video*

At this point the acute angle of the device to harness connection and the rail was approximately 40º, but there was still a significant horizontal component to the ATD's outward motion[49], such that the tension in the connection was sufficient to unlock the device, causing it to slide down the rail for a second period.

Both device and ATD fell a further 500 mm before the device could lock onto the rail again, at which point the ATD's motion was almost wholly downwards and inwards.[50] The device firmly reacted the ATD's motion[51] and caused the device's energy absorber to deploy and extend, in so doing dissipating a certain amount of the fall energy.

The deceleration of 3.84g headwards in the z axis and an acceleration of 5.31g frontwards in the x axis were registered at this point. This latter acceleration was responsible for rapidly swinging the ATD inwards towards the rail, impacting the chest at 5.57g backwards in the x axis. At no point did the head strike the rail or any part of the sliding arrest device / connection.

The post-drop test suspension position can be seen in Figure 69.

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[49] *Backwards in the x axis*
[50] *Frontwards in the x axis*
[51] *The rail bowed significantly at this point.*

Figure 68 Kinematic sequence of ATD fall trajectory from test 8 (FAS 1)

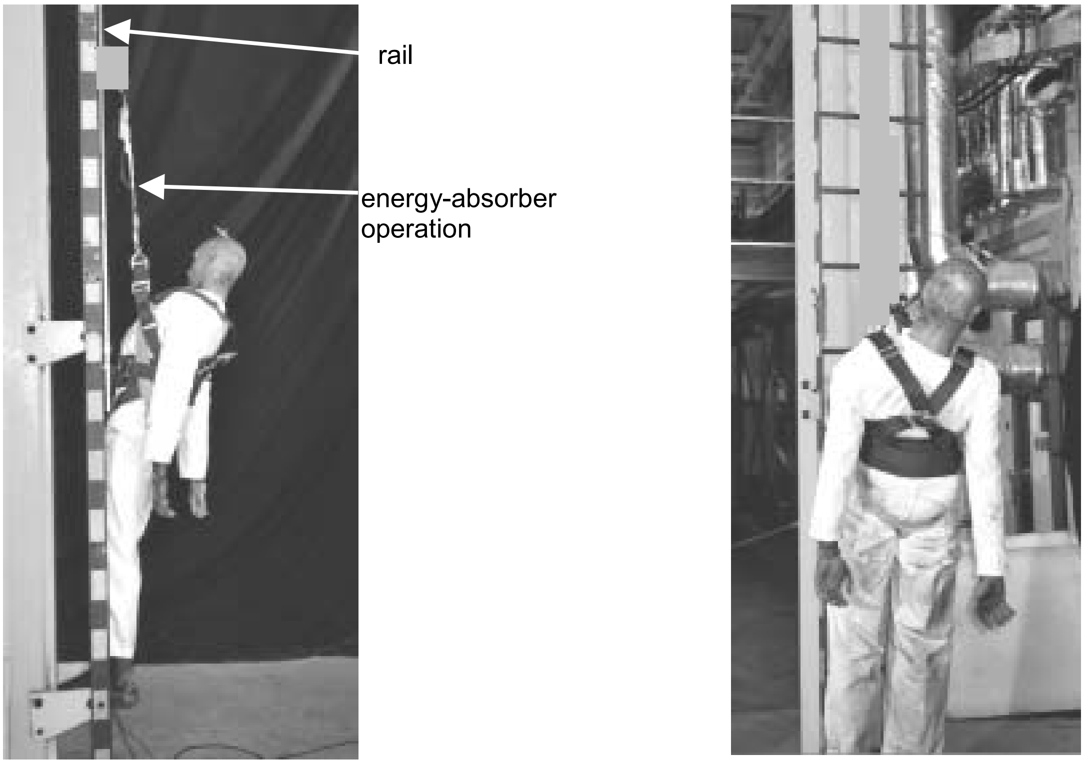

Figure 69 Two views of post-drop test suspension position

5.6.3 Drop-Test No. 9

FAS 1 was used in this test. The sliding arrest device had an integral short energy-absorbing lanyard and connector of 0.33m overall length for connecting to the harness. The position of the ATD just before release is shown in Figure 70.

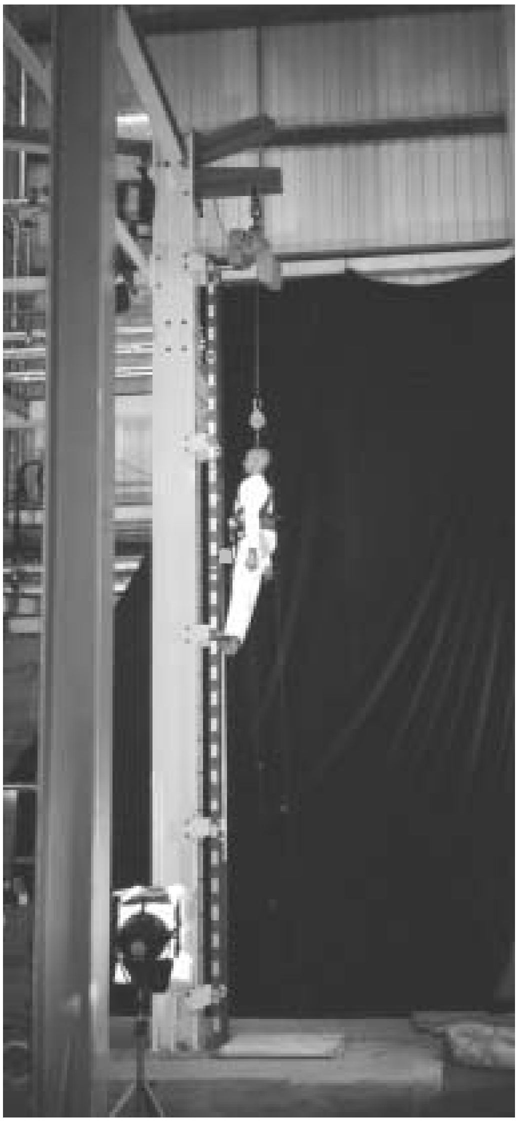

Figure 70 ATD just before release

Upon release, the ATD fell a distance of 1.98m before being brought to a complete stop. The sliding arrest device skidded 0.605m down the rail before finally locking onto it. Energy absorber extension was 0.17m.

The following deceleration maxima were registered: 4.65g headwards in the z axis, 2.66g sidewards to the left in the y axis, and 5.2g backwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 71. In a similar manner to Test No. 8, the ATD fell away from the ladder, pivoting about the feet, with the body folding about the waist. Both sliding arrest device and ATD fell together whilst the device to harness connection remained taut, but when it went slack, the device locked onto the rail. At this point the device had slid 550 mm down the rail. The device then suddenly unlocked and locked again almost immediately, (within approximately 0.1s), sliding less than 50mm down the rail.

The ATD then fell past the device, and the connection reacted the load of the falling ATD, causing the device's energy absorber to deploy.

The deceleration of 4.65g headwards in the z axis and an acceleration of 4.62g frontwards in the x axis were registered at this point. This latter acceleration was responsible for rapidly swinging the ATD inwards towards the rail, impacting the chest at 5.2g backwards in the x axis. At no point did the head strike the rail or any part of the sliding arrest device / connection.

The post-drop test suspension position can be seen in Figure 72.

Figure 71 Kinematic sequence of ATD fall trajectory from test 9 (FAS 1)

Figure 72 Post-drop test suspension position

5.6.4 Drop-Test No. 10

FAS 1 was used in this test. The sliding arrest device had an integral short energy-absorbing lanyard and connector of 0.33m overall length for connecting to the harness. The position of the ATD just before release is shown in Figure 73.

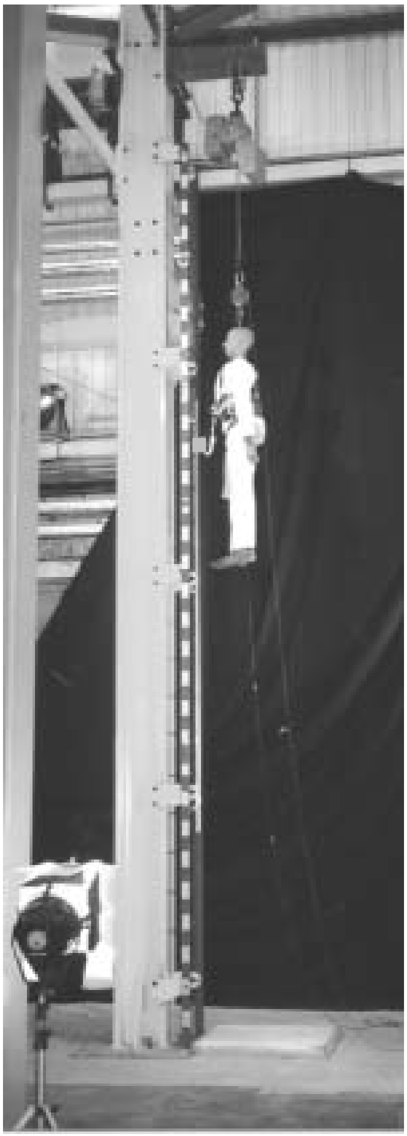

Figure 73 ATD just before release

Upon release, the ATD fell a distance of 1.3 m before being brought to a complete stop. The sliding arrest device skidded 0.1 m down the rail before finally locking onto it. The energy absorber did not extend.

The following deceleration maxima were registered: 4.03g headwards in the z axis, 2.48g sidewards to the left in the y axis, and 5.62g frontwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 74. In this test, with both hands and feet off the ladder, the ATD was lowered at a constant speed of 0.145 m/s before being released, in an attempt to recreate a worker descending the ladder and then falling-off[52].

The ATD fell in an upright posture. The sliding arrest device locked onto the rail very rapidly (within 100mm of release). The ATD then fell past the device, and the connection reacted the load. However the tear-ply energy absorber did not deploy.

The deceleration of 4.03g headwards in the z axis and an acceleration of 5.62g frontwards in the x axis were registered at this point. This latter acceleration was responsible for rapidly swinging the ATD inwards towards the rail, impacting the chest at 4.51g backwards in the x axis. At no point did the head strike the rail or any part of the sliding arrest device / connection[53].

The post-drop test suspension position can be seen in Figure 75.

[52] *All of the world's standards for ladder-mounted FAS base their test methods on the presumption that the worker will be standing still at the point of falling. This may not be the case; the worker may be ascending or descending. Since the author was aware that the performance of some FAS can be affected by motion prior to release, this factor was assessed for in this particular test.*

[53] *As with the previous two tests, the arrest load pulled the torso part of the ATD upwards at the sternal attachment point, and the body adopted a slightly reversed jackknife posture; the head was inertially pushed towards the chest first, before rotating backwards.*

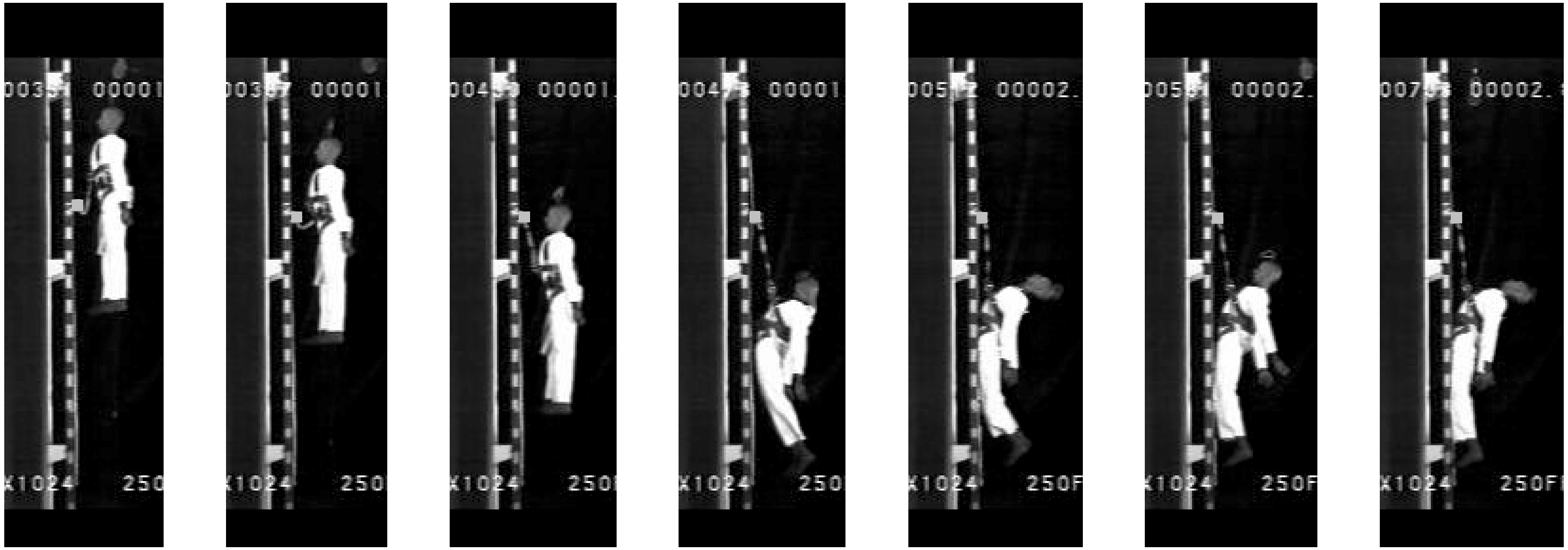

Figure 74 Kinematic sequence of ATD fall trajectory from test 10 (FAS 1)

Figure 75 Post-drop test suspension position

5.6.5 Drop-Test No. 11

FAS 2 was used in this test. The sliding arrest device had an short, integral shackle-connector of 0.135m overall length for connecting to the harness. The position of the ATD just before release is shown in Figure 76.

Figure 76 ATD just before release

Upon release, the ATD fell a distance of 0.5m before being brought to a complete stop. The sliding arrest device skidded 0.04m down the rail before finally locking onto it. The accelerometer was not triggered in this test – it is assumed that deceleration levels did not exceed the 2g triggering threshold[54].

The kinematic sequence of the fall trajectory is shown in Figure 77. The ATD fell away from the ladder is a slightly jackknifed posture. The device locked onto the rail very rapidly, within 40mm of release. As the ATD fell past the device, the horizontal component of it's outward motion was insufficient to unlock the device. As the fall arrest load became reacted by the device, the ATD was swung into the rail. The head hit the arrest device although not forcibly[55].

The harness appeared to keep the ATD in a very upright position throughout the fall-arrest sequence and appeared to afford a comfortable post-drop test suspension position, as can be seen in Figure 78.

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[54] *The sliding arrest device did react very quickly. Also the ATD did get it's feet wedged against another set of rungs after release; this may have helped to absorb some energy without being sensed by the accelerometer.*

[55] *A tri-axial accelerometer had not been fitted to the head of the ATD in order to reduce the complexity of measurement; however it may be a sensible addition in future research.*

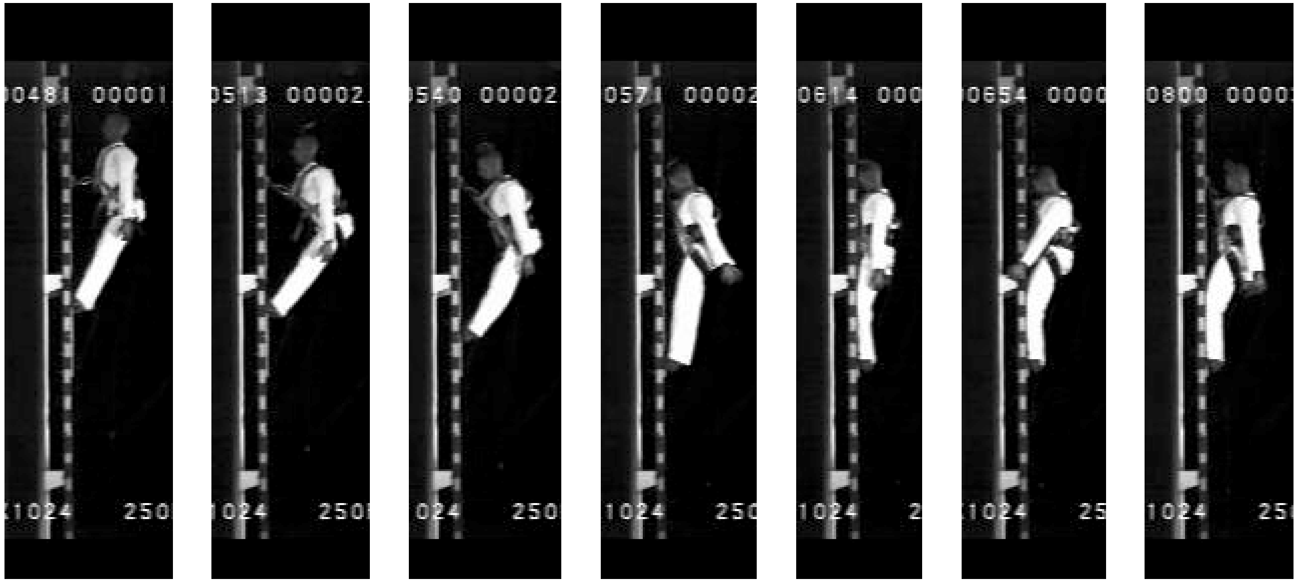

Figure 77 Kinematic sequence of ATD fall trajectory from test 11 (FAS 2)

Figure 78 Post-drop test suspension position

5.6.6 Drop-Test No. 12

FAS 2 was used in this test. The sliding arrest device had an short, integral shackle-connector of 0.135m overall length for connecting to the harness. The position of the ATD just before release is shown in Figure 79.

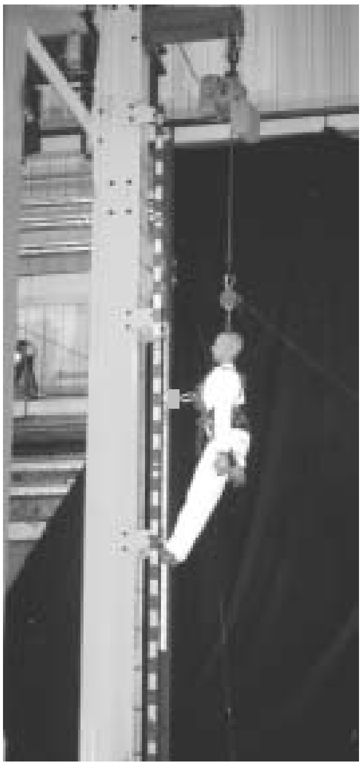

Figure 79 ATD just before release

Upon release, the ATD fell a distance of 1.7m before the sliding arrest device disengaged from the rail; the ATD then fell a further distance of 2.3m before impacting the test house floor.

The following deceleration maxima were registered: 10.51g footwards in the z axis, 23.85g sidewards to the left in the y axis, and 22.21g frontwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 80. Initially, the ATD fell away from the ladder, pivoting about the feet, which remained on the rungs, with the body folding about the waist. This folding became more progressive, with the upper torso pulling away from the ladder, as seen by the harness straps being stretched from the body. This prevented the locking action of the sliding arrest device.

After the device had slid 500mm down the rail, the left foot came off the rung, but the right foot remained, causing the right leg to act like a strut between the ladder and the harness. This action continued to prevent the locking action of the device. Both device and ATD fell together as the right leg became horizontal, and then inclined upwards, as the whole ATD rotated downwards about the right foot.

At this point the ATD started swinging in towards the rail and the sliding arrest device came off the rail end. The ATD fell back-first to the test house floor, impacting in a partially inverted, oblique attitude. The final resting position is shown in Figure 81.

Figure 80 Kinematic sequence of ATD fall trajectory from test 12 (FAS 2)

This impact corroborates the deceleration of 10.51g footwards in the z axis, 23.85g sidewards to the left in the y axis, and 22.21g frontwards in the x axis. It should be noted that no padding was placed on the test floor to offset ATD impacts, as occurrences such as this were not expected.

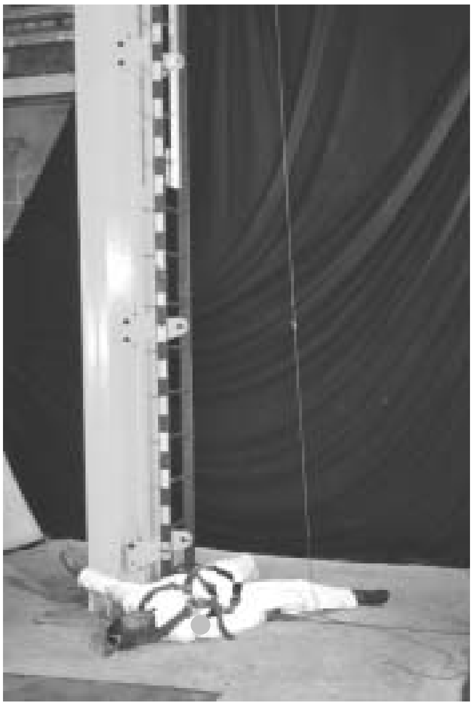

Figure 81 Outcome of test No. 12

These tests were intended to simulate a fall on a rail system at any particular point. They were not specifically evaluating what might happen when a fall took place near to the rail-end. Accordingly, it was understood that the sliding arrest devices would lock onto their respective rails within a reasonable distance[56] and so end-stops were not fitted to the rail-end. If a stop had been fitted, it may have prevented release of the device from the rail. If this had happened, the arrest decelerations would still have been very high, due to the momentum of the ATD at that point. In fact, the end-stop may have sheared off, because typically, end-stops are not designed for the emergency stop of arrest devices. There is no test to validate such an occurrence in EN 353 (2002), see footnote below. Stops are simply designed to prevent inadvertent disengagement from the rail in normal use, when a climber is near the rail-end [57].

Although the sliding arrest device failed to lock onto rail, with eventual disengagement from bottom of rail, it is believed that if there had been sufficient length of rail available, the device would have eventually locked onto rail, resulting in an overall ATD fall distance of approximately 2.1 m. This estimate is based upon the fact that in Test No. 13, a similar rail and locking method was used to that in Test No. 12, and the ATD exhibited an identical fall trajectory up to the point of device disengagement.

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[56] *EN 353-1 (2002), the European standard typically used as part of the CE marking/certification scheme required under the PPE Regulations (2002), stipulates that a falling 100 kg test mass is to be fully arrested within 1.0 m of the release point.*
[57] *This may be at a significant height above ground level*

5.6.7 Drop-Test No. 13

FAS 3 was used in this test. The sliding arrest device had an short, integral shackle-connector of 0.135m overall length for connecting to the harness. The position of the ATD just before release is shown in Figure 82.

Figure 82 ATD just before release

Upon release, the ATD fell a distance of 2.16 m before being brought to a complete stop. The sliding arrest device skidded 1.65 m down the rail before finally locking onto it.

The following deceleration maxima were registered: 7.45g headwards in the z axis, 13.87g sidewards to the right in the y axis, and 12.72g backwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 83. Initially, the ATD fell away from the ladder, pivoting about the feet, which remained on the rungs, with the body folding about the waist. This folding became more progressive, with the upper torso pulling away from the ladder, as seen by the harness straps being stretched away from the body. This prevented the locking action of the sliding arrest device.

After the device had slid 600mm down the rail, the left then the right foot came off the rung, but the right foot caught a rung again, causing the right leg to act like a strut between the ladder and the harness. This action continued to prevent the locking action of the device. Both device and ATD fell together as the right leg tended to pivot towards the horizontal.

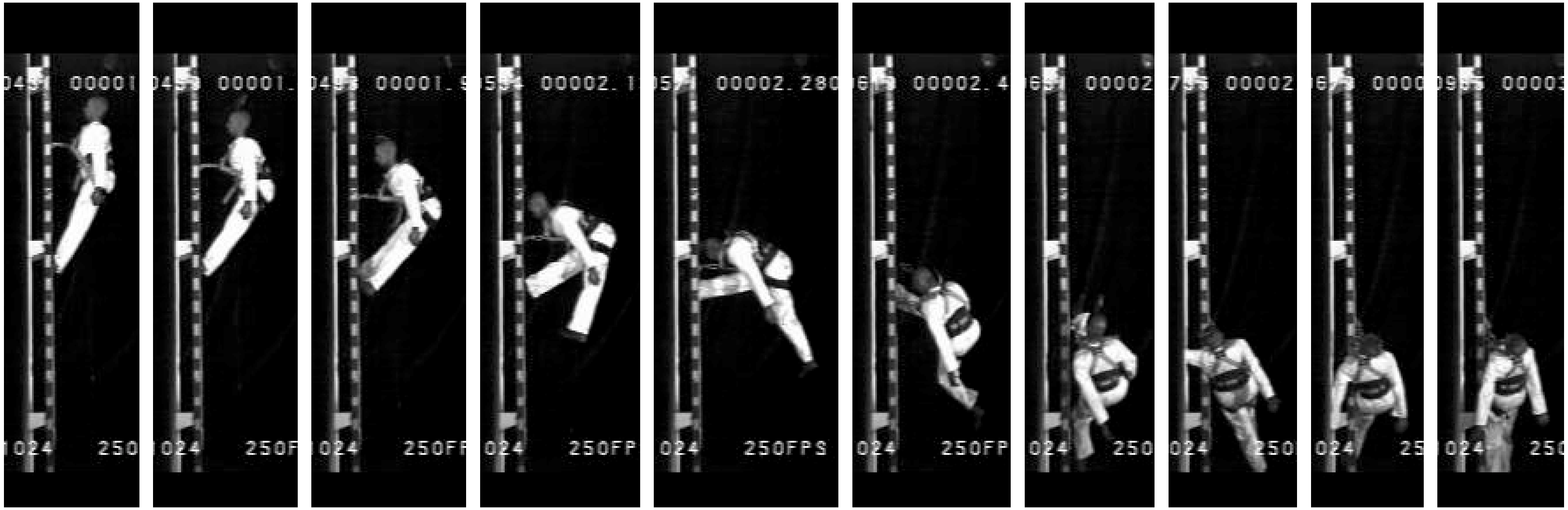

Figure 83 Kinematic sequence of ATD fall trajectory from test 13 (FAS 3)

Meanwhile the body continued to fold about the waist, and eventually the head struck the arrest device, after having slid 1150 mm down the rail. (The descent of the device had slowed down somewhat in response to the pulling action of the ATD in the horizontal plane).[58]

The right leg became horizontal, after the arrest device had slid 1350 mm down the rail. This caused the motion of the ATD to become unbalanced and it fell to the left (in the y axis) across the ladder. There was further inclination of the right leg whereupon there was sufficient release in harness connection tension to allow the device to lock onto the rail.

This allowed an arrest to take place with the left side of the ATD striking the ladder. This accounts for the 13.87g deceleration sideways to the right in the y axis, and the 12.72g deceleration backwards in the x axis. The body finally adopted a post-drop test suspension attitude across the ladder, see Figure 84.

Figure 84 Post-drop test suspension position

[58] *Backwards, in the x axis*

5.6.8 Drop-Test No. 14

FAS 3 was used in this test. The sliding arrest device had an short, integral shackle-connector of 0.135m overall length for connecting to the harness. The position of the ATD just before release is shown in Figure 85.

Figure 85 ATD just before release

Upon release, the head of the ATD fell through a distance of 0.9 m before being brought to a complete stop. The sliding arrest device skidded 0.76 m down the rail before being stopped by the motion of the ATD; it did not lock.

The following deceleration maxima were registered: 1.73g headwards in the z axis, 0.3g sidewards to the left in the y axis, and 1.1g frontwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 86. Initially, the ATD fell away from the ladder, pivoting about the feet. The pull away from the ladder was in evidence by the stretching of the harness straps away from the chest and the straightness of the harness connection. These factors combined to prevent the sliding arrest device from locking onto the rail.

Motion continued with a progressive folding of the body about the waist, and, since the feet did not come off the rung, the thighs became horizontal. This forced the knees into the ladder, again causing the upper torso to pull away from the ladder and preventing the device from locking onto the rail. The device continued to slide down the rail between the ATD's knees.

As the ATD proceeded to fall back about the folded legs the thighs became more inclined and the knees came away from the ladder, with device continuing to slide between the legs.

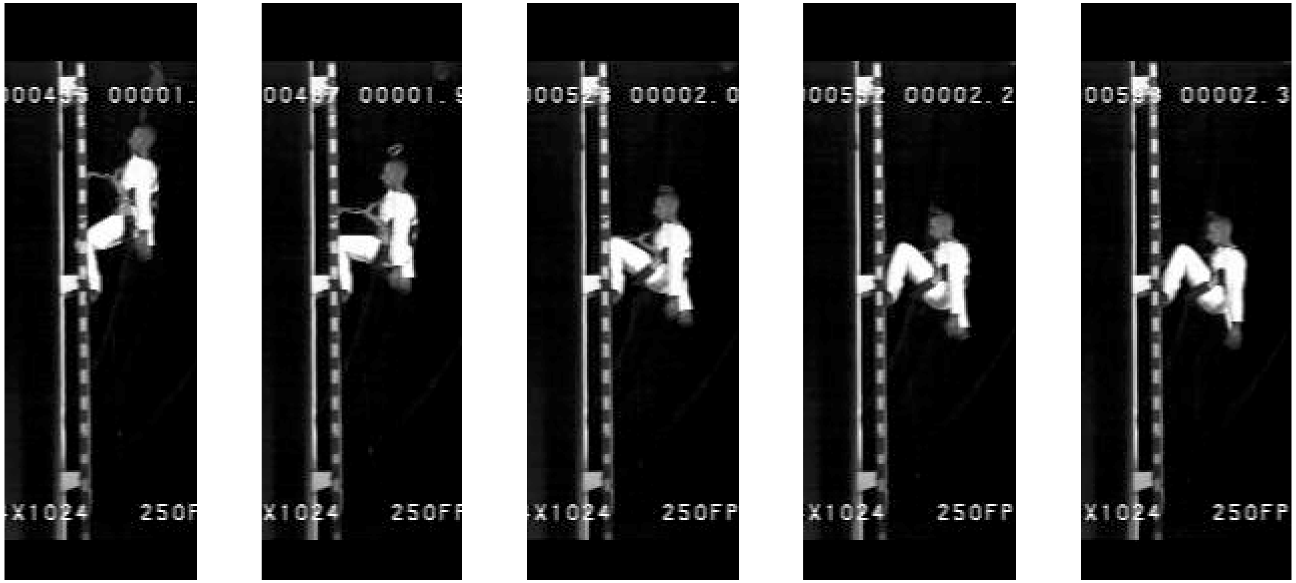

Figure 86 Kinematic sequence of ATD fall trajectory from test 14 (FAS 3)

Eventually, the motion of the ATD was arrested by the almost fully folded legs acting as compression springs between the ladder and the ATD's chest. This wedging, outward pushing action of the legs prevented the device from locking onto the rail.

The post-drop test suspension position can be seen in Figure 87.

Figure 87 Side and plan view of post-drop test suspension position

5.6.9 Drop-Test No. 15

FAS 4 was used in this test. The sliding arrest device had a short, integral energy-absorbing lanyard, pivoting link and connector of 0.27m overall length for connecting to the harness. The position of the ATD just before release and after the fall is shown in Figure 88.

Figure 88 ATD just before release (left hand view) and in post-drop suspension (right hand view)

Upon release, the ATD fell a distance of 0.73 m before being brought to a complete stop. The sliding arrest device skidded 0.035 m down the rail before finally locking onto it. The energy-absorber did not operate.

The following deceleration maxima were registered: 2.12g headwards in the z axis, 1.12g sidewards to the right in the y axis, and 2.1g backwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 89. Initially, the ATD fell away from the ladder, pivoting about the feet, which remained on the rungs, causing the folding of the body about the waist, characteristic in so many of the previous tests. The sliding arrest device locked onto the rail quite quickly, and despite the progressing folding motion of the body about the waist, and the outward motion of the whole ATD, evidenced by the harness being pulled away from the body, the arrest device appeared to remain in it's locked position.

The continuing outward motion of the ATD eventually pulled the feet off the rungs; the ATD was then pulled down and in towards the rail as part of the final arrest sequence. The lower part of the body struck the rail with an impact deceleration of 2.1g in the x axis. The ATD's head hit the energy-absorbing element of the harness connection, which did not extend during the arrest sequence.

Figure 89 Kinematic sequence of ATD fall trajectory from test 15 (FAS 4)

5.6.10 Drop-Test No. 16

FAS 4 was used in this test. The sliding arrest device had a short, integral energy-absorbing lanyard, pivoting link and connector of 0.27m overall length for connecting to the harness. The position of the ATD just before release and after the fall is shown in Figure 90.

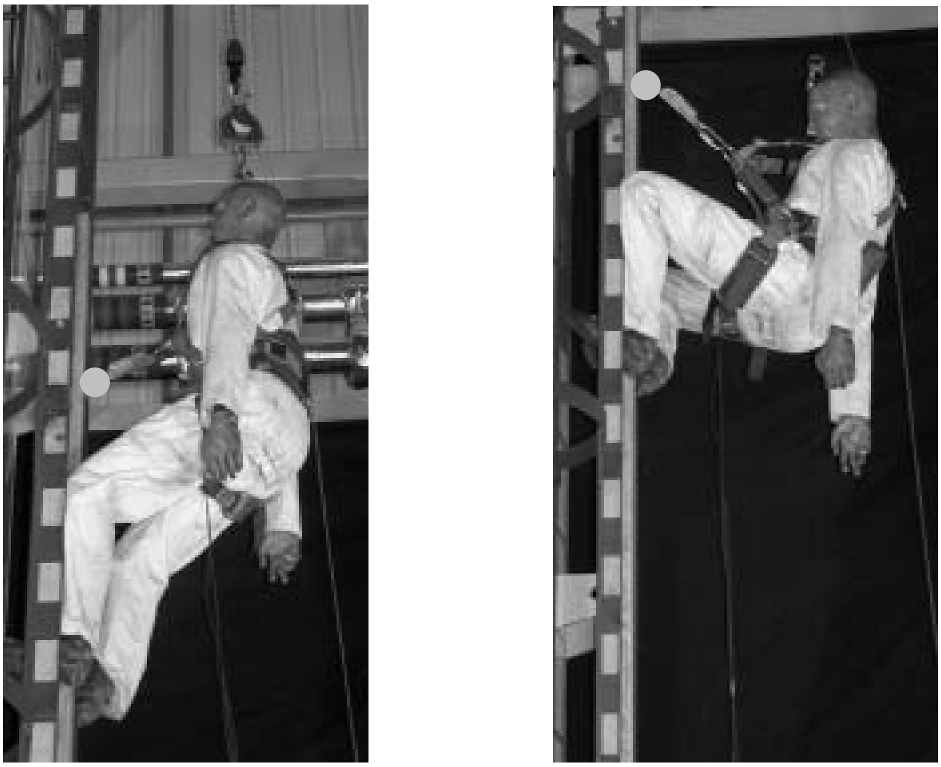

Figure 90 ATD just before release (left hand view) and in post-drop suspension (right hand view)

Upon release, the head of the ATD fell through a distance of 0.6 m before being brought to a complete stop. The sliding arrest device skidded 0.03 m down the rail before locking onto the rail. The energy-absorber did not operate.

The following deceleration maxima were registered: 2.67g headwards in the z axis, 1.68g sidewards to the right in the y axis, and 2.86g backwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 91. Initially, the ATD fell away from the ladder, pivoting about the feet, which remained on the rungs, causing the folding of the body about the waist, characteristic in so many of the previous tests. The sliding arrest device locked onto the rail quite quickly, and despite the progressing folding motion of the body about the waist, and the outward motion of the whole ATD, evidenced by the harness being pulled away from the body, the arrest device appeared to remain in it's locked position.

The feet remained on the same rung as at the release point, with the thighs becoming horizontal. This forced the knees into the ladder, similar to the motion as described in test No. 14. However in this case the arrest device had locked, and remained in place above the legs. The ATD was eventually arrested in a sitting position, with the knees against the ladder.

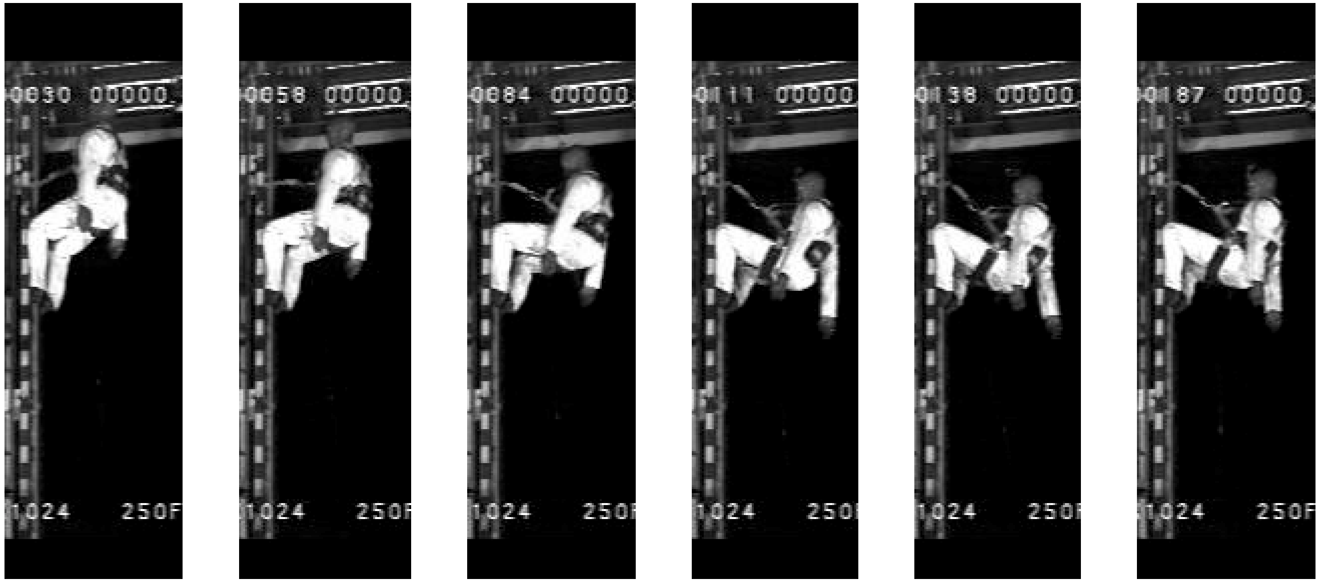

Figure 91 Kinematic sequence of ATD fall trajectory from test 16 (FAS 4)

5.6.11 Drop-Test No. 17

FAS 5 was used in this test. The sliding arrest device had an short, integral shackle-connector of 0.15m overall length for connecting to the harness, and had a secondary arresting mechanism in addition to the normal means. The position of the ATD before release and after the fall is shown in Figure 92.

Figure 92 ATD just before release (left hand view) and in post-drop suspension (right hand view)

Upon release, the ATD fell a distance of 0.48 m before being brought to a complete stop. The sliding arrest device skidded 0.022 m down the rail before locking onto it.

The following deceleration maxima were registered: 2.67g headwards in the z axis, 1.3g sidewards to the left in the y axis, and 1.62g backwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 93. Initially, the ATD fell away from the ladder, pivoting about the feet, which remained on the rungs, causing folding of the body about the waist, characteristic in so many of the previous tests. The sliding arrest device locked onto the rail quite quickly, and despite the tension in the harness connection caused by the outward motion of the ATD, evidenced by the harness being pulled away from the body, the arrest device remained in it's locked position.

The continuing outward motion of the ATD eventually pulled the feet off the rungs; the ATD was then pulled down and in towards the rail as part of the final arrest sequence. The lower part of the body struck the rail with an impact deceleration of 1.62g backwards in the x axis.

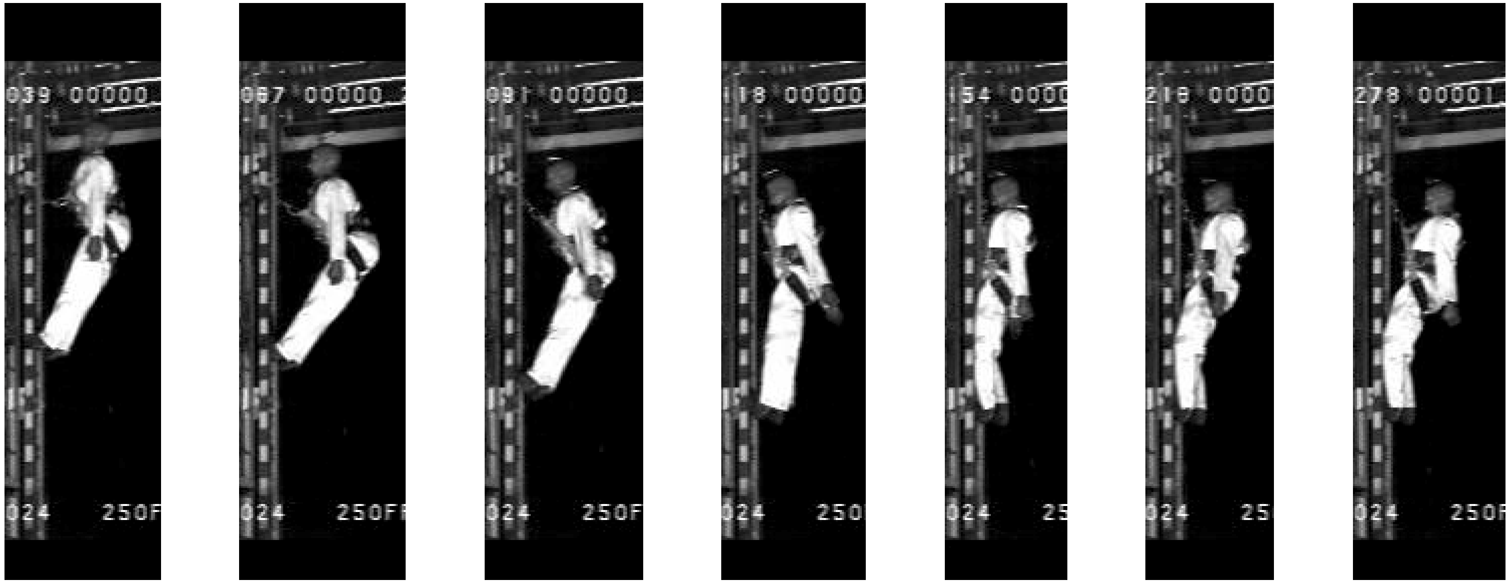

Figure 93 Kinematic sequence of ATD fall trajectory from test 17 (FAS 5)

5.6.12 Drop-Test No. 18

FAS 5 was used in this test. The sliding arrest device had an short, integral shackle-connector of 0.15m overall length for connecting to the harness, and had a secondary arresting mechanism in addition to the normal means. The position of the ATD before release and after the fall is shown in Figure 94.

Figure 94 ATD just before release (left hand view) and in post-drop suspension (right hand view)

Upon release, the head of the ATD fell through a distance of 0.65 m before being brought to a complete stop. The sliding arrest device skidded 0.255 m down the rail before locking onto the rail.

The following deceleration maxima were registered: 3.1g headwards in the z axis, 0.69g sidewards to the right in the y axis, and 1.68g backwards in the x axis.

The kinematic sequence of the fall trajectory is shown in Figure 95. Initially, the ATD fell away from the ladder, pivoting about the feet, which remained on the rungs, causing the folding of the body about the waist, characteristic in many of the previous tests. The sliding arrest device continued to slide down the rail, and despite the outward motion of the ATD, pulling against the device, it locked onto the rail within 255mm of the release point. This was due to the secondary arresting mechanism operating where the normal arrest mechanism could not.

The feet remained on the same rung as at the release point, with the thighs becoming horizontal. This forced the knees into the ladder, similar to the motion as described in test No. 14. However in this case the arrest device had locked, and remained in place above the legs. The ATD was eventually arrested in a sitting position, with the knees against the ladder.

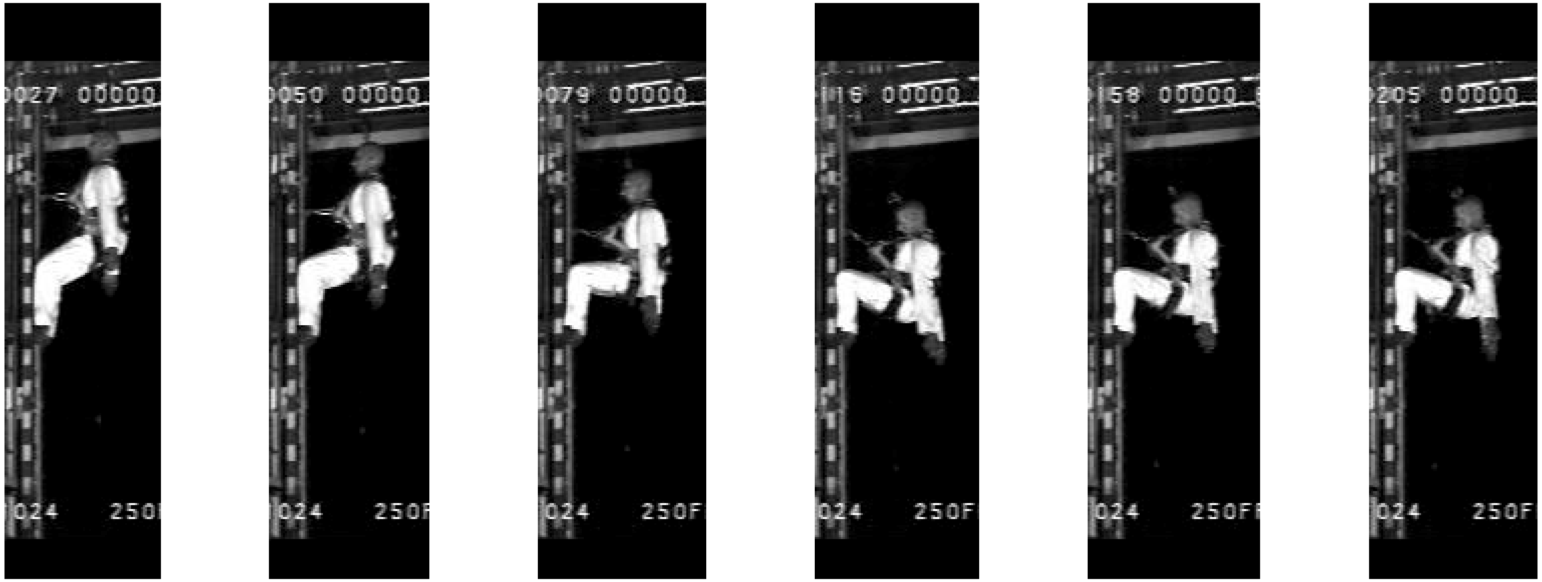

Figure 95 Kinematic sequence of ATD fall trajectory from test 18 (FAS 5)

6. DISCUSSION AND CONCLUSIONS

6.1 LITERATURE REVIEW

6.1.1 General

Almost 100 references covering the years 1952 – 2004 were studied to address the purpose of this research and are detailed in Section 9.

It is accepted that there may be other literature or information which the author is presently unaware of, the contents of which could affect this review.

The literature search produced a very small yield of relevant titles, even when extending the time envelope back over a number of decades. The main documents that were found to be of interest were items of legislation, official guidance and voluntary standards. Unfortunately, research papers and trade / miscellaneous publications were in the minority.

The earliest date that was established for the use of caged or hooped ladders from this research was 1956, although it could have been as early as 1935, see page 26 of this report. Caged ladders are specified in both legislative and guidance documents throughout the world for the purposes of providing some form of protection when gaining access between levels. In most cases it is unclear from the document concerned whether or not cages are meant to prevent falls or protect against falls in any way. A number are written in an ambiguous or confusing way so that the whole matter of protection is vague. Most offer ladder-mounted FAS as an alternative to caged ladders, and are able to state that such FAS can positively arrest a fall from a height, based on results of tests, but are unable to make the same statement about caged ladders.

This is typified by the OSHA statement in clause 2.6.3 of this report which says: "questions have arisen regarding the effectiveness of cages in protecting employees and OSHA by this notice solicits comments, supported by information and data, regarding the extent to which reliance on cages either protects or endangers employees". It would seem that OSHA themselves do not know what ladder cages actually do in the event of a fall.

As part of the exercise, three comprehensive research projects were reviewed which dealt with ergonomic, biomechanical and anthropometrical criteria when working at height. Two of these were to be utilised in writing American legislation. A number of topics cited were of interest from a falls from a height perspective and were reviewed in the main body of this report. Examples include (i) guardrail dimensions and the study of bodies falling through the rails, (ii) the point of impact on the body in falls according to free fall height, and (iii) ladder inclination effects on torso-to-ladder distance. In one case a great deal of effort had been expended in the anthropometric detailing of fixed ladder dimensions, but it was quite amazing to find that there was no overt mention at all to cages and their dimensions. It may be that cages were assessed in another research investigation, but given the comprehensive content and coverage of the research studied and the total lack of mention of cages in the bibliographies in those reports, it seems difficult to accept that any assessments on cages were ever made.

6.1.2 Key points

A number of key points in regard to caged ladders, (and ladder-based FAS, where relevant to this research), were identified in the literature review and are grouped under respective headings below with page number for reference. Statements within quotation marks are direct quotations from the document under consideration.

Definitions of cage and FAS - pages 12, 20-22, 27 and 29

- The definitions of the two protection methods give some clues as to their purpose. In American legislation, a ladder cage is defined as "an enclosure that is fastened to the side rails of the fixed ladder or to the structure to encircle the climbing space of the ladder for the safety of the person who must climb the ladder". A ladder-mounted FAS is defined as: "any device, other than a cage, designed to eliminate or reduce the possibility of accidental falls". There appears to be a discrimination in the levels of safety afforded by the two methods, the cage appears only to be able to contribute to "safety of the person", whatever that is, whereas the FAS is designed to eliminate or reduce the possibility of accidental falls, which is very clear. The conclusion from these definitions is that cages do not eliminate or reduce the possibility of accidental falls.

- In later American legislation a ladder-mounted FAS is defined in terms of positively stopping a fall, whereas cages are defined in terms of a barrier enclosing a space. It is clear from this that a cage does not have a known capability to positively stop falls.

- In a British Standard a safety hoop is described as: "a bar fixed to both stringers to enclose the path of persons climbing the ladder, to prevent them falling outwards". The question this statement raises is what will happen if a person falls downwards?

- In an American Standard a cage is defined as: "a barrier, that is an enclosure mounted on the side rails of the fixed ladder or fastened to the structure to enclose the climbing space of the ladder in order to safeguard the employee climbing the ladder". A ladder safety system is defined as: "an assembly of components whose function is to arrest the fall of a user……". Again, there is a clear distinction between the levels of safety attributable to hoops and FAS. The phrase "safeguard the employee" is vague, whereas "arrest the fall of a user" is very definite and clear.

- More updated definitions were found in a draft European/ISO standard. An "anti-fall device" is defined as: "a technical measure to prevent or reduce the risk of people falling from fixed ladders – commonly used anti-fall devices are safety cages and guided type fall arresters on a rigid anchorage line" (FAS). A safety cage is defined as: "an assembly comprising of framework which serves to limit the risk of people falling from the ladder". A guided type fall arrester on a rigid anchorage line (FAS) is defined as: "protective equipment fixed to a ladder used in combination with personal protective equipment that everyone has available before being allowed to use the ladder".

  These definitions appear to be quite confusing. The anti-fall device definition says that both cages and arresters are anti-fall measures. The cage definition then expresses that the cage limits the risk of a fall, but the fall arrester is just described using the ambiguous term of "protective equipment". These definitions are not consistent, and discriminate to some extent against fall arresters, i.e. that fall arresters are personal equipment, which "everyone needs before being allowed to climb".

Flight height and staggered runs - pages 9, 10, 14, 18, 24, 25, 27, 32 and 38

- A UK Approved Code of Practice (ACoP) advises that fixed ladder runs of more than 6.0 m should normally have a landing or other adequate resting place at every 6.0 m point, and, "each run should, where possible, be out of line with last run, to reduce the distance a person might fall". This is very surprising, since the statement is indicating that such a strategy effectively reduces the distance a person may fall to 6.0 m onto the next landing platform. A free fall of 6.0 m results in an impact velocity of around 24 m.p.h (10.85 m/s). This would probably cause severe or fatal injury from such an impact. This is in direct contradiction to the legislative part of the Code which requires that: "so far as is reasonably practical, suitable and effective measures shall be taken to prevent ...any person falling a distance likely to cause personal injury"[59].

- In UK construction regulations the maximum flight height is even greater at 9.0 m. Footnote 59 below also applies.

- In American legislation cages are required on ladders of more than 20 feet (6.1 m) to a maximum unbroken length of 30 feet (9.15 m). It is very interesting to note that the 6.1 m figure correlates to the maximum unbroken run of ladder under the UK ACoP and that the 9.15 m correlates to the maximum unbroken run of ladder under the UK's construction regulations (1996). It would seem that the U.S. legislation has specified the two figures as a dimensional tolerance, whilst the UK has applied the two limits to two different types of legislation.

  The same American legislation requires offset landing platforms to be provided at 9.15 m intervals for ladders protected by cages or FAS, and at 6.1 m intervals for unprotected ladders. It seems that the frequency of the platform location is reduced for unprotected ladder runs, on the basis that a fall of 6.1 m onto a platform is acceptable.

- In an American fixed ladder standard, caged ladders are to be made up from multiple sections, each section horizontally offset from adjacent sections, with a maximum climbing length of 50 ft (15.2 m) between landing platforms.

- A draft European standard requires a flight height of 10 m maximum, "but preferably no more than 6 m".

- A U.K. engineering handbook makes an overt mention of the fact that intermediate landings act as catch platforms to stop the fall of a worker, in case safety hoops don't. It says: "ladders should not rise more than 6 m without the provision of an intermediate landing; this should preferably break the line of the ladder…….. and will prevent a fall to a lower level……although this need not apply to access ladders on chimneys and similar high structures", and: "safety hoops should be provided where there is a risk of the user falling from a height of 2.0 m or more…".

  What is of concern is that the advice effectively allows a worker to fall down a hooped ladder for a potential 6 m. But the same statement seems to be saying that hoops can offer some form of protection against falls from a height, i.e. "they should be provided where there is a risk of the user falling from a height of 2.0 m or more". These statements seem to be in conflict with each other, and, to the reader, the situation is quite confusing.

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[59] It should be noted that this document is scheduled for replacement with the forthcoming Working at Height Regulations, Health and Safety Commission (2003).

Further statements in the handbook endorse the catch platform purpose: “the line of a ladder should be broken at landings in order to limit the free fall distance of any one who may be using the ladder.” This distance may be an incredible 9 m: “for ladders used for occasional access the maximum distance between platforms is increased from that given in BS 5395 of 6 m to 9 m”.

Comparison of protection between caged ladders and FAS - pages 9, 18-20, 25, 27, 30-32, 39 and 40

- The UK ACoP advises that fixed ladders over 2.5 m high should be fitted with safety hoops or a permanently fixed FAS. This seems to suggest that fall protection is provided by either of these two methods on ladders in excess of this height, and seems to put both methods on a par with each other.

- In American legislation, the offset ladder platform interval subject is further complicated when the use of FAS are considered. The Code states: “Ladder safety devices may be used on tower, water tank and chimney ladders over 20 feet in unbroken length in lieu of cage protection. No landing platform is required in these cases”. The question is then raised as to why no landing platforms are needed when FAS are employed. It seems logical to deduce that landing platforms are connected with method of fall protection.

  The conclusion drawn from the offset landing information (see also page 141 of this report) is that the American Code appears to be using offset landing platforms as a means to catch falls. A 6.1 m fall down an unprotected ladder appears to be survivable, whereas a 9.15 m fall is not. Also a 9.15 m fall may be slowed down by a caged ladder, but needs a landing platform to stop it completely. The FAS requires no landing platforms because it will stop the fall of a worker relatively quickly.

- Information from the American fall protection market confirms this deduction. The perception being that caged ladders cannot stop a fall of a worker with any measure of confidence so, more and more, ladder mounted FAS are being installed on ladders which had cages fitted as part of the original installation. So both cage and FAS are being fitted to ladders.

- In American construction legislation, requirements concerning protection on fixed ladders appear to discriminate between the levels of protection as follows:

  - Ladder-mounted FAS are capable of reliably arresting a fall and hence need no additional protective measures

  - Retractable arresters are capable of reliably arresting a fall, but a rest platform should be installed every 45.7 m. This either reflects the tiring effects of climbing whilst connected with the lifeline attached to the body, or may reflect the maximum length of retractable arresters produced, which is 50 m.

  - Caged ladder flights cannot be relied on to arrest a fall, therefore they need to be offset and need catching platforms at maximum intervals of 15 m.

- In an OSHA proposal for altering American legislation, it was recognised that earlier legislation required the use of caged ladders but did not allow employers sufficient flexibility to use other available methods, (personal protective equipment). OSHA state that the equipment covered by the proposal can provide employees who are climbing with protection equivalent to or superior to that provided by cages. This seems to indicate that ladder cages do not give the same level of fall protection compared to the proposed fall protection systems.

- An American fixed ladder standard sets different requirements for cages and FAS in terms of platform intervals. For caged ladders, they need to be offset every 15.2 m with platforms, but where FAS are used, the ladder may be continuous, without offsets, but rest platforms are needed at maximum intervals of 45.7 m. Also a FAS may be used in combination with a cage.

  The same standard uses the phrase "landing platform" when describing caged ladders, and "rest platform" when describing ladders with FAS. Why are there two different terms for each method? Neither of the terms are defined in the standard, which is unusual, since there are a large number of definitions, but the use of two different terms suggests two different functions. Also, in the case of a caged ladder, the "landing platforms" are offset, i.e. the climb is interrupted by the platform, so the worker has to negotiate the platform before proceeding with the next part of the climb. With the FAS, the "rest platforms" are not offset; the worker has the option to "rest" on them if required.

  The conclusion drawn from the above is that the "landing platforms" were originally conceived not so much to provide rest areas, but to provide "catch areas" which would probably stop someone falling down a caged ladder. This deduction is supported by the statement: "A ladder safety system (FAS) may be used in combination with a cage". It is difficult to understand why a FAS would want be fitted to a caged ladder, if the caged ladder could arrest a fall.

  It would seem that there is uncertainty in regard to the fall-arresting effectiveness of caged ladders, and that the fitting of FAS in conjunction with a cage gives a greater assurance. However the question remains as to whether both systems are compatible with each other in terms of arresting a fall.

- In a draft European standard the confusion in the choice of protection method continues. First of all cages are prioritised: "Priority shall be given to the choice of the cage, as it is a collective means which is always present and the actual level of safety does not depend on the activity of the operator". Then the confusion: "an appropriate individual anti-fall protection device is able to arrest a fall better than a cage".

  Collective measures in general are the preferred means of protection, but only where the effectiveness of those measures can acceptably lower the risk involved. Also the phrase: "the actual level of safety does not depend on the activity of the operator" is difficult to comprehend. First of all, what is the actual level of safety afforded by cages? Secondly, body attitude at the onset of a fall in a caged ladder may affect whether a limb or other part of the body catches or jams against a hoop during the fall, or whether the fall continues down to the platform below. This is actually shown to be the case from the results of the test programme, refer clause 5.4.

The advice about collective measures being the preferred means of protection is thrown into confusion by the statement about FAS being able to arrest a fall better than a cage. The greatest risk when climbing a ladder is that of falling-off the ladder, so FAS should be the preferred choice.

- In a draft British Standard covering fixed ladders, there is clear discrimination against the use of FAS in regard to choosing either a cage or FAS for fall protection, e.g: “a passive protection system, for example, safety cage, shall be the preferred choice. Where it is not possible to use a cage, individual protective equipment shall be provided. A fall arrester shall be provided only where low frequency and specialised access (e.g. maintenance) is required”. The standard does not state why cages should be preferred, nor does it state to what degree of protection is given by them.

- An American safety directory describes the pros and cons of caged ladders. These are:

  - Cages are a one-time installation with low maintenance requirements

  - Little or no training procedure for safe climbing is required

  - Caging gives low personal protection. At most it gives psychological protection and serves as grab bars for a falling worker.

  In contrast: “Climbing safety devices (FAS) offer a personal safety system which positively limits a worker’s fall”.

- In an American Society of Safety Engineers publication reference is made to proposed changes to U.S. legislation. There is a clear trend away from relying on hoops for fall protection. Cages are seen by safety professionals as failing to provide positive fall protection, at best providing psychological comfort and resting points, and that FAS should be used in addition to cages for effective personal fall protection.

- The difficulty in climbing up caged ladders with equipment can present a problem. In a query, a U.S. Sports Association put questions to OSHA in regard to caged ladders on ski lift towers. Difficulties had arisen when skis became entangled in cage structures, which was seen as a hazard, particularly in bad weather with accumulation of ice on the cage. Although FAS are proposed for use instead of cages, it would be important to show that they could perform the arresting function in icing conditions.

Cage requirements - pages 21, 23-25, 38 and 40

- In later American legislation, cages do have a requirement other than dimensional in that they: “shall be of rigid construction that allows unobstructed use but prevents an employee from falling through or dislodging the cage by falling against it”. This recognises the risk of falling through the cage, but not the risk of falling down it.

- Canadian legislation makes an explicit mention of the fact that cages are expected to arrest the fall of a worker from a fixed ladder: “a fixed ladder … shall be fitted with a cage … in such a manner that it will catch an employee who loses his grip and falls backwards or sideways off the ladder”.

Perhaps Canadian legislators want to remove any doubt about caged ladders, because in addition to the "catching" of the worker, there is specific mention that the cage should perform this protective role irrespective of the direction of the falling-off motion, whether in a backwards or sideways direction. No fall-arrest test method is stipulated or referred to for the cage, but such methods are referred to for FAS, which are mentioned later on in these particular regulations.

A further requirement in the Canadian legislation for caged ladders is that fixed ladders and cages shall be designed and constructed to withstand all loads that may be imposed on them.

- In a British Standard, the cage uprights are described as "bracing" for the hoops. The question: "were the uprights introduced at a later stage in safety hoop development for bracing, or were they intended as part of the original protective arrangements?" was pondered, especially in the light of discovering hoops without uprights in the survey part of the research.

  There are also instructions about abuse: "care should be taken to ensure that neither ladders, safety hoops or straps are used to support additional loads such as lifting appliances, scaffolding, etc, for which they are not designed." And: "the provision of safety hoops may be a temptation to experienced operatives to mount the ladder by means of the hoops instead of the rungs. This should be prohibited".

- In a British Standard code of practice the idea of giving hoops extra protection is mentioned: "In particularly hazardous and exposed situations, mesh panels may be used to cover the ladder cage".

- An American safety engineering handbook makes a ergonomic point: "If a cage is fitted, then it must permit easy movement on the ladder but restrict how far away from the ladder the body can move". This seems to confirm that the cage dimensions are crucial, anthropometrically.

- There would appear to be evidence to suggest that cages were not provided as a back-supporting means, and that cages cannot stop the fall of a person when in certain postures. A query was put to OSHA about working off fixed ladders as opposed to using them for climbing, by leaning back against the cage with the feet still on the ladder rungs, but with the hands off the stiles. OSHA states that: "a cage is usually designed to provide fall protection while moving up or down the ladder – not while working with both hands off the ladder". Also: "a cage is not designed to provide fall protection for a worker using the cage for support, or working with both hands off the ladder". In other words, cages cannot provide fall protection when the body is in certain postures. This seems a strange reply – but perhaps it indicates that if both feet were to slip off the rung, then the worker would probably fall down the cage.

  However, OSHA goes on to apply the same criteria to FAS: "most ladder-mounted FAS are not designed to support a worker leaning out from the ladder; they are usually designed to protect a worker while fully on the ladder".

  OSHA then make it clear that such use of cages or FAS would violate American law: "using ladder safety systems (FAS) or cages for support would violate Code of Federal Regulations 29 Part 1926.1053 (1996)".

Cage dimensions - pages 12, 14-16, 33 and 38

- American legislation sets quite specific dimensions on the sizes of cages on ladders, and the setting of these dimensions appear to reflect some kind of anthropometric basis.

  Of particular note, the said legislation sets a dimension from the ladder rungs to a worker's back to create a clearance, in order to allow the climb without obstruction. The respective cage dimension (rung to back of cage) is between 52 and 76 mm less. This means that the climber will have to "squeeze into" a smaller dimension when climbing a caged ladder, i.e. they will have to climb in a more erect position as shown in Figure 12. The reduced dimension may have been (i) aimed at providing security in a psychological sense (i.e. been able to sense the immediate proximity of the back of the cage), or (ii) it may have been aimed at providing a resting position (i.e. the worker would be able to lean back against the back of the cage and rest the arms, in particular), or (iii) it may have been aimed at an attempt to cause the worker's body to lock or jam in the confined space of the cage if they slipped off the ladder. However this all depends of the worker's size and arm length, etc.

- A summary of hoop dimensions (rung to back of hoop and hoop width) is presented in Table 2. This draws on all documents reviewed that disclosed sizes. These were from American, British and European mainland sources. Each of the dimensions has a tolerance, expressed as a minimum and maximum value. Whilst there are differences in tolerances between the same dimensions according to the document concerned, there is considerable similarity between the nominal dimensions themselves. In general the American dimension are smaller than the UK or mainland European counterparts. In two British documents, the tolerance is geared to ladder incline angle. Larger hoop dimensions are allowed for the arching of the back when climbing an inclined ladder.

- Apart from the comments above and those under "trap-door sizes" following, this part of the research did not satisfactorily identify the basis for the setting of cage dimensions.

Trap-door sizes - pages 23, 31 and 32

- In a British Standard, safety hoops are specified either conforming to a circular pattern or a rectangular pattern. No explanation is given as to why there are two different patterns. One theory is that hoop dimensions were based on trap-door sizes, where a ladder would have pass through a platform and form a hatch. Since hatchways may either be circular or rectangular then the same would follow with hoops.

- Trap-doors in platforms are described in a draft European standard for fixed ladders. The point of interest is in the statement: "the dimensions of the opening shall be at least equal to the dimensions (diameter) of a safety cage". The reason for the interest is that the research had not shone any light on why safety hoop dimensions are set as they are.

  Prompted by the above trap-door statement, one theory that can be put forward is that hoop dimensions could have been created from trap-door dimensions.

Holes in platforms are dangerous because of the risk of workers falling through them, so they tend to made as small as possible, whilst allowing a man to pass through. Consequently, anthropometrical data has to be consulted. In a U.S. military standard the 95^{th} percentile diameter to allow a “heavily clothed person” access through a circular aperture in a horizontal surface is 760 mm.

When studying safety hoop sizes from various documents, it can be seen that the 760 mm dimension is virtually identical to the majority of hoop dimensions quoted. So the trap-door dimension could have automatically led to the setting of the hoop dimensions by certain groups.

Number of vertical uprights versus falling out of cage - pages 15, 21, 23, 31 and 38

- It seems that one possible feature that cages possess is the ability to stop someone from falling outwards from the ladder, i.e. if the cage wasn’t there, then a worker who fell would fall outwards into free space. However, for that to work, the worker’s body would have be prevented from passing through any of the apertures formed by the intersections of hoops and uprights.

- In American legislation, 7 uprights are specified at approximately 9.5 inch (241.3 mm) intervals around the cage, and hoops are specified every 4 feet (1.2 m). This gives an aperture area of about $0.29m^2$. This virtually eliminates the possibility of a person falling through the apertures and hence out of the cage, but it may increase the possibility of a worker being “funnelled” down a cage in a fall situation without being stopped.

- In British Standards, 3 uprights are specified, one at the centre back position and the two others evenly spaced between that hoop and the stiles. Hoop spacing is 0.91 m. This gives an aperture area of about $0.54m^2$.

- In a draft European standard a maximum vertical distance between hoops of 1.5 m is specified, with a maximum distance between uprights of 300 mm. This in effect creates 5 bars as opposed to the UK’s 3 and the U.S.A.’s 7. Also the spacing of safety cages has to be designed so that the apertures are not more than $0.4\ m^2$.

  It would appear that Europe has accident data to show that workers have been falling through these gaps, or else the perception of that risk has changed and hence the reduction in allowable aperture area to $0.4\ m^2$.

- In a British engineering handbook there are indications that at one time in the U.K. some caged ladder installations did in fact only have 2 uprights, which would have greatly increased the possibility of someone falling through the cage to the ground or other substantial platform. The use of a third upright is “strongly advised and preferred for the majority of applications”. During the survey part of the project a crane (Figure 21) was seen with a caged access ladder that appeared to have only two uprights. It is extremely unlikely that this arrangement would stop the fall of a worker down or through the hoops.

Hoop joining guard rail at top of ladder - pages 9, 14 and 23

- There are requirements in various documents that where access from the top of a hooped ladder leads to a platform, then the top hoop should be in line and joined to the platform's uppermost guard rail. The same requirement exists in the case with a short ladder of 2.5 m or less - a single hoop is required, which again is to be in line and joined to the platform's uppermost guard rail. It would seem that there is an expectation that a single hoop can provide some form of guard at the top of the ladder, where the climbing motion changes direction from the vertical to the horizontal, when a worker may be particularly prone to falling backwards or sideways. In effect, the guard railing on the platform integrates with the "guard railing" on the ladder.

Inclined ladders - pages 12 and 37

- There appears to be a perception that, for inclined ladders, the risk of falling significant distances is less. A U.S. book on safety engineering refers to the features of fixed, vertical ladders. It refers to the greater likelihood of falling off a vertical ladder rather than onto it, as with an inclined ladder, justifying the need for fall protection when using vertical ladders.

Guard rails at bottom of ladder - pages 17 and 31

- In American legislation, where a caged ladder exits in close proximity to a guardrail bordering an elevated platform, the cage is joined into the guard rail in order to form a caged structure. This ensures that if a worker falls or stumbles backwards when exiting the ladder, (where the cage ends), any momentum will not cause them to fall over the guardrail since any unguarded space between the guardrail and ladder cage is blocked.

- In a European draft standard, the exit point risk at the bottom of a ladder is described as: "a risk of falling is considered to exist when the platform at the base of a ladder is unprotected and the edge of which is less than 3m away from the ladder". In addition, the principle behind the American legislation is confirmed, because the standard requires that where guardrails are located within 1.5 m of the bottom of a caged ladder, the cage of the ladder has to be extended down to join the guardrail.

Ladder-mounted FAS requirements - pages 19, 20 and 28

- In American construction legislation and in an American fixed ladder standard, ladder-mounted FAS have ergonomic, fall-arresting performance and strength requirements, whereas caged ladders do not. Key points include:

    - The sliding arrest device has to lock and hold onto the rail or cable within 6 inches (150 mm) after the fall occurs

    - The sliding arrest device connection between device and harness is not to exceed 23 cm in length

    - For cable-based FAS, where the cable is exposed to wind, to have cable guides at a minimum spacing of 7.6 m and maximum spacing of 12.2 m along the entire length of the cable, to prevent wind damage

- The rail or cable is to have mountings or cable guides designed and installed so as not to reduce the design strength of the ladder

- Impact loads resulting from the use of FAS have to be taken into account in the ladder design.

There are no fall-arrest requirements for caged ladders.

- It is interesting to note that the American fixed ladder standard was the first document to be reviewed which mentions the need for rescue operations in the context of FAS requirements. (There is no mention of the need for rescue after a fall in a cage).

6.2 SURVEY

6.2.1 General

The literature search and review was supplemented by a small scale survey of 12 fixed ladder manufacturers and users, who were contacted to see if they could answer questions that had not been satisfactorily answered from the results of the literature search. The questions asked were:

- What are ladder safety hoops?

- What do they do?

- What is their historical background and development?

- What is their fall-arrest capability?

- Has any research been conducted?

- What documents, currently available, contain any information on ladder safety hoops?

- Are ladder safety hoops fitted in preference to a ladder-mounted FAS as the preferred protection method or vice versa? Why?

The results of this exercise was disappointing in terms of what was known. Consequently, other sources of information were considered. This included some on-site studies of caged ladders themselves to see what could be learnt, and also various approaches to standard-writing committees were made.

6.2.2 Key points

The ladder manufacturers and steel fabricators contacted knew little about caged ladders. Most were simply producing them to BS 4211 (1994), and could readily quote dimensions and materials, but very little information could be elicited apart from that.

When asked about whether there was a preference for hoops or for FAS, most said that they would fit both systems. This included a manufacturer who specialised in glass-fibre ladders.

Some mentioned the cost of transporting sections of hoops to site, which made them too expensive compared to installing a FAS, especially over a long ladder run.

It was claimed that a German standard, DIN 18799 Part 3 (1999), which details "rűckenschutzkorb" (ladder safety hoops) for chimneys, contains important information. An English translation of DIN 18799 Part 3 (1999) was not obtainable during the timeframe of the project, but would be a key document to obtain in future research.

Generally, information received from the standards-writing committees was very limited and none of the survey questions were directly answered. In some cases claims were made but no test data or research references could be quoted to substantiate the claim. However, one source was of particular relevance in regard to relating accidents to cage design. French national organisations had carried out research, some key points of which were available. Project time restraints prevented further investigation into obtaining the full details of the research but this would be an important aspect to follow up on in any future work.

The key points in regard to the survey, as described in clause 6.2.1, are grouped under respective headings below with page number for reference.

Extent of protection – risk assessment – page 44

- One of the main problems arising from the users of caged ladders in this enquiry, and from other previous work on this topic, was that of uncertainty. Personnel who conduct risk assessments on work at height in the course of their duties cannot say with any degree of certainty whether safety hoops reduce the risk of falling or not. This is because there are no known test methods which subject the apparatus to a simulated fall as with FAS.

- There was also concern expressed that a falling worker may severely injure themselves on the hoops as a result of limb entanglement or localised impact. All this leads to some companies installing FAS within cages, which can make climbing up the ladder very difficult. There is also the important question whether the impacts against the cage during a fall would interfere with the locking action of the sliding fall arrest device.

Rescue – page 44

- There were comments about the potential difficulty arising if a rescue was required to recover a worker who had fallen whilst within a cage. The perceived entanglement of limbs would be a concern – how would the worker be lifted in order to disentangle the limbs from the apertures formed by the hoops and vertical bars, so that they then could be lowered.

Perception of risk – page 44

In a number of caged ladder installations studied on site, it was discovered how the design of the ladder had been tailor-made to counter the envisaged risk of falling.

- A company had identified a significant risk of a worker falling through the apertures of a 3-upright caged ladder, and had specified meshing to cover the apertures. Otherwise any fall through the apertures would have meant a fall into the river, with almost certain fatal consequences.

- In the design of a tower crane, a company had perceived that a caged ladder running up to the control cabin might prevent a fall outwards, but not downwards. Consequently the caged ladder used for the crane had been broken up into a large number of inclined sections, each of some 2.5 - 3.0 m length, so that a worker climbing up/down would adopt a zigzag motion between each flight, which had guardrails at the exit point. The thinking behind this approach appeared to be that if a worker fell down one of the cage sections, then it might be a relatively short stumble.

Work positioning – pages 46-51

- A number of fixed ladders giving access to signalling posts were observed on the UK rail network. Some had a single hoop arrangement at the top of the ladder which was smaller than the hoop size in the case of conventional hooped ladders.

  It appeared that these were (i) designed to prevent an erect worker from falling backwards, and (ii) with the feet still on the rungs, to allow a worker to lean back against the hoop, allowing both hands to be free for attending to the task in hand. This is a similar technique to that of using a pole strap with a safety harness.

- Other hooped ladders were discovered with hoops that were smaller than those on conventional hooped ladders. Climbing through these hoops was quite difficult as when compared to a conventional hooped ladder but, once through, they were ideal for leaning back in a work-positioning stance.

  This lead to the hypothesis that perhaps, originally, hoops were for work-positioning purposes, and they were developed with vertical braces so as to guard the path of a worker from falling outwards from the ladder.

Cage accidents, design and flight height – pages 52-54

- From the European standards viewpoint, emphasis was placed on the need for 5 uprights on a cage, and that cages without these are not acceptable.

- Apparently the dimensions of the hoops were the result of test methods, but when asked for the documentation which described these methods and the results, this could not be produced.

- As a result of accident statistics, a new French standard was produced and issued in 1974. This specified improved safety requirements that included a reduced maximum flight height of 9 m (from 12 m) and a safety cage design that included five uprights.

- Later analysis of French accident statistics led to the following conclusions, (it was recognised that a fall through the apertures of a 3-upright cage was possible, so a five upright specification had been established with a maximum aperture area of 0.4 m^2):

  - No fatal accidents were recorded where safety cages were provided with 5 uprights and the ladder flights were under 6 m in height.

  - There were only a small number of accidents on fixed ladders with flights between 6 and 9 m in height

  - Fatalities were recorded where fixed ladders had flight heights in excess of 9 m

- Fatalities were recorded where the free spaces between safety cage vertical bars were considered excessive, i.e. where safety cages were provided with 3 vertical bars.

The French response was to implement an immediate reduction in the flight height of all fixed ladders and requested immediate action to be taken in order to reduce flight heights of all existing fixed ladders to 6 m. This, "had the positive result of the reduction in the maximum height of a fall". This clearly indicates that flight height is linked directly to falling distance.

Fall protection – pages 52-54

- European standards understanding is that: "safety cages do not prevent downward falls, but they can stop falls with a backwards-motion of the user's body. Therefore this kind of protection is only permitted up to a falling height of 10 m; but with ISO 14122-4 this is reduced to 6m, if there are broken flights".

  No information was available as to how safety cages can stop a backwards fall; no test data could be offered.

  This again raises the question: is it safe to allow a person to fall down a cage either 6 or 10 m, as the case may be?

- British standards understanding is that the arrest of a backwards fall is assumed in a caged ladder, but if both feet come off a rung, resulting in a fall downwards, then there is no guarantee of arrest.

6.3 UK FALL ACCIDENTS IN HOOPED LADDERS

- Thirty-three fixed-ladder accidents were reviewed (Section 4), covering 1985-2003.

- In three cases, although the sources were not in doubt, the accounts were verbal with no documentary back-up. In all three cases the ladders concerned were hooped:

  - In one case a worker fell backwards and out through a cage aperture; his colleague, who had been following directly beneath, managed to get him back within the confines of the cage again.

  - In the second case a worker fell to his death.

  - In the third case a worker fell, but his arms and armpits caught a hoop, and although he was injured, this broke his fall.

- In a further two cases, which were documented in safety reports, a worker fell near to the bottom of a ladder, just where the cage terminates. Both outcomes were fatal.

- Twenty-eight accidents were identified by using the HSE Field Operations Directorate database. Although each of the ladders in 20 of the cases would have almost certainly been caged, the investigating officer had not made a definite mention of that, so these accidents were not reviewed in detail. Seven of the accidents did involve a caged ladder, and all of these involved a fall to the platform below or to the ground. This indicates that the cages concerned were not effective in arresting the fall.

Injuries of various severities were recorded. In some cases the fall distance was recorded, in other cases it wasn't or else was an estimation. In a further case a worker was killed in falling down a caged ladder, but it wasn't clear from the report if the worker fell from a caged or uncaged portion of the ladder.

Further investigation into obtaining the full details of these and other accidents would be an important aspect to follow up on in any future work.

6.4 DROP-TESTS

6.4.1 General

Seven drop-tests were conducted with a 3-upright caged ladder conforming to BS 4211 (1994) using a Sierra Stan ATD as the test surrogate. The horizontal proximity and the posture of the ATD in respect to the cage and test ladder was recorded prior to release in each case. Upon release, deceleration with respect to time was recorded in the three principal axis (x, y, z) via a tri-axial accelerometer mounted to the thoracic area of the ATD's spine, and the fall trajectory was recorded using high speed digital video at 250 pictures per second. This enabled fall distance to be established and post-test analysis of the ATD's motion. The results are presented in clause 5.4.

With the hoops and uprights of the cage removed, a further eleven drop-tests were conducted using five different kinds of FAS. Each FAS consisted of a rail which was centrally attached to the rungs of the ladder, a sliding arrest device and a full body harness. The purpose of these tests was to compare the fall-arresting effectiveness of FAS to ladder safety hoops using the same test method and instrumentation. To that end, the Sierra Stan ATD was used as the test surrogate. The horizontal proximity and posture of the ATD, and sliding arrest device position and ATD in respect to measuring vertical fall displacement in respect to the arrest rail was recorded prior to release in each case. Upon release, deceleration with respect to time was recorded in the three principal axis (x, y, z) via a tri-axial accelerometer mounted to the thoracic area of the ATD's spine, and the fall trajectory was recorded using high speed digital video at 250 pictures per second. This enabled post-test analysis of the ATD's motion. The results are presented in clause 5.6.

It must be stressed that experimental testing seeks to discover what may happen in the environment being created, and the results of such testing does not necessarily mean that the same will actually happen in practice. However the results do give an indication of what could happen.

6.4.2 Human impact tolerance considerations

In the key point clauses following, tentative comparisons of the decelerations recorded from the tests are made with impact tolerance information contained within Snyder (1973), in order to express the likelihood and severity of injury, as the case may be. Snyder (1973) consists of tables of peak deceleration, jolt and duration of impact, and the physiological effects on the human volunteers that took part in various impact experiments. These experiments refer to impact deceleration in the x, y, and z axes and, for the majority of cases, took place with the volunteer in a seated, restrained position. Some other information on free fall impacts onto surfaces is also tabulated, but this is limited. No absolute impact tolerance levels are specified or are expressed in Snyder (1973) in regard to the tables. As Snyder comments, various researchers have established different end points as criteria. Tolerance definitions range from: "a value of impact or load which produces a painful reaction", to "a limit beyond which either the subject or the experimenter fears to go lest there be serious injury".

Injury has been termed either "reversible" or "irreversible" depending on whether or not the individual can recover.

Human impact tolerance information has always been notoriously difficult to obtain or establish in regard to human fall arrest circumstances, because very little research has been carried out specific to this form of impact. Instead, researchers have had to rely on research carried out in other biodynamic fields such as the ejection seat, parachute or vehicle restraint industries, and the body of opinion which has grown from that. However, the application of this data and opinion to fall-arresting circumstances is fraught with difficulties.

A lot of data has been obtained from young healthy male volunteers under rigidly controlled test conditions and careful medical supervision, which have been voluntarily terminated at levels below irreversible injury. In addition, with simulated car crash and aircraft ejection research, the body is restrained in specific postures and is typically decelerated in one plane, both factors of which greatly influence impact tolerance. Eiband (1959) states that human tolerance to sudden deceleration depends upon: (i) the direction in which the deceleration is applied to the body, (ii) the magnitude of the decelerating force, (iii) how long the deceleration is applied, (iv) how rapidly the deceleration is applied (the jolt), and (v) how the occupant's body is supported during the deceleration.

Such research information cannot be readily transferred to industrial fall-arresting circumstances, which are quite different. However, parachute-opening-shock research was utilised in the setting of a maximum arrest force in current European fall-arrest standards, because the impact conditions are nearly the same. There were still difficulties however, because of certain differences and unknown quantities, so the 12 kN limit allowed in the parachuting discipline was halved to arrive at a figure of 6 kN, Crawford (2003).

One of the main concerns of applying aeromedical impact tolerance information to fall-arresting circumstances, is that the main aeromedical information repeatedly stresses that the impact tolerances are based on the fact that the occupant is seated and restrained with the spine in an optimally supported position. In Eiband (1959) for example, mention is made of situations in which the subject's pelvis was not held in place by the restraining system, with the result that all exposures above 18g became intolerable. Vulcan et al (1970) demonstrated that the load capacity of the spine in the z axis could be increased if forward bending movements of the spine were reduced, and so, conversely, where the spine is allowed to bend this will reduce the ability of the body to tolerate impacts in the z axis.

In the case of the fall motion described in the caged ladder test results, the body is not restrained in any way, except for the boundaries of the cage itself. As a result, as can be seen from the kinematic sequence diagrams (e.g. Figure 44), and from slow motion analysis of the high speed video motion, the spine of the ATD is free to bend in response to the impact environment.

It is also worth mentioning at this point that the human spine is made from a number of bones called the vertebrae, each of which has it's own contribution to make in respect of the material properties of the whole spine, Crawford (2003). In clause 4.2 of this report, which records caged ladder accidents from the HSE FOD database, in "event No. 01A073374", an estimated 6 m fall resulted in a cracked vertebra injury. Consequently a fall down a caged ladder can result in impacts sufficient to injure the spine.

As a result of the discussion above, the application of impact tolerance information throughout this report is made with a note of caution where necessary. This is an area which would benefit from further research.

With respect to the fall motion described in the FAS testing, in addition to Snyder (1973) there is some human impact information applicable to fall arrest circumstances, much of which came from the Royal Air Force Institute of Aviation Medicine, a review of which was made in Riches (2002).

For instance in Reader et al (1969), 13 human subjects in full body harnesses tolerated feet-first drop-tests without injury. The interconnection between the harness and the anchor point was via a steel cable, 3.05 m long, the cable being attached to the dorsal and sternal attachment points on the harness according to it's design. The maximum deceleration recorded in the z axis was 4.8 g.

Stevens (1968) and Longrigg (1969) refer to the Royal Aeronautical Establishment Public Open Days in June 1967, where "tear web" (a material used in current day energy-absorbing devices) was being demonstrated as a safety line using human subjects. The subjects, wearing a harness and connected by the tear web, were dropped over a distance of 2.75 m before being arrested. Two types of tear web were used, WR 1017 and WR 1018. Twenty-six demonstration drops were carried out with WR 1017 and twelve with WR 1018. WR 1017 applied an arrest force of between 2.6 – 3.6 kN and WR 1018 applied an arrest force of between 3.9 – 5.2 kN.

Hearon and Brinkley (1984) discusses French research, in which 30 human exposures were recorded in fall-arrest drop tests. A maximum of 7g was recorded in the z axis without injury.

In parachute opening shock research, which as mentioned previously is very akin to fall-arrest shock loading, three individuals tolerated feet-first drop decelerations up to 12g in the z axis over 7 tests when they were dropped in a parachute harness, connected at the shoulders, Beeton et al (1968). In similar circumstances, Ernsting (1967), 3 volunteers in 11 tests tolerated exposures in the z axis of a maximum of 10g. And again in similar circumstances, Reader (1967), 13 drop-tests with humans tolerated exposures in the z axis of a maximum of 9g.

In $+a_x$ impacts, 48 human exposures were tolerated up to a maximum of 16g. Although in a parachute harness, subjects were constrained in a seat, Beeton et al (1968).

6.4.3 Caged ladder testing - key points

- In three of the tests, the ATD fell to the test rig floor (test Nos 1, 4 and 7)
- In two of the tests the ATD's arms/armpits caught on a hoop and stopped the fall (test Nos 5 and 6)
- In one of the tests the ATD's buttocks were wedged against a hoop and upright, stopping the fall (test No 2)
- In one of the tests the ATD fell and sat on a hoop (test No 3)
- In test Nos 1-6, the ATD's feet were on the rung at the pre-release position. In this position it was expected that that the ATD would be caught by the cage, following the implied understanding from the literature review and survey that a backwards fall could be stopped by a cage if the feet stayed on the rungs. The cage did stop four of the simulated falls. In two of these the feet did stay on the rungs (test Nos 2 and 3). In the other two the feet came off the rungs temporarily and then were caught up again, but the catching aspect of the cage had more to do with the arms.

In the two tests where the ATD was not stopped the feet came off the rungs and did not get caught up again. This was also the case in test No 7, where the feet were not on the rungs at the pre-release position.

- In the tests where the ATD had a more erect position upon release, or where the ATD was near to the ladder upon release, there was a greater tendency for it to fall over a greater distance. Conversely, where the ATD was released in a more folded body attitude about the waist, or where it developed a folded attitude in the fall trajectory, there was more likelihood that it would interfere with the cage.

- If upon release the fall trajectory of the ATD was such that the lower back/buttocks would strike the intersection of a hoop and back upright, there was a tendency for the ATD to jam at that point, e.g test No 2. This was also partially demonstrated in test Nos 4, 5 and 6, but the momentum of the ATD in those tests was greater than any jamming effect caused by the cage.

- In test No 3, the ATD's lower torso fell out of one of the cage's apertures, and the buttocks struck the hoop. When first witnessing the test, it was felt that the ATD was going to fall out through the aperture and strike the floor in an inverted impact posture. However, this did not happen and the ATD remained finely balanced on the hoop in it's final resting position; if the upper torso had swung slightly more outwards in the fall simulation then the ATD may have fallen out.

  Since this research had established that there had been accidents to do with falling-out of a cage, it was decided to mimic the trajectory of test No 3, to see if the ATD could pass through the aperture. This was achieved by slowly lowering the ATD incrementally, starting with the same body attitude as at the end of test No 3. It was discovered that the ATD could easily pass through the aperture (Figure 29 refers).

- In comparing the test results with some of the accident reports described in Sections 3 and 4, it would appear that some of the test results were re-creating the accident occurrences as reported, eg:

  - Test No 3 - near-miss fall-through re-creating French cage fall-through and fall-through communications tower incident, refer clauses 3.4 and 4.1 respectively

  - Test Nos 5 and 6 – catching hoops by the armpit re-creating new building incident, refer clause 4.1

  - Test Nos 1, 4 and 7 – falling erect and impacting test floor with some degree of interference with cage. This may have re-created the fatal accident (clause 4.1) and possibly some of the accidents (clause 4.2), where the injured party fell to the ground or the next platform level, without being fully stopped by the cage. In these cases the injured party was described as having "lost their footing" i.e. the feet had come off the rungs.

- In test Nos 1 and 3, it is estimated that the headward decelerations of 18g and 17.88g respectively in the z axis would have been sufficiently high enough to cause extreme if not fatal injury to a real person falling in similar circumstances. In both tests, the ATD's buttocks struck a hoop when the back was bent to cause the maximum deceleration.

- The opinion is that in test No 4, given the three impacts to the head (not recorded), the overall fall trajectory and the 23.42g headwards decelerations in the z axis, that a real person falling in similar circumstances would have suffered fatal injuries.

- In test No 7, the headward deceleration in the z axis was lower, at 11.98g, than that recorded in the other tests where the ATD fell to the floor (test Nos 1 and 4). The reason for this is that a larger portion of the ATD struck the padding at the bottom of the cage than in the other tests, which would have absorbed a considerable amount of the fall-energy. It was noted that the ATD did strike the padding in a folded body attitude, in a similar fashion to that in test No 1, and that, if the padding had not been present, (as in a real situation), then opinion is that a real person falling in similar circumstances would have suffered extreme if not fatal injuries.

- In test Nos 5 and 6, although the ATD fell a distance of 1.6 m and 2.3 m respectively, before being stopped, the deceleration figures were relatively low, (less than 2g in test No 5 and less than 7g in all axes in test No 6). Injury would have probably been limited to the armpits and arms in the case of a real person falling in similar circumstances.

- The opinion is that in test No 2, no injury would have occurred.

- In all of the tests, the ATD was released either in a backwards-falling or downwards-falling posture, there was no sideways-falling posture. This meant that, typically, the ATD would strike the back of the cage onto the central back upright. Only on one occasion (test No 3) did the ATD slew sideways away from the back upright and start to fall-out through an aperture. This was probably initiated by the right hand being on the rungs at the point of release causing a falling backwards motion to the ATD's right. A sideways-falling pre-release posture is something that should be evaluated in future work.

6.4.4 Ladder-mounted FAS testing - key points

- In all but one of the tests (test No 12) the FAS arrested the fall of the ATD.

- The distances that the ATD fell through before being completely arrested were excessive in some cases, given that the requirement in EN 353-1 (2002) stipulates that a falling 100 kg test mass is to be fully arrested within 1.0 m of the release point. In five of the tests (Nos 8, 9, 10, 12 and 13) the fall distance was more than 1.0 m, and in four of these it was 2 m or over.

  In each case where the fall distance was excessive, this was due to the sliding arrest device either being unable to lock onto the rail, or, once locked onto the rail, it could not remain locked in place and required further attempts to lock. This "delayed lock-on" was due either:

  - to the backward falling motion of the ATD falling outwards and away from the rail and/or

  - the ATD leg(s) interfering with the ladder

  Figure 97 shows the sequence of events in the former case and Figure 98 shows the latter.

In both cases there was sufficient outward horizontal force provided to keep the locking lever of the arrest device away from the rail, i.e. tension was maintained in the device-to-harness connection against the spring. This allowed the device to continue to slide down the rail.

In the falling backwards and outwards case the force is supplied by the outward motion of the ATD (Figure 97). "Unlocked descent" continues until the motion of the ATD becomes more downward than outward, whereupon the tension decays in the connection and the spring can bring the locking mechanism onto the rail.

In the leg interference case (Figure 98) the force is supplied by the leg(s) pushing the torso part of the body away from the ladder. "Unlocked descent" continues until the foot (feet) come of the ladder whereupon the tension decays in the connection and the spring can bring the locking mechanism onto the rail.

In both cases, providing there is no further pushing action outwards from the rail the device remains locked in place, becoming a fixed point to react the fall motion and any energy-absorber operation. However if the pushing action remains to any extent, the arrest device may take several attempts to lock onto the rail, or else it might never.

These tests show that FAS may need additional space to arrest in than that allowed under standardised testing.

- In the cases of delayed lock-on as described above, the affect appears to have been initiated by the folding action of ATD about the waist as it fell from the ladder, and appears to have been exacerbated where:
    - o the device-to-harness connection was relatively long, or,
    - o where the harness strap arrangement at the chest allowed a relatively large amount of stretching, Figure 96.

Figure 96 Example of harness stretch

It is possible that other horizontal displacements may exacerbate delayed lock-on, for example the sideways deflection that is generated during a fall between two intermediate anchor points of a ladder-mounted FAS based on cable, as opposed to a rigid rail. These FAS should be assessed in any future work.

- In each of the drop-tests, a karabiner was used to connect the eyebolt in the ATD's head to the quick release mechanism. Upon release, the ATD fell with the karabiner attached to the head eyebolt. The extra mass of the karabiner (approximately 0.12 kg) increased the ATD's head mass of 5.44 kg by 2%. This is unlikely to have affected test results; however a different method of release could be utilised in future work, especially where a head-mounted accelerometer is used.

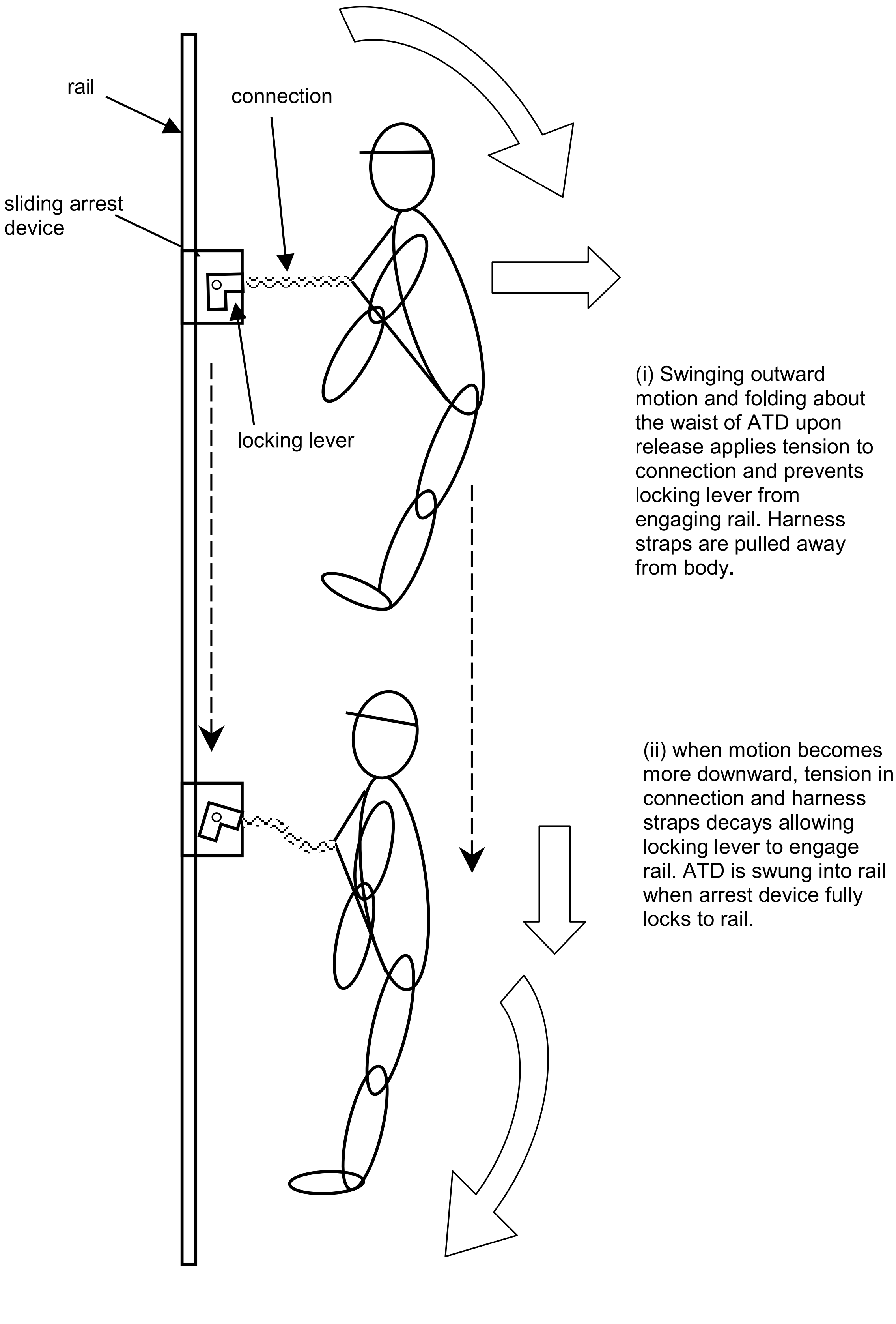
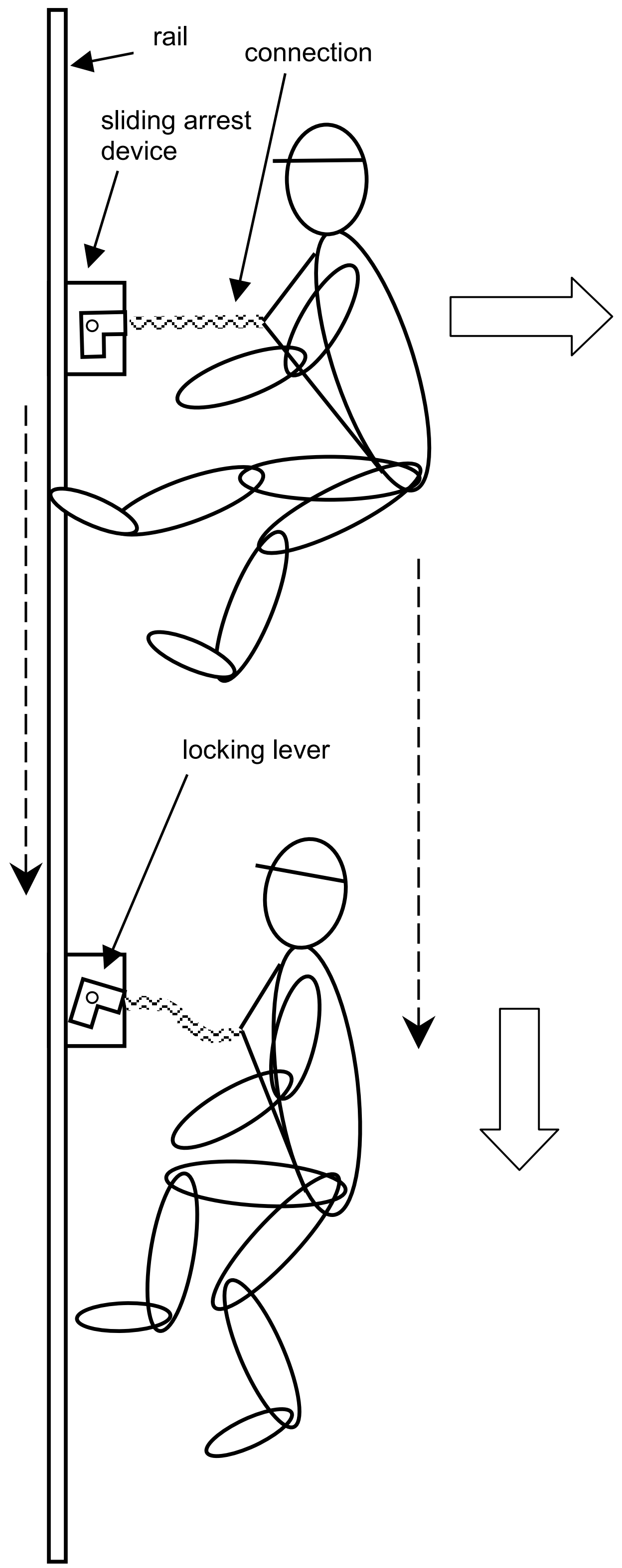


Figure 97 Two snapshots in time which show how the falling backwards and outwards motion of ATD delays the locking-on action of the sliding arrest device



(i) Leg interference with ladder pushes torso away from the ladder applying tension to connection and prevents locking lever from engaging rail. Harness straps are pulled away from body.

(ii) When foot (or feet) eventually come off ladder, tension in connection and harness straps decays allowing locking lever to engage rail. ATD is swung into rail when arrest device fully locks to rail.

Figure 98 Two snapshots in time which show how leg interference delays the locking-on action of the sliding arrest device

- In the case of test No 14, where the post-drop test position of the ATD was very unusual, the interference of the legs delayed the locking-on action of the arrest device to such an extent that the device, in the end, could not lock on at all. The motion of the fall was arrested, instead, by the pushing outward action of the folded legs between the ladder and the ATD's chest.

  When the manufacturers of the FAS evaluated in test No 14 were shown[60] the test results and high speed video of the motion, they set about themselves to see if this particular motion could be reproduced. They attached a human volunteer using the same harness to the same FAS arrangement, and started the test using the same pre-release geometry as in test No 14. The volunteer was attached to a winch, and was slowly and incrementally lowered, to observe what position would be adopted. The manufacturers discovered that it was relatively easy to reproduce the fall motion as observed in test No 14, which gives some degree of credence to the relevance of the results, and demonstrates the ATD's ability to model human motion accurately in those circumstances. Test Nos 16 and 18 also reproduced this motion, although in those cases the sliding arrest device did manage to lock onto the rail.

- In test No 12, although the sliding arrest device failed to lock onto the rail, with eventual disengagement from bottom of rail, it is believed that if there had been sufficient length of rail available, the device would have eventually locked onto rail, resulting in an overall ATD fall distance of approximately 2.1 m. This estimate is based upon the fact that, in test No 13, a similar rail and locking method was used to that in test No 12, and the ATD exhibited an identical fall trajectory up to the point of device disengagement.

- In test Nos 11, 15, 16 and 17 the arrest devices locked-onto the rail within 40 mm of release and, therefore, the delayed lock-on was not an issue. This meant that the ATD could be arrested within a maximum distance of 0.73 m. (Test No 15 also arrested the ATD within 0.73 m but the sliding arrest device needed 255 mm of rail travel before lock-on).

  In the cases where the arrest devices did have energy-absorbing mechanisms these did not operate and, when collectively considered with the arrest devices that had none, the maximum deceleration was 3.1g headwards (z axis), 1.68g (y axis) and 2.86g backwards (x axis).

  This indicates that:

  - it is possible to design arrest devices that are not vulnerable to the delayed lock-on phenomena as described above, and;

  - that the use of energy-absorbers to reduce impact forces/accelerations was redundant in these cases.

- In the case of test No 10, the ATD was released in an erect posture, with hands and feet off the ladder, whilst being lowered at the winch speed to simulate a man descending the ladder. Whilst the arrest device locked with the minimum of delay, the ATD's fall distance was still 1.3 m, which, in comparison with the criterion under EN 353-1 (2002), would constitute a test failure.

[60] At the HSE's request, each of the manufacturers whose FAS was evaluated under this research was sent a copy of the results and the high speed video motion for their particular FAS.

Part of this fall distance can be explained by the harness stretch produced, which is not a factor that has to be considered in the EN 353-1 test, since no harness is used[61]. It might also be thought that part of the fall distance could be explained by the extension of the energy-absorbing mechanism. However in this test the mechanism did not operate, which is surprising, as the identical mechanism had operated on identical arrest devices in test Nos 8 and 9. This does not necessarily mean that the energy-absorbing mechanism malfunctioned however, because comparison of the respective decelerations in all three axis between test Nos 8-10 reveals little difference in magnitudes. It is probable that in test No 9 the force in the connection did not reach that level required to operate the energy-absorbing mechanism.

The explanation for the longer fall distance probably lies in the fact that the ATD and sliding arrest device had momentum before the release point, i.e. both were travelling down at a constant speed of 0.145 m/s prior to release. This momentum would have to be retarded by the FAS, in addition to that generated by the acceleration of the free fall itself. In the EN 353-1 test the test weight is stationary before being released, i.e. it has no additional velocity at the point of release.

This test shows that when a worker is ascending or descending a ladder, FAS may need additional space to complete the arrest process than that allowed under standardised testing where the worker is assumed to be stationary.

- In test Nos 8, 9 and 10 the harness was not very effective in preventing the ATD from going into a reverse-jackknifing posture, whereas in test Nos 11 and 15-18, the harness was able to support the ATD's spine a near-vertical position.

- In test Nos 8-11 and 14-18, where the ATD was arrested, impact decelerations were relatively low in the z and y axes. The highest deceleration in the z axis was 4.65g headwards and 3.49g sidewards to the right in the y axis. The opinion is that a real person falling in similar circumstances would not have suffered undue injury based on those decelerations in the z and y axes.

- In general, x axis decelerations were higher or at a comparative level to those in the z and y axes. This was particularly the case where delayed lock-on had occurred and where the ATD's motion was suddenly diverted towards the rail when the arrest device finally locked-on. This resulted in a rapid impact of the ATD's torso into the rail accounting for the maximum x axis impacts. In some cases, but not all, this included the impact of the head against the rail. Since an accelerometer was not fitted inside the ATD's skull the magnitude of these impacts is not known. Any future work should include an accelerometer in this position.

  The highest deceleration in the x axis was 5.6 g backwards, caused by swing falling into the ladder and the opinion is that such decelerations on a real person falling in similar circumstances would probably cause some minor injury.

  This has important ramifications for future FAS testing since, traditionally, measurement of impact has been confined to the z axis, but these tests show that measurement is also at least (if not more) as important in the x axis, especially if delayed lock-on is a possibility.

[61] *The device connection is directly coupled to the test weight*

- Test No 13 was an exception to the points made above, in that the decelerations were relatively high (7.45g headwards in the z axis, 13.87g sidewards to the right in the y axis and 12.72g backwards in the x axis). The fall distance (2.16 m) was also excessive, caused by delayed lock-on as a result of the ATD's legs interfering with the ladder.

  The high impact decelerations were again caused by the ATD swing-falling into the ladder but were much higher than in the other tests, mainly because of the leg interference as mentioned above. The opinion is that such decelerations on a real person falling in similar circumstances would probably cause some form of major injury.

- In test No 12, the FAS concerned failed to arrest the ATD as a result of delayed lock-on. Eventually, the arrest device ran out of rail and fell off the end.

  This underlines the necessity not only to have an end-stop fitted to prevent release of the arrest device but also, in the case where the end of the rail is elevated, that such a stop should also be able to perform the function of the arrest device if the lock-on is delayed.

  From the point of release, the ATD fell some 4.0 m before impacting the test house floor, (measured using the arrest device as the datum), which in this case was not padded, so the impacts were realistic. These were: 10.51g footwards in the z axis, 23.85g sidewards to the left in the y axis and 22.21g frontwards in the x axis. Although some 1.7 m of the fall was not free fall, i.e. due the arrest device sliding down the rail and the legs interfering with the ladder, these decelerations still give some estimate of impact corresponding to free fall distance.

- In all of the tests, the ATD was released either in a backwards-falling or downwards-falling posture, there was no sideways-falling posture. A sideways-falling pre-release posture is something that should be evaluated in future work.

7. DEVELOPMENTS SUBSEQUENT TO TEST PROGRAMME

7.1 INTRODUCTION

After the test programme was complete, some of the FAS test result information was disseminated via interim reports. This led to a number of developments. These are reported on here since they are relevant to the overall investigation

At the HSE's request, each of the manufacturers whose ladder-based FAS was evaluated under this research was sent a copy of the results and the high speed video motion for their particular FAS.

In addition, it was decided to give CEN/TC 160 [62] a briefing on the test results, at their annual meeting held on 17th September 2003. The briefing focused on the lock-on delay phenomenon in the ladder-based FAS tests, which resulted in a number of FAS producing excessive fall distances when compared to the requirement laid down in EN 353-1 (2002).

In response, a number of organisations interested in the briefing referred to recent accident investigation information which they thought might be of interest to the author. Some of this information was sent to the author. Some is confidential so the full details cannot be disclosed; some arrived too late and needed translation so could not be considered in detail within this report. Details have been included where possible, but any future work should follow up and report in more detail on this information.

7.2 EUROPEAN ACCIDENTS

7.2.1 Holland

In Holland three accidents were reported, all involving ladder-mounted FAS based on a rail with a sliding arrest device.

The common aspect of these accidents is that in all cases the worker fell through a greater distance than 1.0 m, without being stopped[63]. Although the exact cause is not known, it is thought, given the evidence available, that the sliding arrest device failed to lock onto the rail due to delay problems identified in this research.

In two cases the accidents were fatal. In both cases the bottom of the ladder was at an elevated position. Examples of this application include: (i) permanent suspension ladders for window cleaning (the situation in which one of the accidents occurred), and (ii) ladders that start some point above the ground for safety reasons (e.g. unauthorised access prevention). This latter application is typical on advertising and communications masts and electricity pylons.

In one case the worker fell, the arrest device failed to lock, and the device then fell out of the bottom of the rail as no end stop was fitted. Both device and worker fell to the ground and the worker died. The fall distance is not known.

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[62] *This European Standards Committee, via their working groups, is responsible for the European fall protection standards including EN 353-1 (2002) which covers ladder-mounted FAS.*

[63] *The requirement under EN 353-1 (2002) is that the FAS in question has to arrest a falling 100 kg mass or 100 kg sandbag within 1.0 m of its release point. The mass or sand bag has to be released without any initial velocity and so that it's direction of travel at release is wholly downwards.*

This accident appears to confirm the results of test No 12.

In the other case the circumstances were nearly identical, except on this occasion an end-stop was fitted. The worker fell, the arrest device failed to lock, and the device then struck the end stop which sheared off. The device fell out of the bottom of the rail. Both device and worker fell to the ground and the worker died. The fall distance is not known.

The details of the third accident are not known.

In one of the cases the incompatibility of the full body harness with the FAS was thought to have exacerbated the lock-on delay of the sliding arrest device.

As a result of these accidents, one of the measures that the Netherlands standards authority (NEN) implemented was to put a warning into their national implementation of EN 353-1 (2002).[64] This, amongst other things, makes reference to the fact that steel-cabled ladder-mounted FAS may be susceptible to the problems that caused the accidents, and that there are no end-stop strength requirements within the present version of EN 353-1. (See also clause 5.6.6). A copy of the warning can found in Appendix 5.

7.2.2 Germany and Austria

In Germany five accidents were reported, all involving ladder-mounted FAS based on a rail with a sliding arrest device. Not all the accidents resulted in fatalities, which meant that some feedback was possible from the workers who had fallen. Some details are as follows:

- Case 1 – The worker fell more than 5 m past the end-stop. The rail support brackets were 3 m apart. The worker's mass was above 100 kg.

- Case 2 – The worker of 70 kg mass, fell 6 to 8 m on a tower before the arrest device stopped the fall.

- Case 3 – The worker fell 6 m before the arrest device tried to stop the fall. A connector broke and then the worker fell a short distance before another part of the worker's lanyard caught onto something. The fall may have started as the worker was disengaging a work positioning device.

- Case 4 – The worker fell 6 m which was almost stopped by the arrest device, but on impact a connector broke and then after a short fall the worker was stopped with his feet.

- Case 5 – The worker suffered a heart attack. He fell backwards and downwards some 8 to 9 m, and was found dead on the surface which he fell onto. The arrest device had been connected to the centre front abdominal attachment point on the harness.

In one of the cases (it is not known which one), the worker was wearing a waist belt instead of a full body harness.

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[64] *When a European standard is published, the Members of CEN, (the European standards body), have to implement the European standard in their respective country. In the UK the Member Body is the British Standards Institution. Hence a European standard is prefixed with the letters "EN" e.g. EN 353-1; when implemented in the UK it becomes a British Standard, e.g. BS EN 353-1.*

Tests which simulated the accident in Case 1 above were conducted in Germany and showed that the arrest device in question may take up to 5 m to complete the arrest. The identified cause was the horizontal force caused by a backwards-falling person which delays or prevents the locking-on action of the arrest device. This is the same conclusion as that made under this research.

An accident in Austria was reported in which the worker fell through an excessive distance whilst connected to ladder-mounted FAS. The only detail available was that the connection between the arrest device and harness was 30 cm in length.

7.2.3 France and Belgium

In France a number of accidents were reported, together with one in Belgium. Some details are as follows:

- Case 1 – In 2003, an Instructor, who trains workers in the use of FAS as part of his remit, had an accident himself whilst attached to a rail-based ladder-mounted FAS. He was actually training other workers how to use the FAS in question when he fell an unknown distance and broke his foot in several places. He needed extensive medical treatment.

- Case 2 – In March 2004 a worker died when the sliding arrest device to which he was attached to failed to lock when he fell. The manufacturer of the FAS attempted on two occasions to reconstruct the accident by drop-testing. In both cases the dummy (type unknown) was not arrested by the FAS.

Details of a number of other accidents which had occurred in France and Belgium were sent to the author, but these were not translated. Investigation of these items could form part of future work.

7.2.4 United Kingdom

Safety Warning

In response to the interim test results and the accident information, the HSE drafted a safety warning for BSI Technical Committee PH/5, the standards-making group responsible for EN 353-1 in the UK. Amended after a meeting in February 2004, the text was sent to CEN/TC 160, the European Standards committee responsible for EN 353-1 at European level. This was then published as document number CEN/TC 160 N 824. In addition, the HSE highlighted this safety warning in a press release, No. E074:04 on the June 1st 2004. This can be accessed at the HSE website: http://www.hse.gov.uk/press/2004/e04074.htm.

Accident

In regard to accidents, there was an occurrence in the UK in 2001 in which the author was part of the investigation team. The worker had been climbing a tower whilst attached to a rail-based ladder-mounted FAS. He fell and was arrested by the FAS, but he thought that he had fallen too far and that the FAS hadn't operated quickly enough, which had unnerved him. He estimated his fall to be at least 2 m, based on his recollection of his position prior to the fall.

A peculiar aspect was that the energy-absorption element had not operated. He also received severe bruising on the chest where the harness straps imparted the arrest force to his (clothed) body.

Upon visual examination, no major fault could be attributed to the FAS. However, a number of factors were determined during the investigation which together had contributed to the excessive fall distance:

- In performing normal (pre-use) lock-on checks on the sliding arrest device, it was discovered that it could take up to 265 mm of rail travel from release to lock-on. This check was performed by first letting the device slide down the rail under its own weight, and then releasing the connection to allow the device to lock, simulating a worker descending and falling. The average of these tests was 190 mm. The manufacturer's limit was 150 mm, indicating that the device was unserviceable. In fact it had a weak spring. But this on its own could not explain the over 2.0 m fall.

- The connection between harness and arrest device was 330 mm.

- Witness marks indicated that the arrest device had made several attempts to lock onto the rail, but had failed to hold on. It was determined from the upper and lower mark on the rail that the arrest device had required 0.88 m of travel on the rail before finally locking and staying on.

- The accident was reconstructed on site with adequate safety precautions in place. The worker was asked to lean back with his feet on the ladder, to see how far back he could lean before the connection on the arrest device became taut. (It was suspected that a falling backwards motion was responsible for the excessive fall distance, and the worker had commented that he had fallen backwards in the incident). It was discovered that the worker could lean back over 500 mm before the connection became taut. This was partly due to the connection length and partly due to harness strap stretch.

When these various measurements were incorporated diagrammatically, it was discovered that the minimum fall distance would have been just under 2.0 m. Although it was proposed to recreate the accident by testing with an ATD, this never occurred, so it was not certain whether the falling backwards action had caused delayed lock-on. However, the evidence did point to this to be the case.

8. RECOMMENDATIONS AND DIRECTIONS FOR FURTHER RESEARCH

8.1 SYNOPSIS

After reviewing the documentation listed in Section 9, together with information from the survey, from accidents and the results from testing, it seems clear that caged ladders cannot provide positive fall-arrest capability, especially in the case of the three-upright design which was tested as part of this research. There is every possibility of a fall down the cage to the ground or other platform.

There would appear, or so it seems, a possibility to stop the fall of a worker in certain circumstances, but this depends upon the attitude of the worker both before the fall and during the fall, and whether or not the worker manages to catch part of his or her body in one of the cage apertures, or manages to trap themselves in the cage some other way. In any event, it is a chance occurrence, and the opinion is that even if the worker could be caught by the cage, it could lead to significant if not fatal injury. In addition the whole method of recovery and rescue would have to be considered, which itself would be fraught with difficulty. The accidents reviewed indicate that workers fall down cages to the next level and are rarely caught. Injuries have been reported.

No test methods were discovered in this research for testing the fall-arresting effectiveness of caged ladders, whereas there are a number of standards in existence for FAS.

The inferences from the documentation reviewed make it clear that caged ladders do not provide the same level of protection as ladder-mounted FAS, although a number indicate that the protection methods are on a par, but confuse the issues or use evasive language. The vast majority, when referring to protective measures, tend to avoid the subject completely by referring to FAS specifically in terms of their fall-arresting effectiveness, and then to caged ladders only in a general protective sense. The whole matter of caged ladder protection is left vague, deliberately in the author’s view.

Furthermore, a number of documents seem to condone or even allow the possibility of falling down a caged ladder to the platform below, in respect of staggered ladder flights. This distance seems to be either 6m, 9m or even 10m, depending on country or industry. The opinion is that this is an extremely dangerous approach.

A number of ladder-mounted FAS were also tested in this research to compare the fall-arresting capability of this equipment with that of caged ladders. With some exceptions, the majority of the tests showed that the FAS were able to arrest the fall of a worker much more positively, effectively and safely than caged ladders could. However, a number of tests revealed that the FAS so tested have a much poorer stopping distance in realistic fall conditions than when tested in a laboratory in accordance with standards that contain minimum performance requirements. This aspect is caused by delayed locking-on of the arrest device and appears to be a factor in a number of European accidents.

8.2 RECOMMENDATIONS AND DIRECTIONS FOR FURTHER WORK

- Two versions of the American National Standard for fixed ladders were reviewed, namely ANSI A14.3 (1984) and the later ANSI A14.3 (1992). This standard has a long lineage, having been originally established in 1923. Subsequent revisions were published in 1935, 1948, 1952, 1956, 1974, 1984 and 1992. Attempts were made to locate these earlier versions, because it was felt that these documents might determine the inception date for caged ladders in the U.S.A. These documents could not be obtained in the available project time, but their acquisition would be important in any further work subsequent to this research.

- It may be that a German standard, DIN 18799 Part 3 (1999), which details "rűckenschutzkorb" (ladder safety hoops) for chimneys, contains important information. An English translation of DIN 18799 Part 3 (1999) was not obtainable during the timeframe of the project, but would be a key document to obtain in future research.

- A common theme with caged ladders that emerged from this report is that a single upper hoop, which in some instances can be joined to the upper rail of a guard rail system, can possibly restrict a worker falling backwards or sideways off the ladder when moving from the horizontal to vertical planes or vice versa. This is a reasonable hypothesis, but its effectiveness should be assessed by testing using similar methods described in this report.

- It would appear that French national organisations have carried out research in regard to fixed ladder accidents and ways of improving the degree of protection afforded by caged ladders. One example of this is the identification of the risk that workers could fall out of the apertures of the cage, which has led to the adoption of five uprights. Project time restraints prevented further investigation into obtaining the full details of the research but it would be an important aspect to follow up on in any future work.

- Measures should be researched and modifications evaluated to determine ways of improving the fall-arresting capability of caged ladders, in order to reliably demonstrate that they can arrest the fall of workers, otherwise their use should be abandoned. The present perception that they afford the same level of protection as FAS should be discounted in future documentation, and their inability to positively arrest the fall of a worker should be made absolutely clear, especially to personnel who have to perform risk assessments for working at height.

- The idea of in some way protecting a worker by "catching" them at platforms at 6 or 9m intervals after they have fallen down a cage should be abandoned with all haste.

- The French-driven European idea of specifying caged ladders with five uprights should be evaluated using similar test methods as used in this research. Whilst the idea of reducing aperture size is a good one, in order to eliminate the falling-out-of-the-cage hazard, it may actually increase the risk of falling down the cage. This is because it reduces the possibility of limb entanglement which, apart from whole-body jamming, appears to the only way of stopping a fall at present. It is for this reason that caged ladders that are meshed in should also be evaluated. This research would indicate there is a greater risk of a fall down a cage if it is meshed in.

- There appears to be a trend where ladder cages are being installed or are being upgraded in retrospect with cable-based, ladder-mounted FAS. This is because there is a perception that caged ladders, on their own, will not positively stop falls. This approach may be commendable but, in the light of this research, it should be evaluated to ensure that both methods are compatible with each other, especially in terms of whether a fall will be stopped or not, and to establish the distance a worker might fall through. There is also the need to ensure that, since the FAS will protrude to some extent into the climbing space, that this does not make climbing more difficult, given the proximity of the rear of the cage. Previous research has demonstrated that unnatural climbing movements can lead to unstable movement on a ladder which increases the likelihood of falling off it.

- A sideways-falling pre-release posture is something that should be evaluated in future caged ladder drop-testing work.

- A tri-axial translational and possibly angular accelerometer should be inserted in the head of the ATD in future research, to enable head impacts to be measured. This test approach would include a different method of connection to the quick release mechanism, i.e. not via the ATD's head as in the present research.

- A larger ATD in terms of dimensions and mass should be used to evaluate caged ladders in future research, to see if capability is affected by size.

- According to the test results of this research, if horizontal loading is applied to the connection at the sliding arrest device of any of the FAS tested, in a situation when a fall occurs, i.e. when a worker falls backwards off a ladder, this may prevent or delay engagement of the locking mechanism at precisely the moment that it is required to lock onto the rail. The device in this situation may need several attempts to lock onto the rail and this may lead to fall distances in excess of that required by EN 353-1 (2002). This is the harmonised European standard which specifies requirements to allow a manufacturer to gain conformity under the PPE Regulations (2002), otherwise known as CE marking of Personal Protective Equipment (PPE).

  The requirement under EN 353-1 (2002) is that the FAS in question has to arrest a falling 100 kg mass or 100 kg sandbag within 1.0 m of its release point. The mass or sand bag has to be released without any initial velocity and so that it's direction of travel at release is wholly downwards. This does not realistically represent what happens in practice when a worker falls off a ladder, as evidenced by the results of this research and the details of recent accidents. There is also historical evidence as mentioned in the next paragraphs.

  In the author's view, the dynamic test requirement in EN 353-1 and corresponding method in EN 364 (1992) cannot be used to give a presumption of conformity under the auspices of the PPE Regulations (2002), because it cannot detect the unsafe situation of lock-on delay, the term used in this report to describe the inability or delay of the sliding arrest device to lock onto the rail. Instead, an interim solution would be to use the "System operational test" of BS 5062 Part 1 (1985), clauses 7.5.3 and E.2.1.2. This test method was designed to detect the very same unsafe lock-on delay characteristic. It should be noted that the test is carried out with the full body harness that is intended for use with the FAS. This is because any incompatibility between the harness and the rest of the system may exacerbate lock-on delay (e.g. the harness stretching observed in this research).

In one of the accidents reported, harness incompatibility was identified as a contributory factor. This is something that cannot be readily identified visually, and hence a system operational test is required to determine the performance of the full FAS acting together. The use of the system operational test would be in addition to the dynamic strength testing requirement in EN 353-1 (2002).

The system operational test of BS 5062 was instigated as a result of investigative drop-tests in 1985 which revealed lock-on delay. These tests are described in an article, Clark (1985), and were reviewed in Riches (2002). Some of the film footage[65] of those drop-tests still survives and has been converted to DVD format, National Engineering Laboratory (2004). One kinematic drop-test sequence is shown from the DVD material in Figure 99. This is a sequence of photographic snapshots in time which describes the motion of the ATD during the drop-test. The snapshots are displayed at random time intervals to reflect significant events in the test. They show the ATD becoming inverted and falling to the ground as the arrest device is prevented from locking onto the rail. This is due to tension in the line connecting the harness to the arrest device. This sequence underlines the dangers of using incompatible equipment and may be representative of the actual accidents reported in clause 7.2.2.

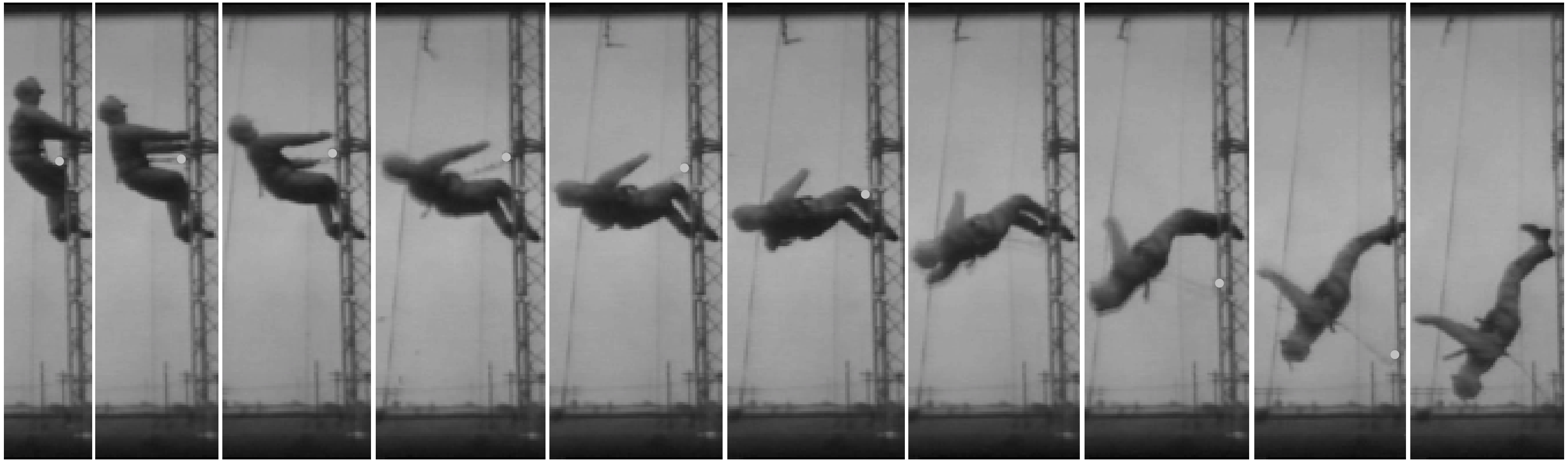
Unfortunately BS 5062 had to be withdrawn on the introduction of BS EN 353-1, and the system operational test was not seen as essential by the majority at the time so it was discarded.

In respect of the above, whereas British Standards or British Standard equivalents of European Standards contain requirements in relation to FAS, it should be understood that they are minimum requirements only; by just designing, testing, manufacturing and generally controlling products to the level required by the standard may not be enough. It is often thought that, when marketing products, if the product meets a standard's requirements then that will be sufficient, and that by gaining a CE mark in the case of PPE means that the PPE will be suitable for the particular task for which it is being sold. This is not necessarily the case, as the testing in the relevant standard is often limited to checking standardised parameters under laboratory conditions and therefore may not cover the specific circumstances of use. A lot more may have to be done in excess of the standard to ensure that products are safe and satisfy legislation, e.g. the PPE Regulations (2002) and the Health and Safety at Work Act (1974).

It should be noted that all British Standards or British Standard equivalents of European Standards contain the following warning at the front of the standard: "Compliance with a British Standard does not of itself confer immunity from legal obligations".

- Ladder-mounted FAS may need greater free space clearances beneath the worker than those based on the results of EN 353-1 tests and manufacturers should be aware of the need to supply this information. Alternative methods of fall protection may be needed.

[65] *A list and brief description of the film material can be found in Riches (2004).*



Note: mark used to deliberately obscure sliding arrest device also assists in tracking the device in the sequence

Figure 99 Kinematic sequence of ATD fall trajectory due to delayed lock-on of sliding fall-arrest device after National Engineering Laboratory (2004)

- EN 353-1 (2002) assumes that when the worker falls, he or she is stationary. The research suggests that if the arrest device is moving, as it would be if a worker was climbing or descending a ladder, then the arrest device will have to disperse the additional momentum of the worker's movement. This should be assessed in greater detail in further research, and test methods in standards amended accordingly.

- It is possible, through design modifications, to counter or prevent the effects of delayed lock-on, and manufacturers should be encouraged to explore new concepts and develop their products accordingly.

- Manufacturers should review the lengths of connections between their sliding arrest device and the harness, and the amount a harness can stretch away from the front of the body, as these are two factors which can exacerbate lock-on delay.

  Connection lengths generally became longer, more expensive and harder to climb with, with the introduction of EN 353-1. This is because energy-absorbers had to be introduced into the connection to keep arrest force down to 6 kN with the introduction of a 100 kg steel test mass.

  This is an example of a test procedure with an inbuilt safety factor which nobody can quantify. In the author's view it is too severe a test and, if a more realistic test method were adopted, which utilised the harness in the test, (representative of real life), the energy absorbers may be able to be deleted. There was evidence for this in the test results of this research, and see also Riches (2002).

- It is possible that other horizontal displacements may exacerbate delayed lock-on, for example the sideways deflection that is generated during a fall between two intermediate anchor points of a ladder-mounted FAS based on cable, as opposed to a rigid rail. These FAS should be evaluated for lock-on delay in any future work. Products under EN 353-2 (2002) may also be affected.

- A sideways-falling pre-release posture is something that should be evaluated in future ladder-mounted FAS drop-testing work as the motion sensor design of arrest devices, by design, cannot sense and react to sideways motion.

- The FAS test results in this report showed that measured impacts in the x axis were at least as, if not more, important than those in the z axis, especially if delayed lock-on occurred. This is because of the magnitude of such impacts in comparison with those in the z axis, which, traditionally, have been seen to be the most important axis. These x axis impacts occur as a result of the ATD swinging into the ladder after the arrest device locks-on, and should be measured in assessing equipment design. They may cause more injury than the vertical arrest impact itself, and are another example of where standardised test methods do not take account of the geometry of the actual fall-arresting circumstances.

- The cut-off frequencies selected in the electronic measurement apparatus can significantly change the outcome of test results. The selection of the frequency should be reviewed in future work to ensure that the current 60 Hz figure is still appropriate and to investigate / recommend other alternatives as appropriate.

- In respect of the above frequency recommendation, ATDs to be used in future research should have their resonant frequencies analysed, to determine what degree of bio-fidelity they have in respect of a human being.

- Details were received on a number of European accidents but were not investigated due to their late arrival and the need for translation. Any future work should follow up and report in more detail on this information.

- It should be noted that both caged ladder and FAS tests were done in test laboratory conditions. Performance in respective tests was not assessed in simulated inclement weather conditions, such as in wet or in icing conditions, which may have had an effect on results. This is something that could be assessed in future work.

- The application of impact tolerance information in terms of assessing fall-arrest protection is an area which would benefit from further research.

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10. FURTHER DETAIL

APPENDIX 1
ACCELERATION-TIME HISTORIES FROM CAGED LADDER TESTS

The following graphs in Figures 100 to 104 are the recorded acceleration histories for test Nos 1, 3, 4, 6 and 7. The measurement system did not trigger for test Nos 2 and 5 and so graphs are not available for these two tests.

The graphs are colour coordinated and correspond to the convention in Figure 5 and Table 1. Green lines correspond to acceleration in the z axis, red lines correspond to acceleration in the y axis and black lines correspond to acceleration in the x axis. A reduced size Figure 5 has been inserted in the top right hand corner of each graph to make reference easier for the reader.

The maximum values of acceleration have also been appended on each graph in both directions for each axis.

The point of release of the ATD is also marked.

Note that in regard to the time axis on the graphs, in some cases this has been moved so not to clash with the graph lines themselves. Consequently it may not always coincide with the "0" value on the acceleration axis.

Note that in Figure 103 (test No 6) there are some small ripples evident prior to the release point. This is 50 Hz mains pick-up/interference. This does not affect the test levels as they are of a greater amplitude. This is the result of a measurement compromise that has to be made when wanting to measure high unpredicted deceleration levels, i.e. +50g to -50g, which gives rise to a large signal to noise ratio. The ripples are more noticeable when deceleration levels measured are towards their lower values, (test No 6 had the lowest deceleration levels in the caged ladder testing).

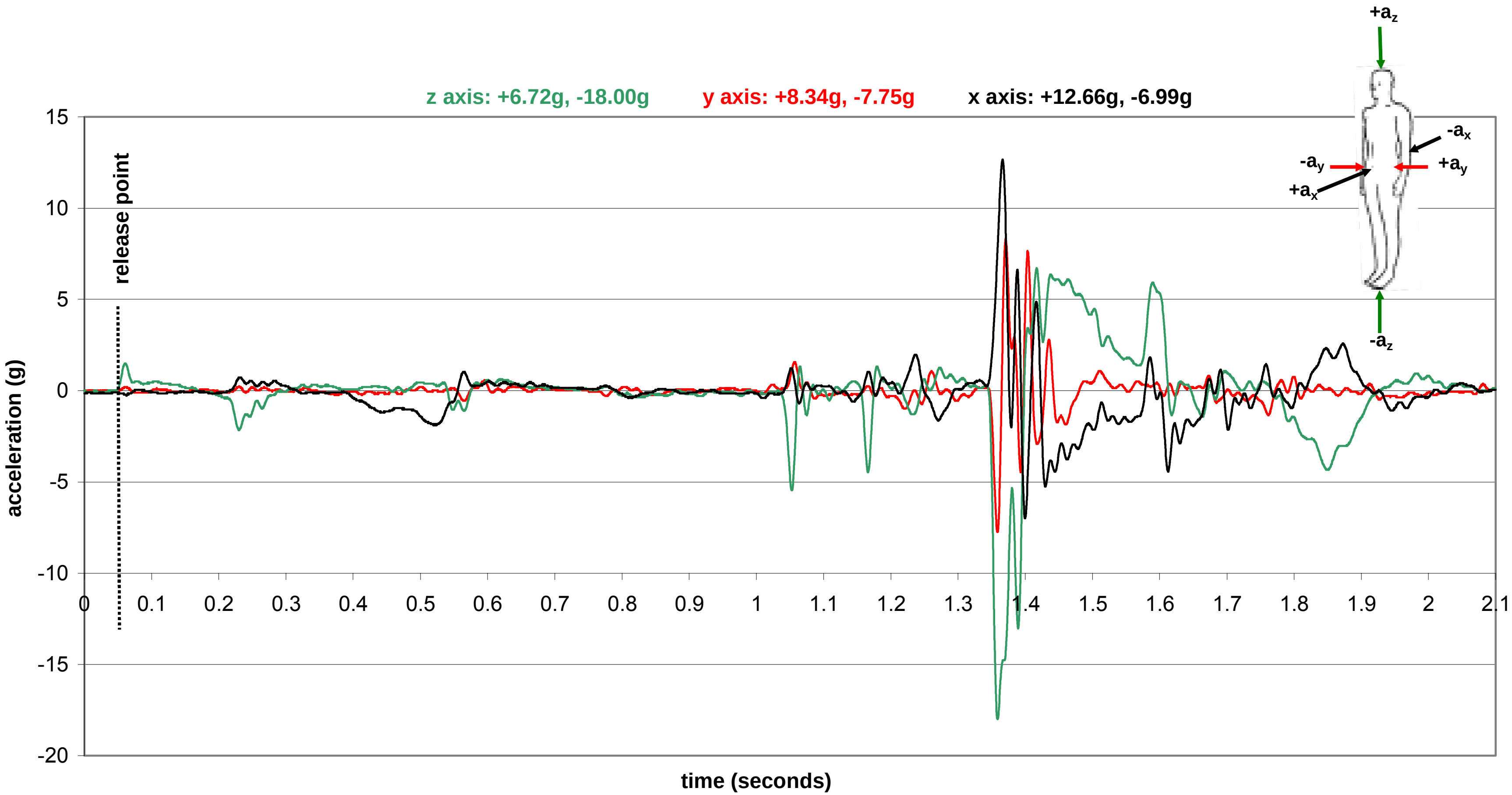


Figure 100 Tri-axial acceleration – time trace for test 1 (caged ladder)

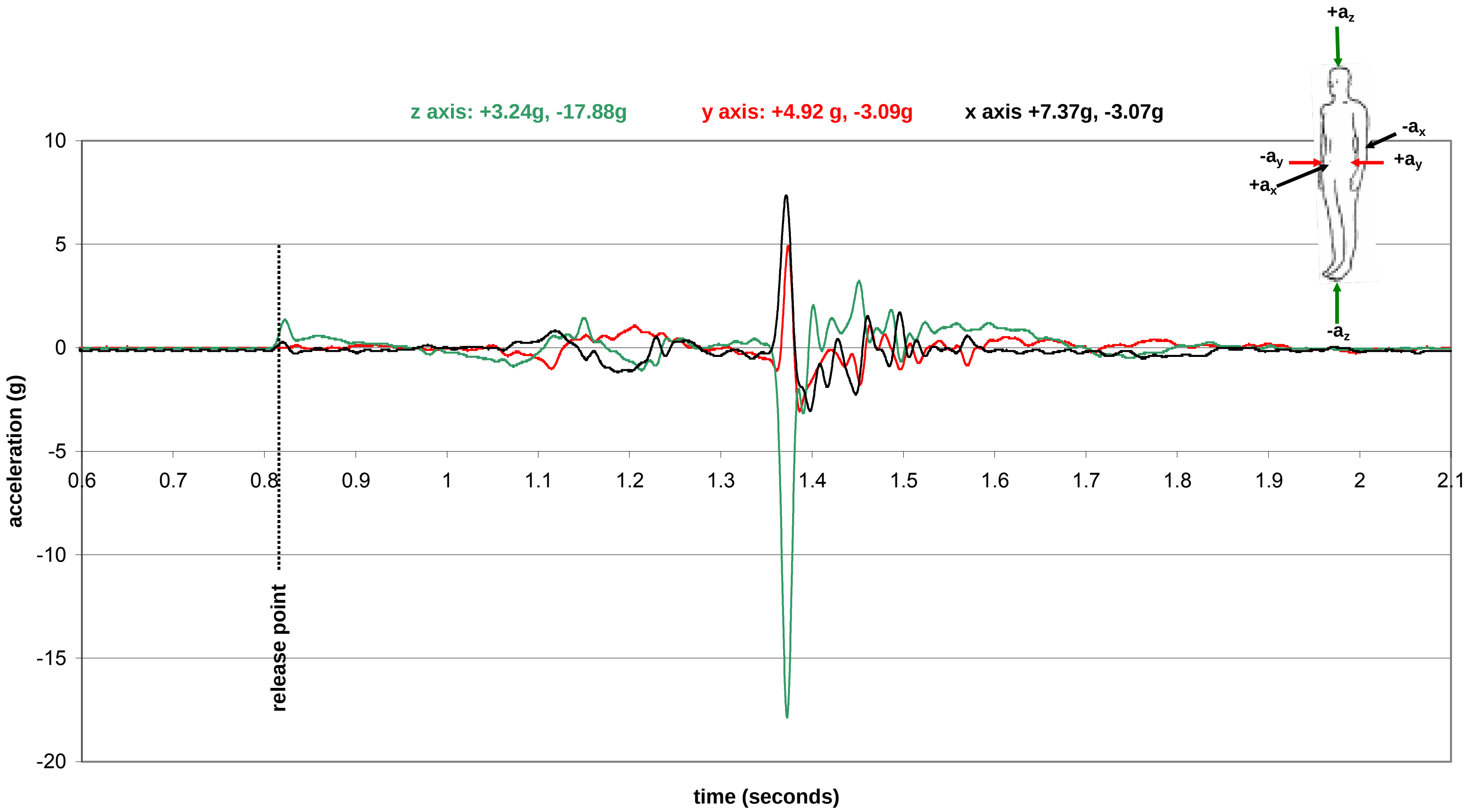


Figure 101 Tri-axial acceleration – time trace for test 3 (caged ladder)

Figure 102 Tri-axial acceleration – time trace for test 4 (caged ladder)

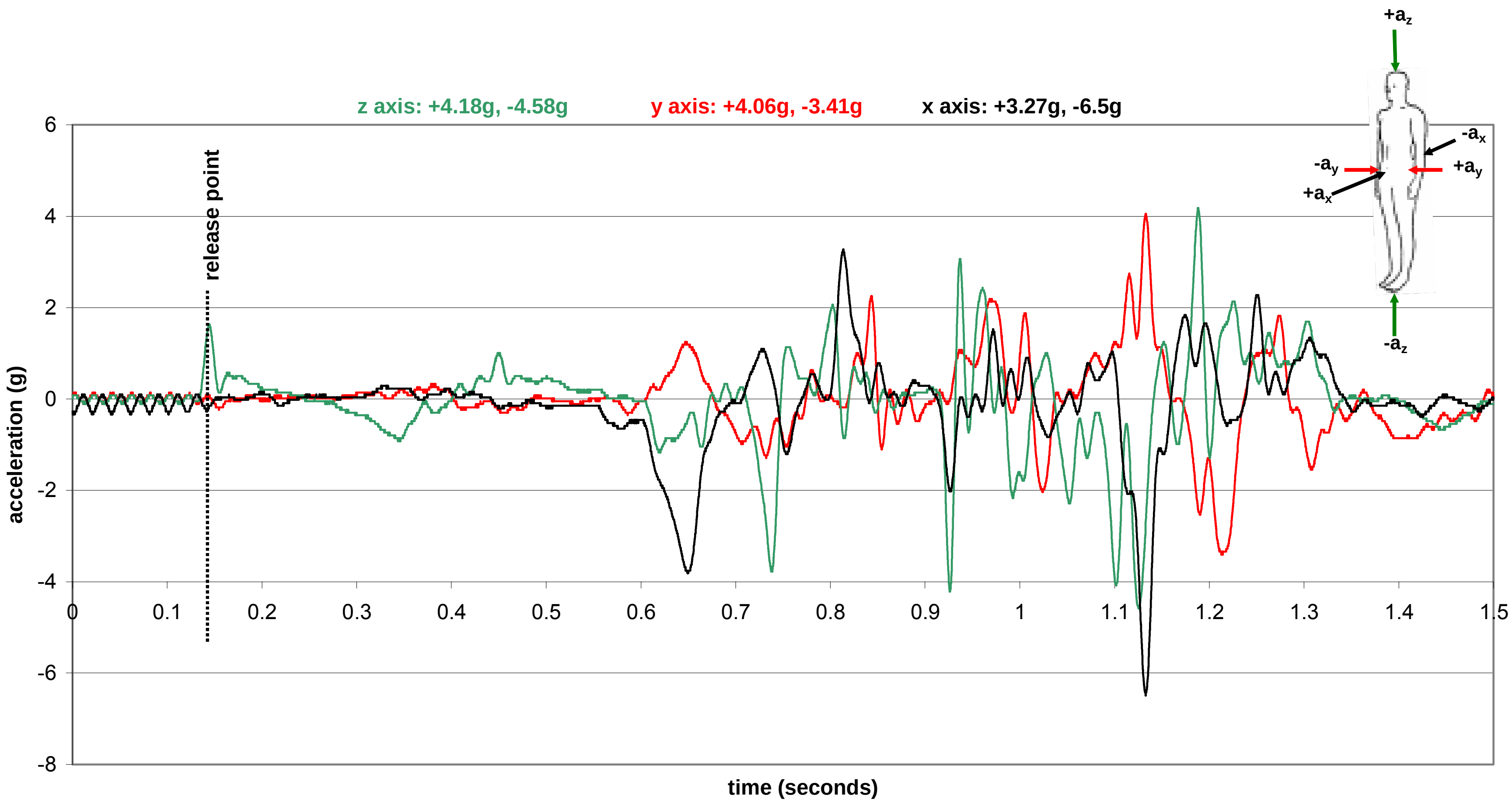


Figure 103 Tri-axial acceleration – time trace for test 6 (caged ladder)

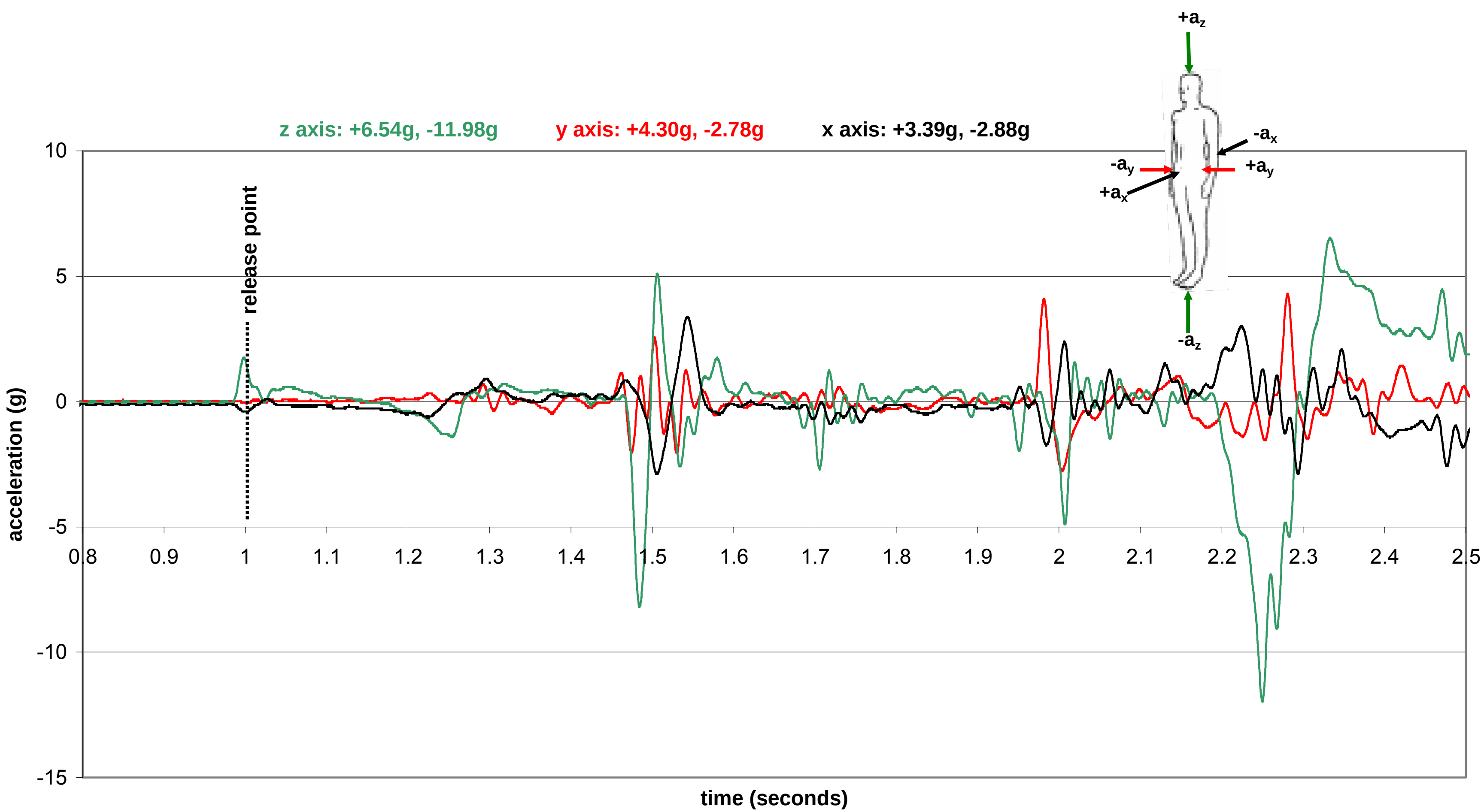


Figure 104 Tri-axial acceleration – time trace for test 7 (caged ladder)

APPENDIX 2
ACCELERATION-TIME HISTORIES FROM LADDER-MOUNTED FAS TESTS

The following graphs in Figures 105 to 114 are the recorded acceleration histories for test Nos 8-10 and 12-18. The measurement system did not trigger for test No 11 and so the graph is not available for this test.

The graphs are colour coordinated and correspond to the convention in Figure 5 and Table 1. Green lines correspond to acceleration in the z axis, red lines correspond to acceleration in the y axis and black lines correspond to acceleration in the x axis. A reduced size Figure 5 has been inserted in the top right hand corner of each graph to make reference easier for the reader. The exception to the convention is that for test Nos 15-18 (Figures 111 to 114), where the polarity of the accelerometer in the z axis was reversed. This does not alter any values and, as will be seen by the reduced copy of Figure 5, $+a_z$ is headwards and $–a_z$ is footwards for those tests.

The maximum values of acceleration have also been appended on each graph in both directions for each axis.

The point of release of the ATD is also marked.

Note that in regard to the time axis on the graphs, in some cases this has been moved so not to clash with the graph lines themselves. Consequently it may not always coincide with the "0" value on the acceleration axis.

Note that in some of the graphs there are some small ripples evident prior to the release point. This is 50 Hz mains pick-up/interference. This does not affect the test levels as they are of a greater amplitude. This is the result of a measurement compromise that has to be made when wanting to measure high unpredicted deceleration levels, i.e. +50g to -50g, which gives rise to a large signal to noise ratio. The ripples are more noticeable when deceleration levels measured are towards their lower values.

Also in test Nos 15-18 (Figures 111 to 114) the graph lines themselves exhibit a "stepped" appearance. This is completely normal because such a large measurement range was set on the measurement equipment to ensure that all deceleration levels were captured. However for these particular tests deceleration levels were so low that step changes in the signal can be observed due to the signal to noise ratio. The results themselves are not affected. The lines could have been "smoothed" if the measurement range had been reduced but this then runs the risk of not capturing higher deceleration levels.

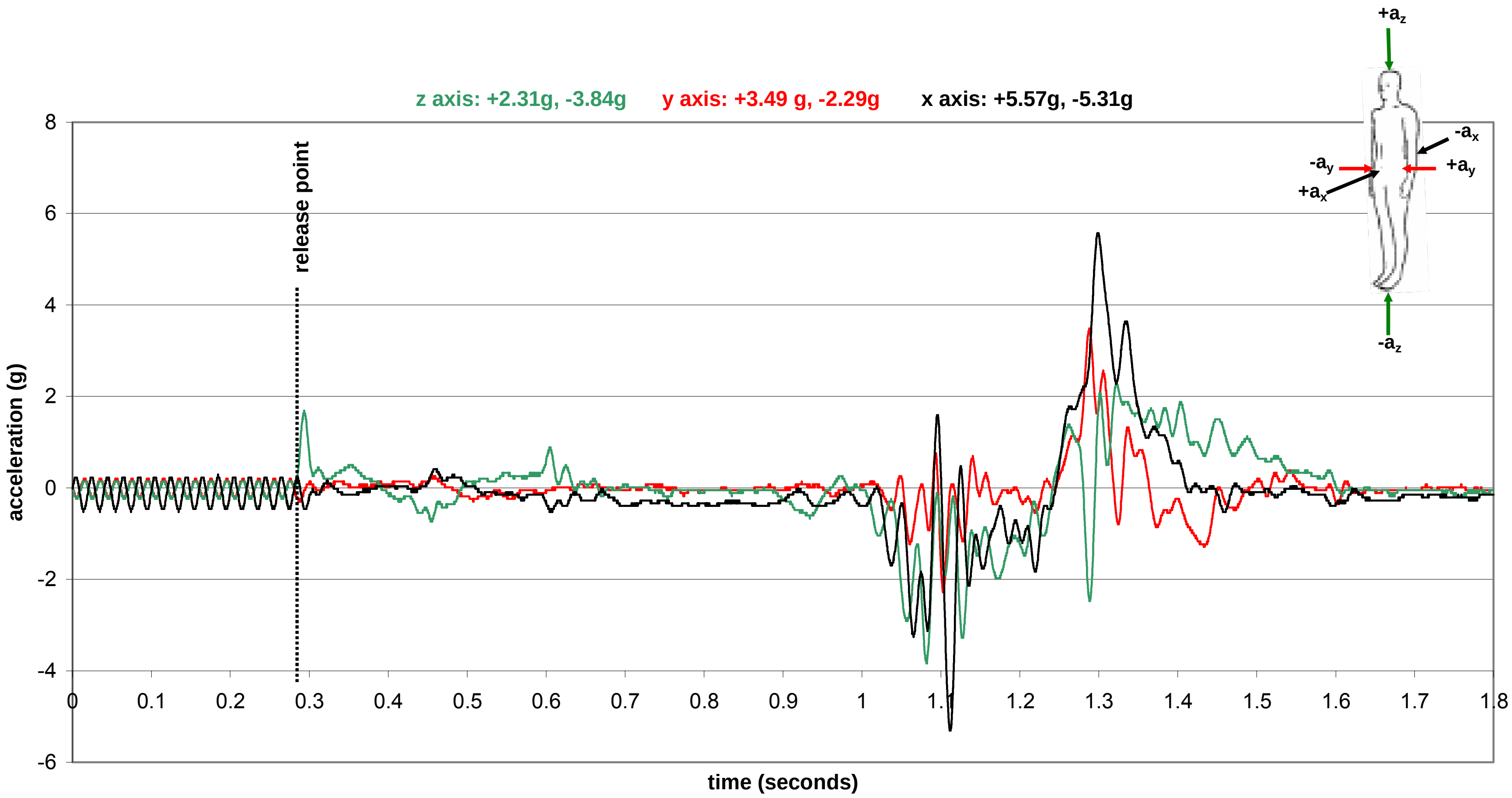


Figure 105 Tri-axial acceleration – time trace for test 8 (FAS 1)

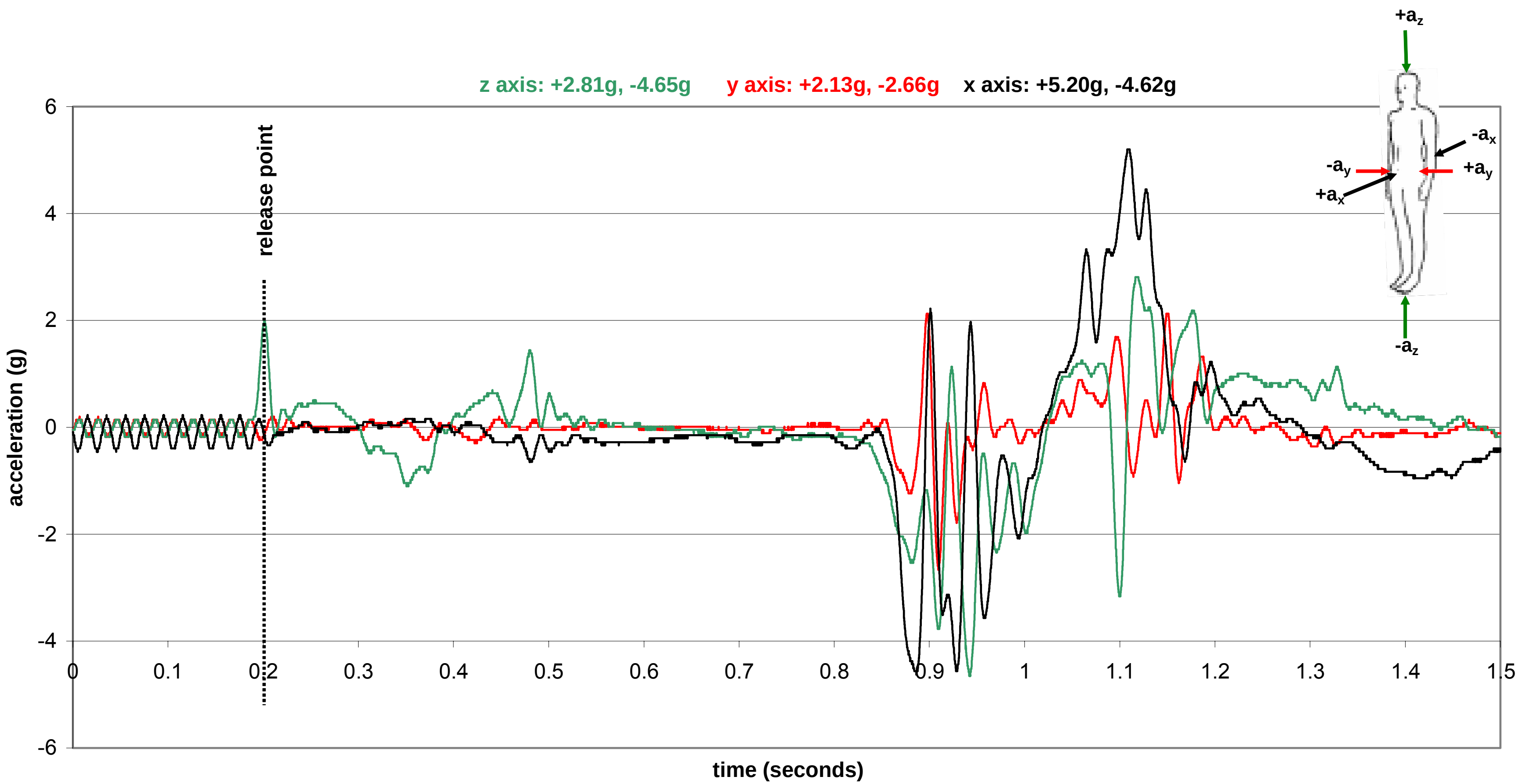


Figure 106 Tri-axial acceleration – time trace for test 9 (FAS 1)

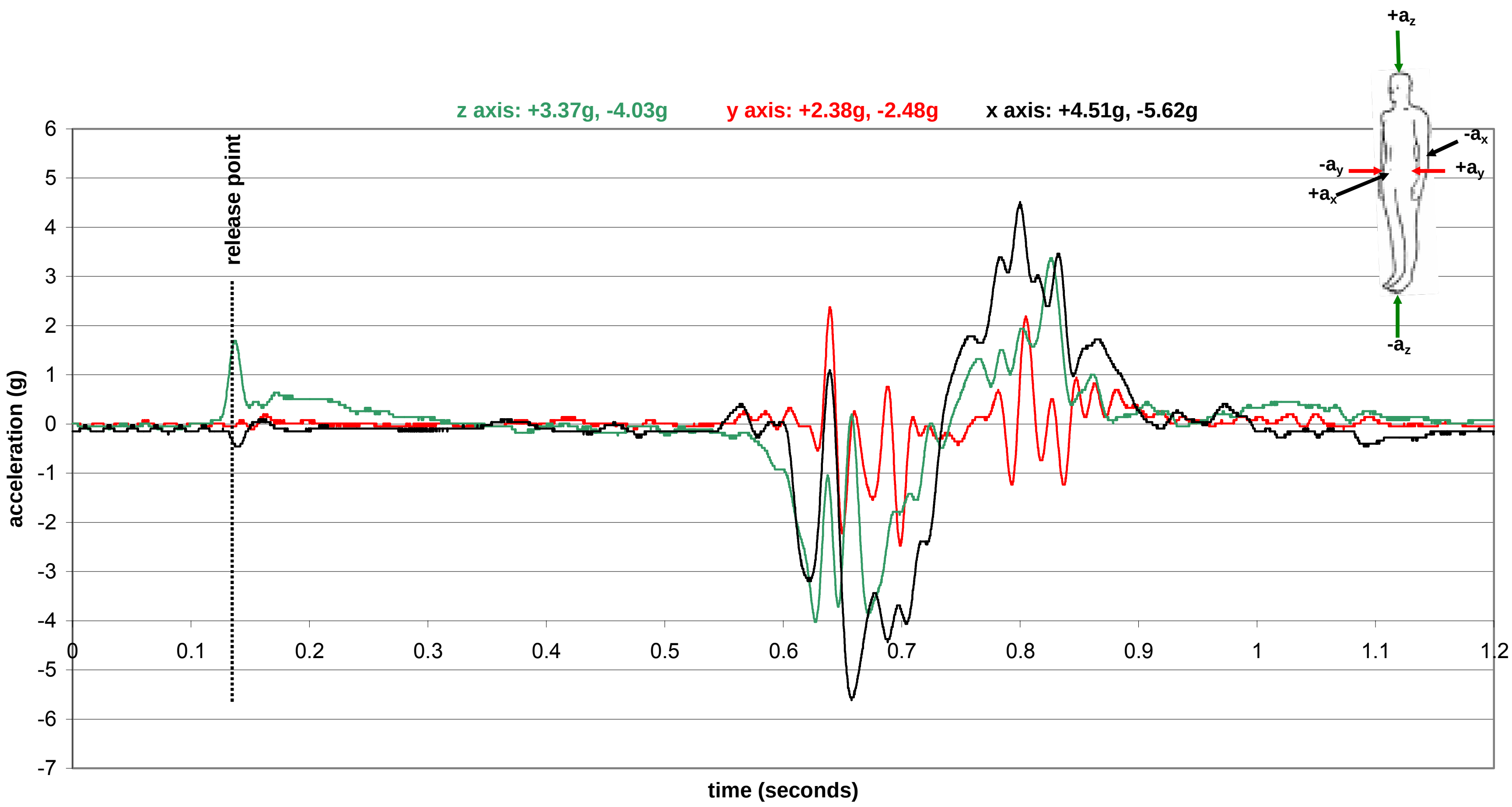


Figure 107 Tri-axial acceleration – time trace for test 10 (FAS 1)

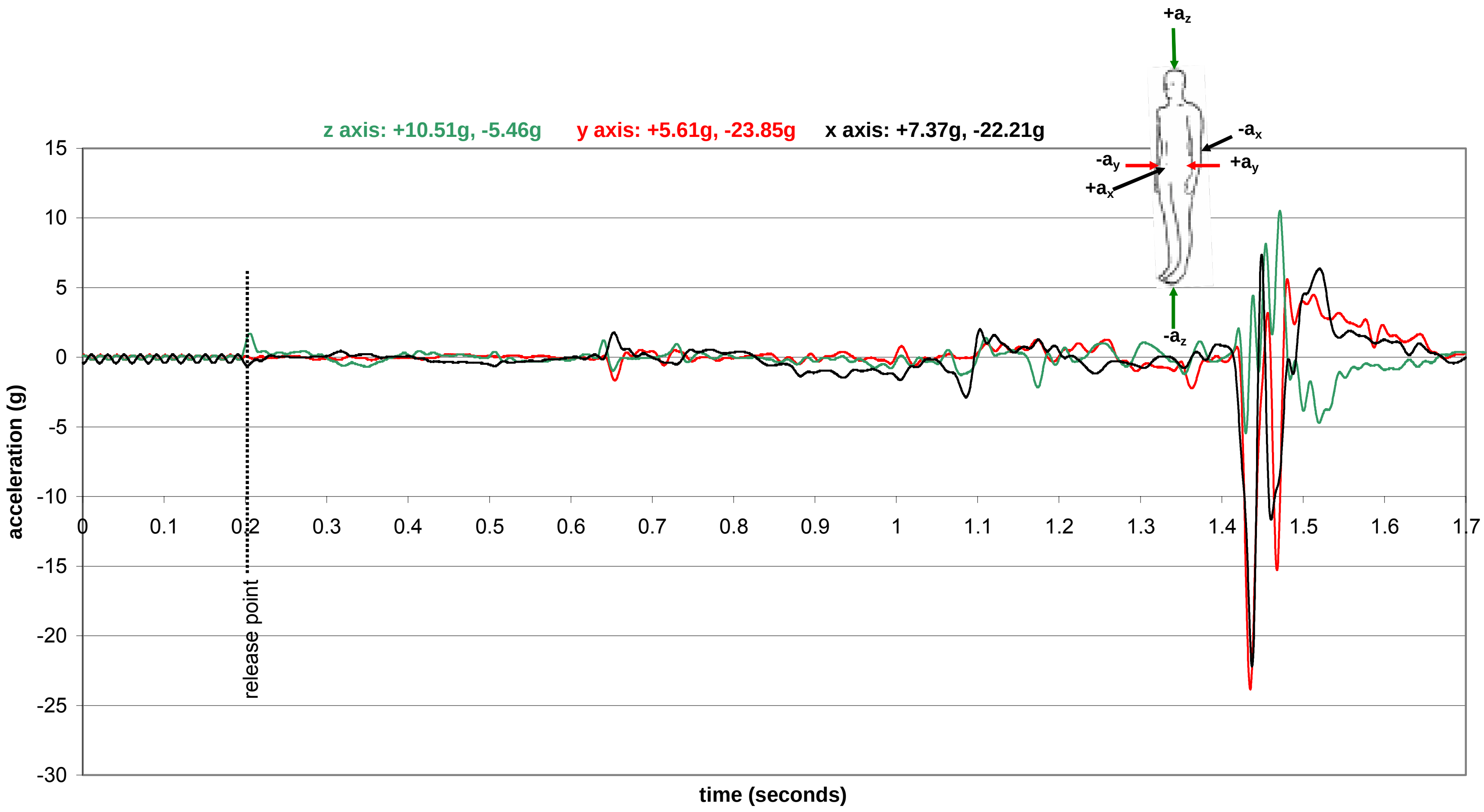


Figure 108 Tri-axial acceleration – time trace for test 12 (FAS 2)

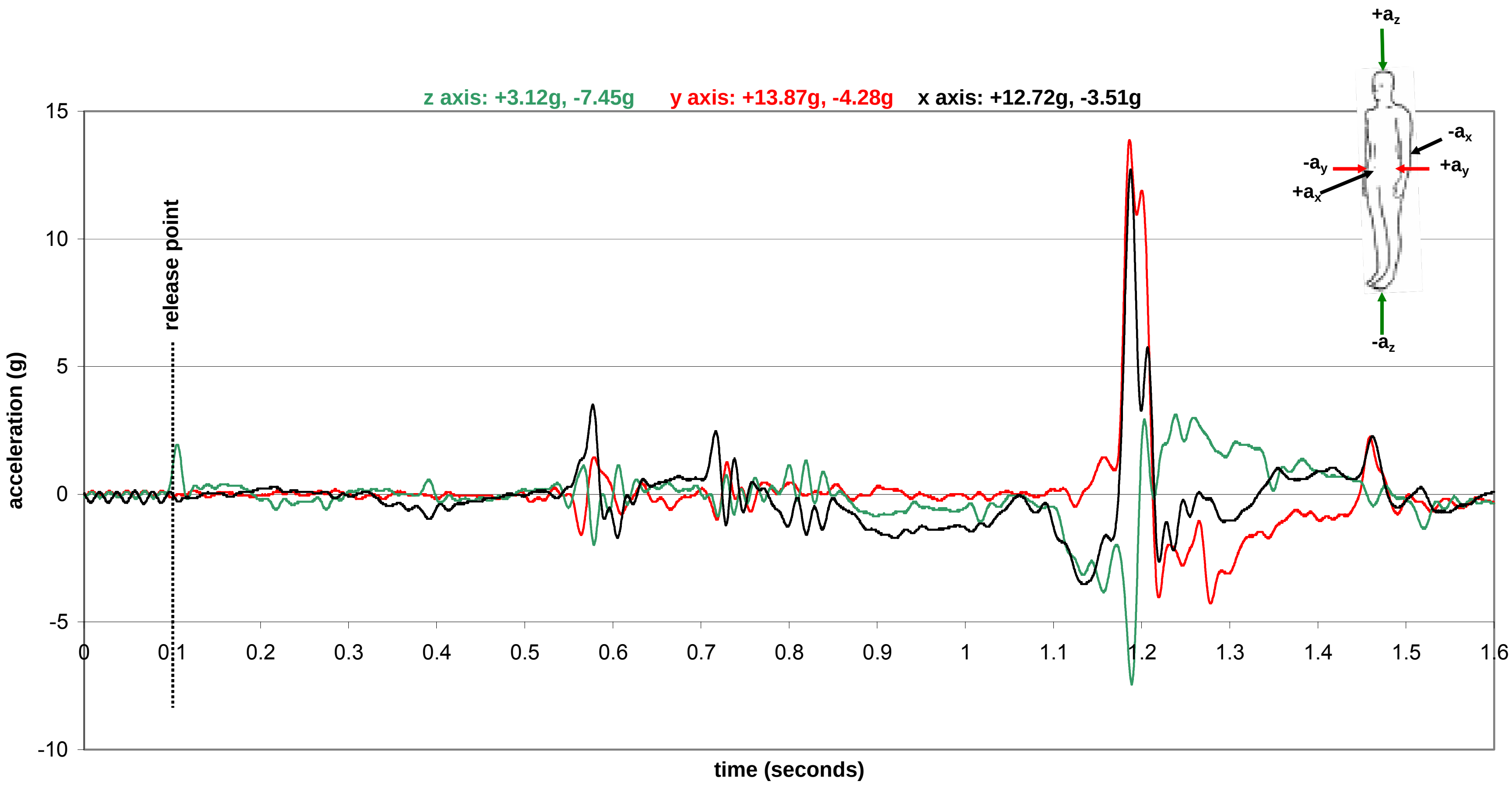


Figure 109 Tri-axial acceleration – time trace for test 13 (FAS 3)

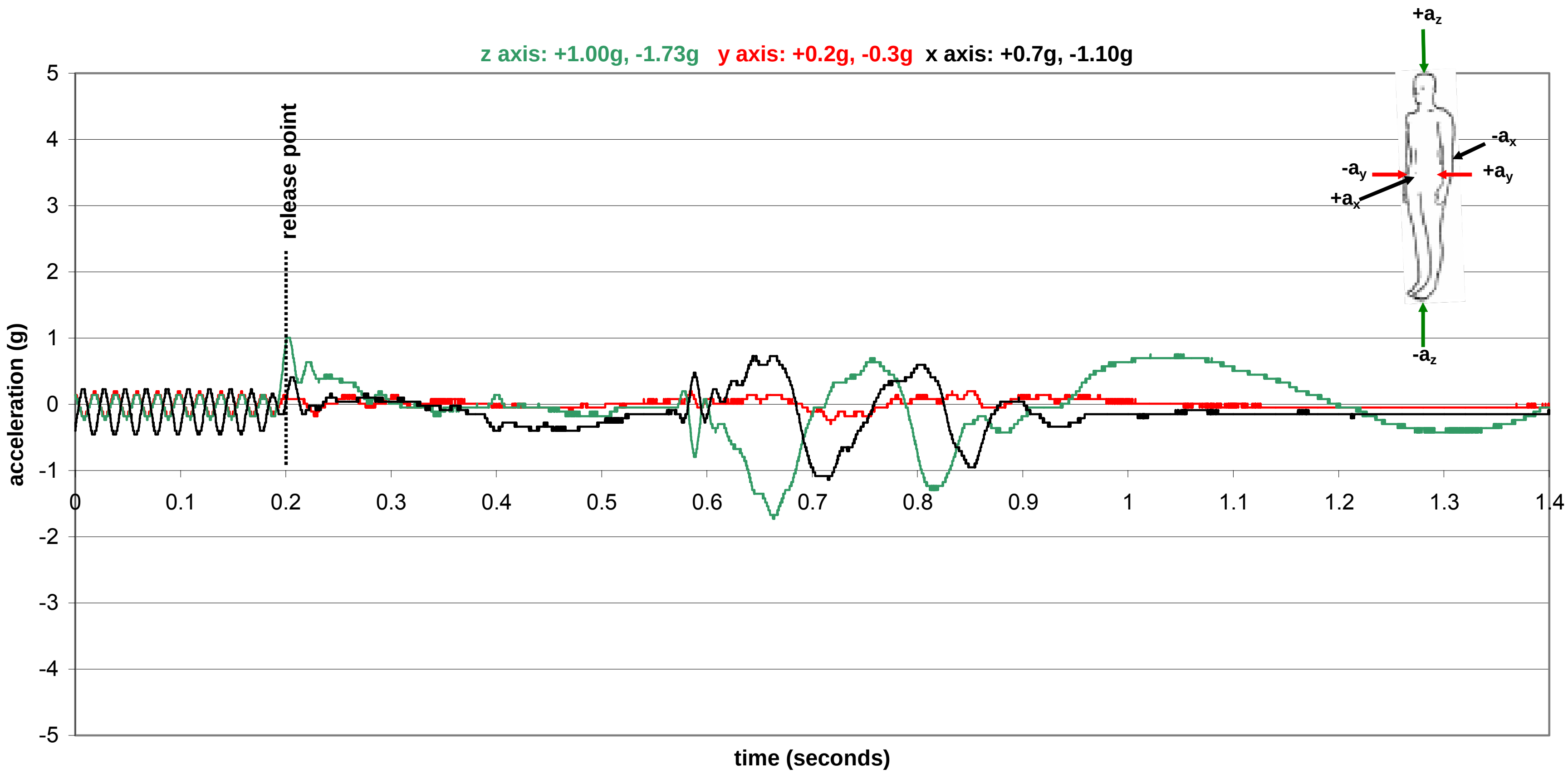


Figure 110 Tri-axial acceleration – time trace for test 14 (FAS 3)

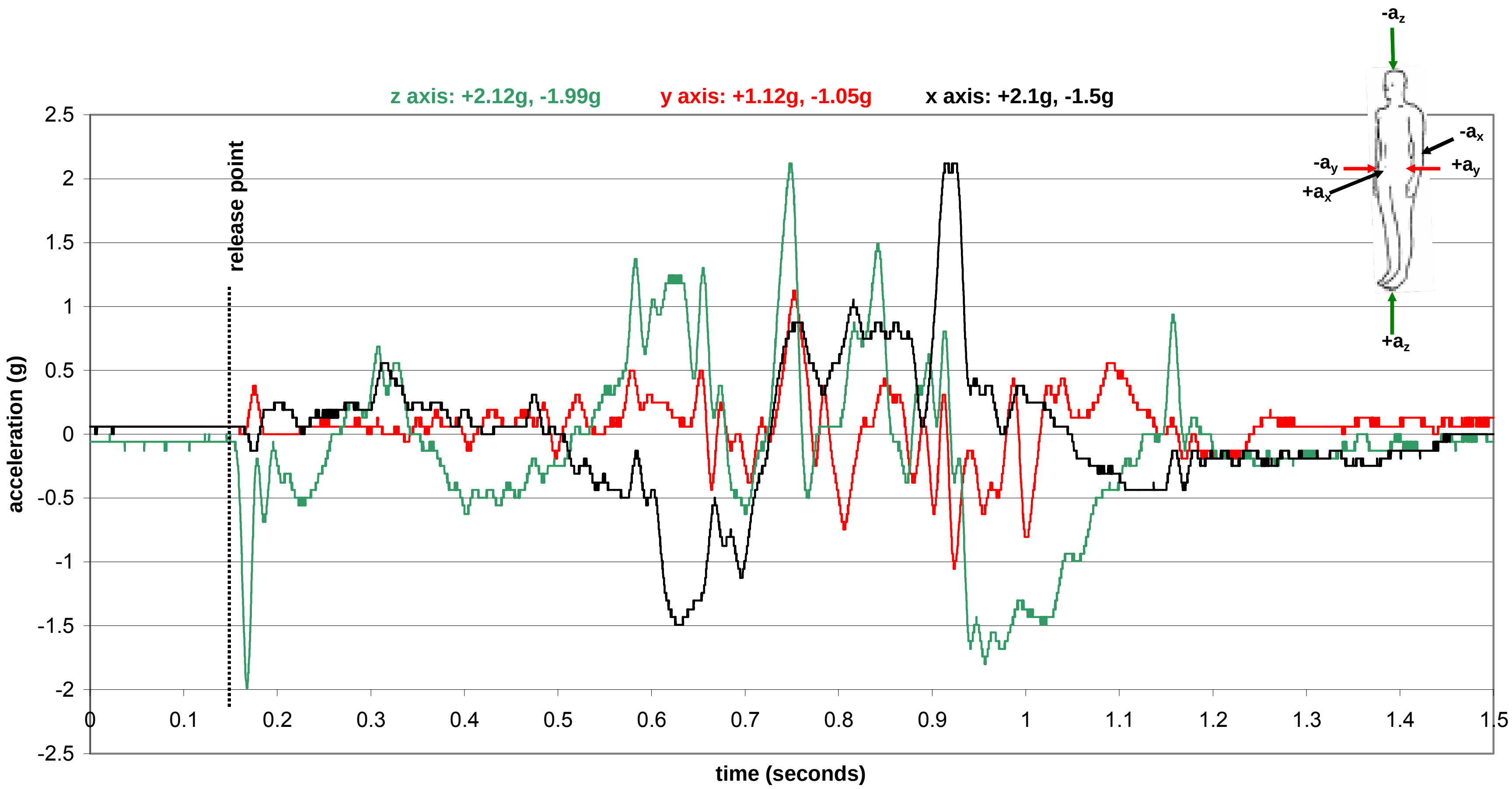


Figure 111 Tri-axial acceleration – time trace for test 15 (FAS 4)

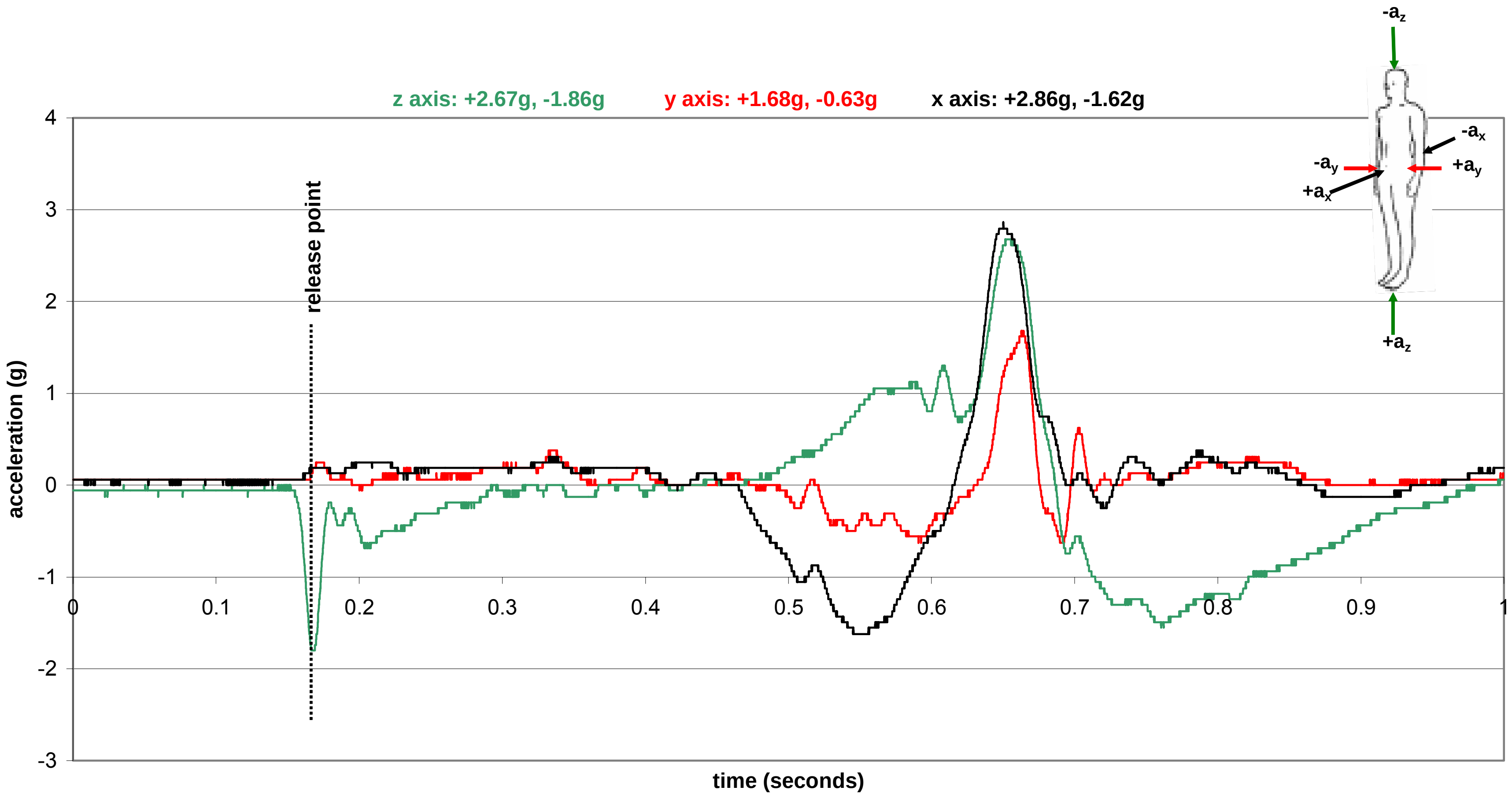


Figure 112 Tri-axial acceleration – time trace for test 16 (FAS 4)

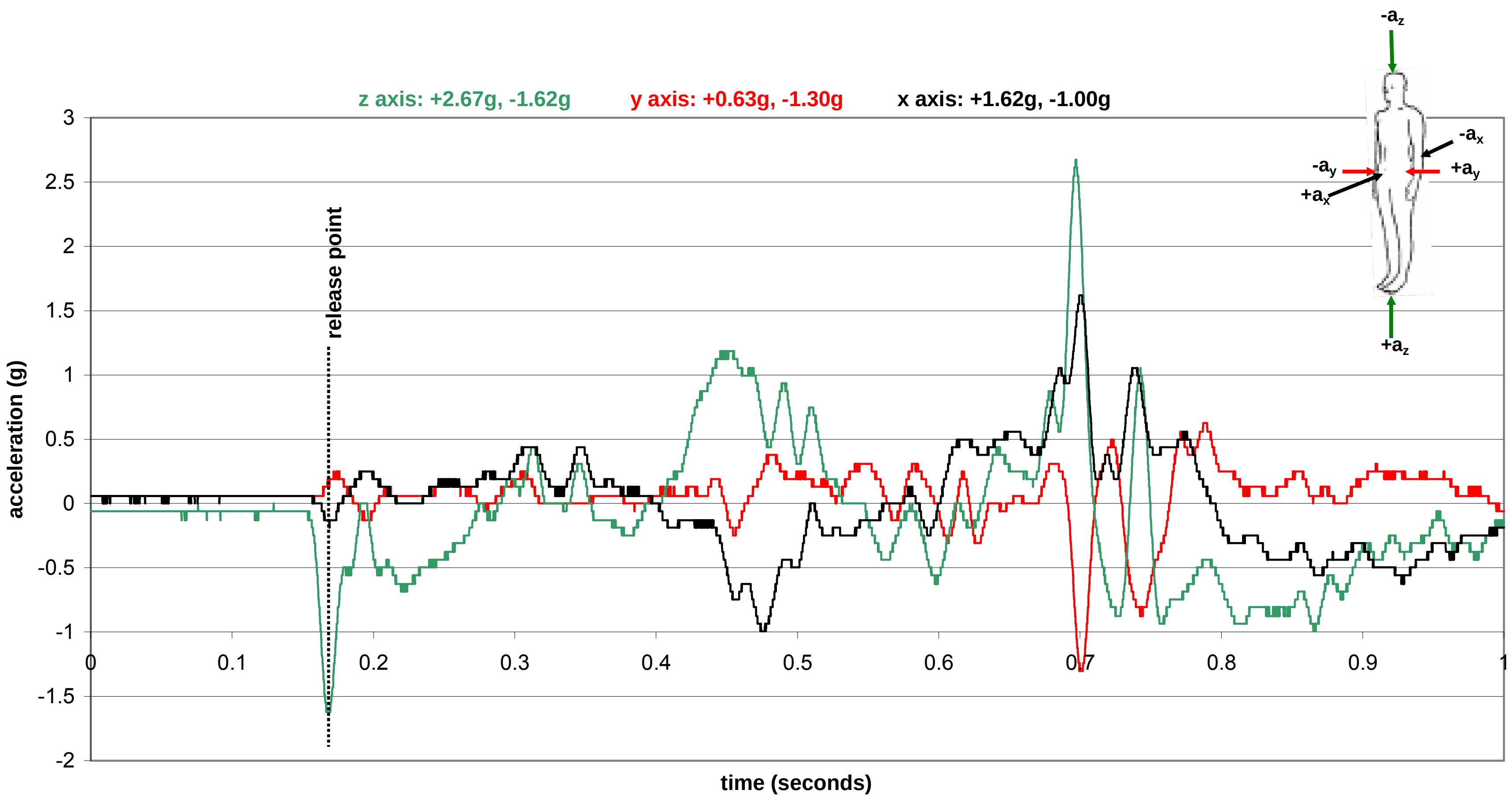


Figure 113 Tri-axial acceleration – time trace for test 17 (FAS 5)

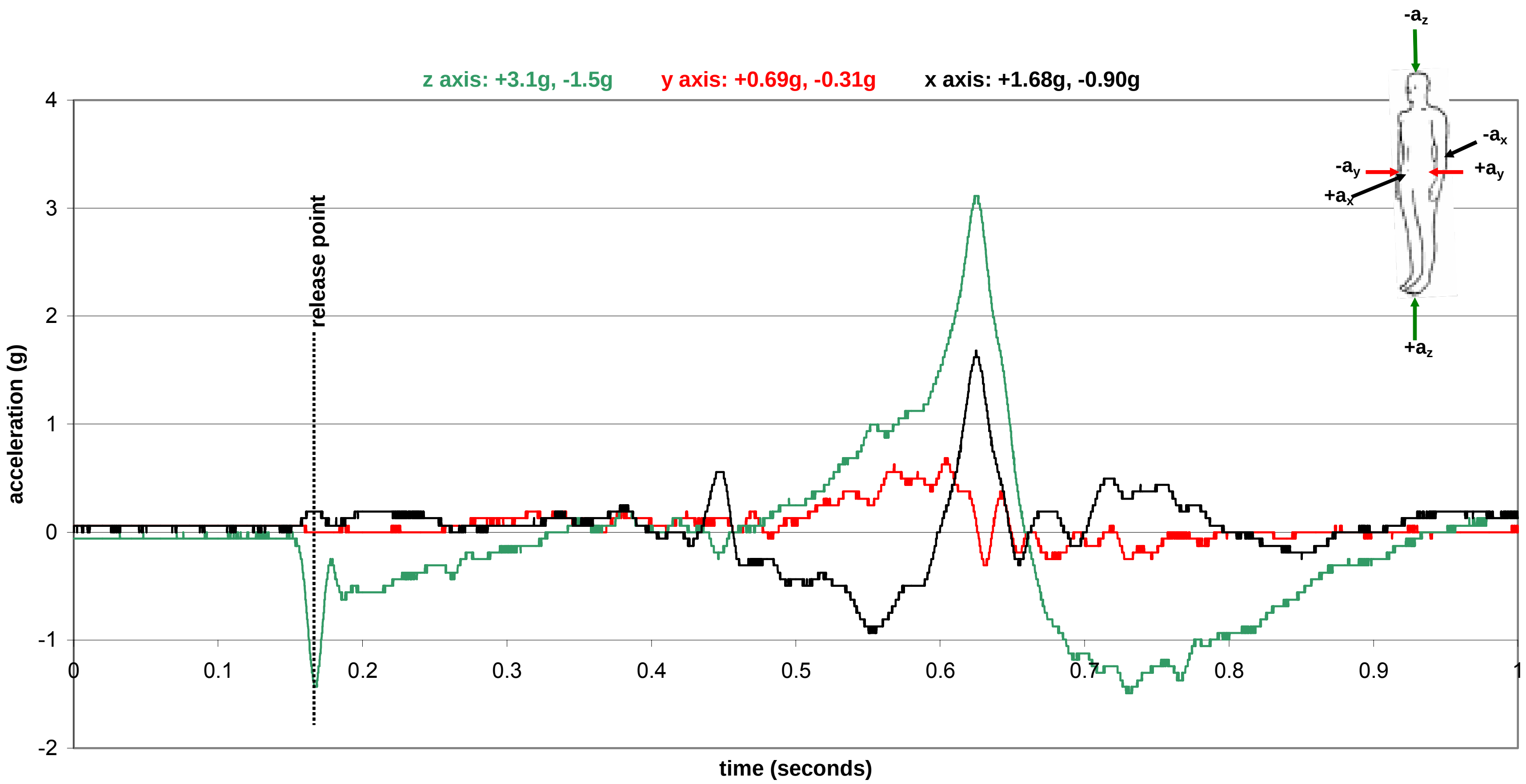


Figure 114 Tri-axial acceleration – time trace for test 18 (FAS 5)

APPENDIX 3
SIERRA STAN

General description

The following information to a large part has been taken from the ATD's documentation, Sierra (1967a), (1967b), (1967c) and (1968). A number of photographs were also taken during the checks performed as part of the test preparation, when the ATD was dismantled. These are included where appropriate.

The Sierra Stan ATD was specifically designed to meet the requirements of the American automotive industry in 1967 but also has been used extensively in all-purpose testing. The ATD is a mechanical model of the 50^{th} percentile adult man, according to the data in U.S. Department of Health, Education and Welfare (1966), and to a lesser extent in Hertzberg et al (1954). Major dimensions can be found in Figures 115 and 116. Total body and parts mass can be found in Table 8. General layout and major structure can be found in Figure 117.

The ATD was made in a semi-seated position which also allows an upright posture. The overall design represented a greater degree of sophistication than previous dummies at the time, the three major advancements including:

- A hip bone structure for lap belt testing
- A highly refined collar bone (clavicle) and shoulder blade (scapula) for shoulder harness testing (Figure 121)
- A chest load deflection device for shoulder harness testing.

Flesh contour and resiliency

The entire skeletal structure is enclosed by polyurethane foam of approximately 50 kg/m^3 density, and a vinyl plastisol skin. The foam and vinyl approximates to the resiliency of human flesh while giving maximum resistance to tearing and puncturing. Access to the internals is via a zip system in the skin.

Joint motion

All the important joint movements of the human body are duplicated in the ATD. Particular attention has been given to torso movements to allow maximum articulation. The lumbar, (lower back), a portion of the thoracic, (chest), and the cervical (neck) spine have a full range of motion to allow a realistic jackknifing attitude during test accelerations, (Figures 118, 120 and 121). The shoulder is fully articulated. See Table 9 for range of motions.

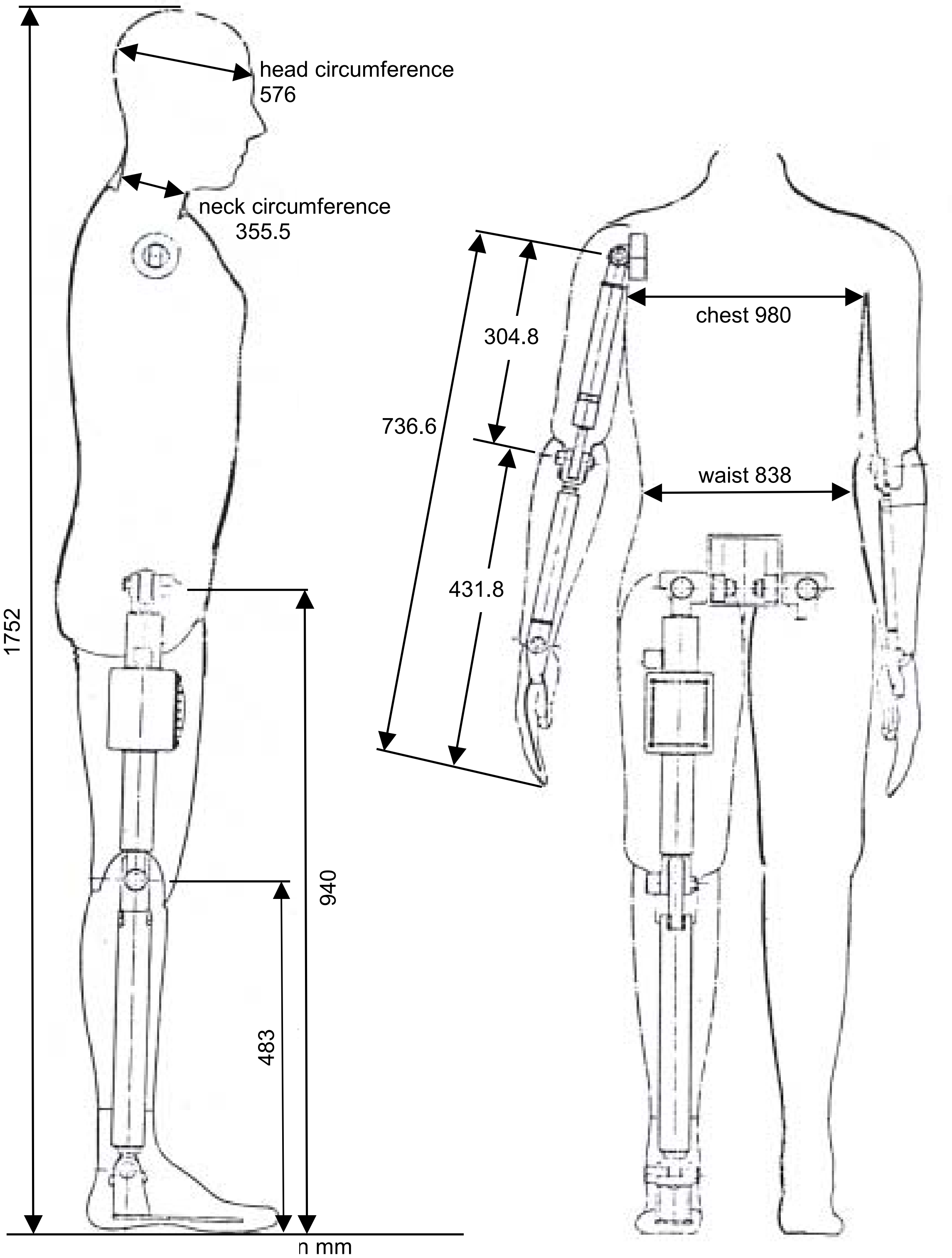
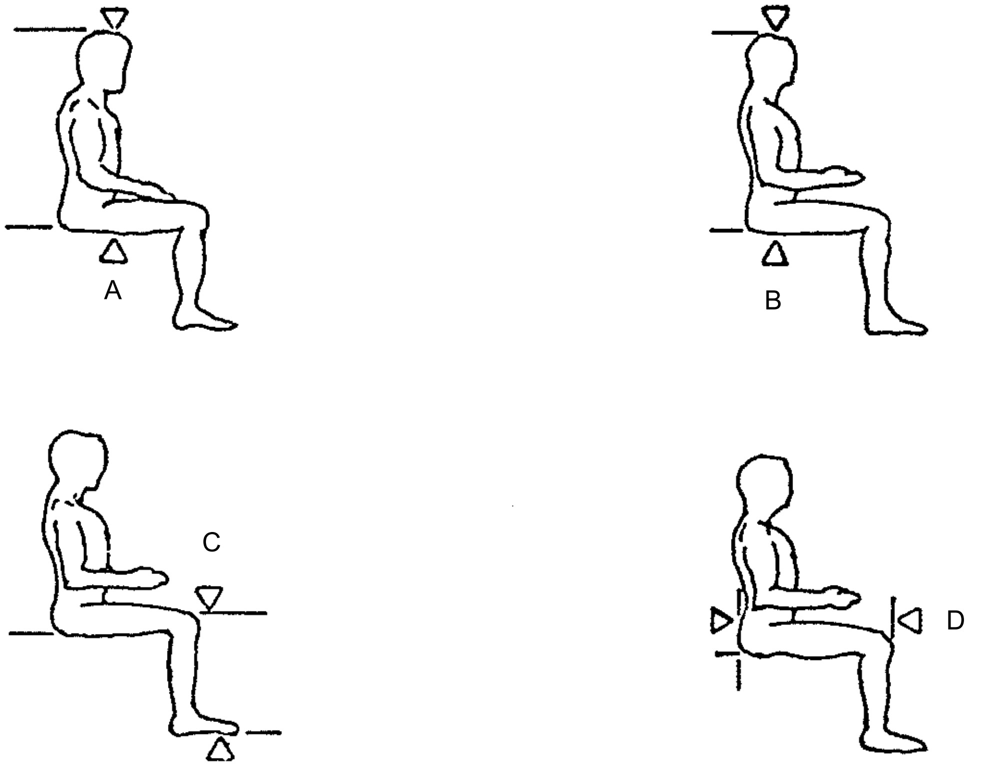

head circumference
576
neck circumference
355.5
1752
940
483
n mm
304.8
736.6
431.8
chest 980
waist 838

Figure 115 Sierra Stan's major dimensions after Sierra (1967a)



Key
A = sitting height, normal 870.0 mm
B = sitting height, erect 901.7 mm
C = knee height 533.4 mm
D = buttock-knee length 597.0 mm

Figure 116 Sierra Stan's major sitting dimensions after Sierra (1967b)

Table 8
Sierra Stan ATD parts and total mass after Sierra (1967b)

Body part	***Mass (kg)***
Head	5.44
Torso	32.24*
Upper arm left	2.31
Upper arm right	2.27
Forearm left	1.50
Forearm right	1.45
Hand left	0.64
Hand right	0.64
Thigh left	8.07
Thigh right	7.98
Shank left	3.08
Shank right	3.12
Foot left	1.18
Foot right	1.09
Total assembly	71.00

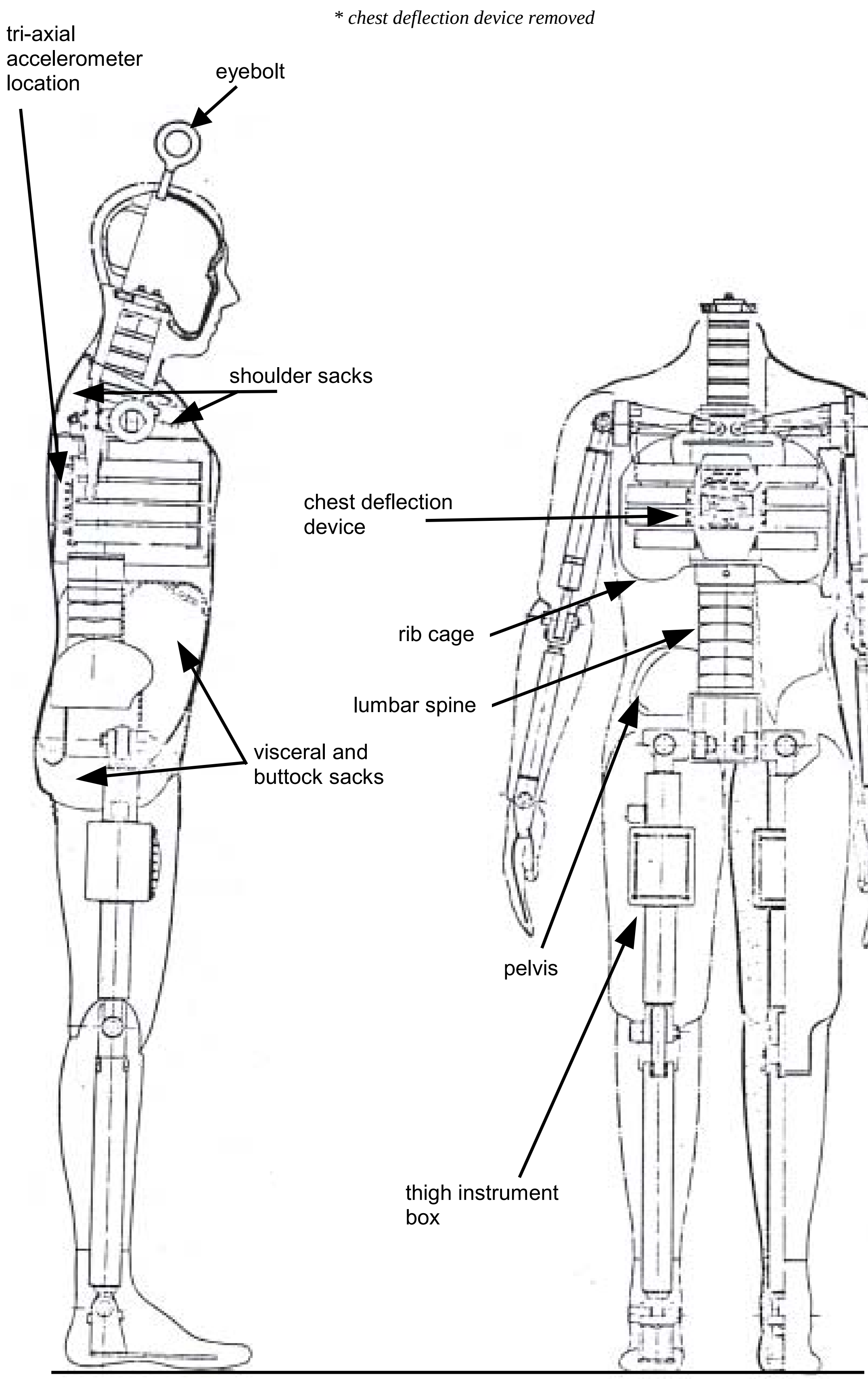


Figure 117 Sierra Stan's general layout after Sierra (1976a)

Table 9
Sierra Stan ATD range of joint motion after Sierra (1967a)

Joint or member moved	*Type of motion*	*Range of motion*
Head (relative to trunk)	Ventriflexion (forward)	60°
	Dorsiflexion (aft)	60°
	Lateroflexion (side to side)	60°
	Rotation	70°
Arm (at shoulder)	Flexion (forward)	180°
	Extension (aft)	60°
	Abduction (up)	135°
	Rotation	90°
	Adduction	15°
Forearm at Elbow	Flexion	145°
	Rotation	90°
Hand (at wrist)	Flexion (palmar)	90°
	Extension (dorsal)	90°
Thigh (at hips)	Flexion (forward)	145°
	Extension (aft)	45°
	Abduction (side)	70°
	Rotation (thigh)	50°
	Adduction	20°
Leg (at knee)	Flexion	135°
Foot (at ankle)	Plantiflexion	30°
	Dorsiflexion	75°
	Lateral (either side)	15°
Shoulder (with respect to torso)	Rotation	40°
	Extension	16 mm
	Retraction	16 mm
Thorax, with respect to pelvis (in lumbar area)	Rotation (to either side)	50°
	Forward bend	60°
	Backward bend	30°
	Lateral (to either side)	55°

Notes:
Flexion – bending or making of angle
Extension – stretching out or straightening
Abduction – moving away from middle of body
Adduction – moving towards middle of body
Rotation – turning or revolving about a long axis
Ventri - front
Dorsi- back

Muscle tone simulation

The joints of all limbs, hip and parts of the shoulder mechanism, are provided with fibre friction washers to allow adjustable resistance of members under acceleration, simulating the effects of muscle tone. The joints have Allen head type bolt adjustments which remain as set under repeated movement of the joint

The ball and socket neck assembly is human like in response and each vertebra is friction adjustable, (Figure 121). The lower thoracic and lumbar spine uses nested discs to model the spinal vertebrae which is adjusted by a spinal cable and spring (Figure 118). The entire articulation of the spinal column is combined.

Instrument provision

Space is provided for in the head, chest, pelvis and thigh for instrumentation. The thorax is sufficiently rigid to provide mounts for instrumentation, including a chest deflection device. This records shoulder strap load against chest deflection.

In the present research this device was removed, and a tri-axial accelerometer was secured to a plate which was firmly bolted to the back of the thorax. The accelerometer protruded into the cavity left by the removal of the chest deflection device (Figure 119).

Strength and construction

The ATD is extremely rugged in all details of construction. The general construction withstands test loads up to 100g disruptive force.

The rib cage structure is of reinforced plastic to allow deflection and the steel ribs and sternum plate act as a framework for the surrounding flesh and foam. The chest deflection rate is compatible with data accrued from tests made on cadavers at Wayne State University.

The shoulder girdle consists of a removable clavicle that operates through a range of articulation to simulate human movement. A spring is provided that allows the clavicle assembly to deflect inwards. The shoulder also provides a scapula for realism (Figure 121). The scapula, clavicle and pelvis may be replaced with frangible parts for realism.[66]

The skull is a life-like shape aluminium casting with a cavity for instrumentation.

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[66] *These components are designed with materials to replicate the actual physical properties of human bones. If they fracture in testing, this is a good indication that the real bones themselves would have fractured.*

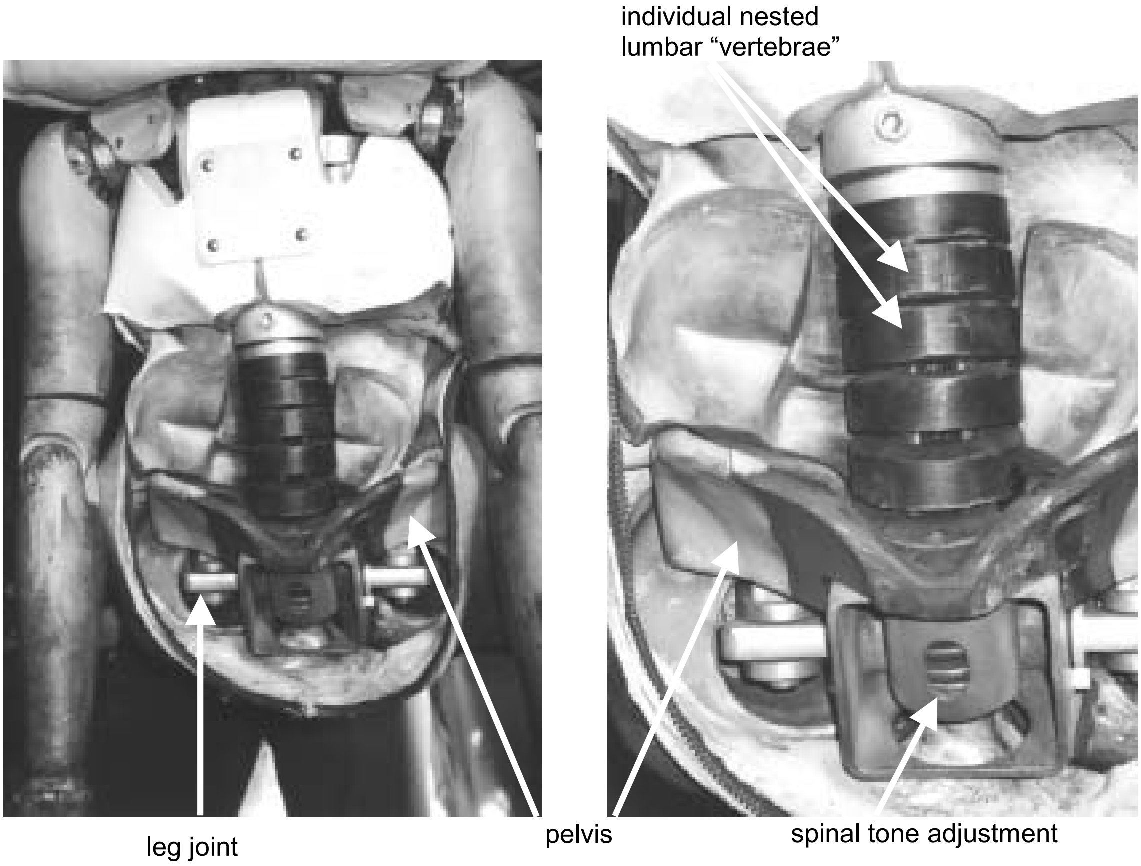

Figure 118 Two views showing articulation of lumbar spine and pelvis (legs raised)

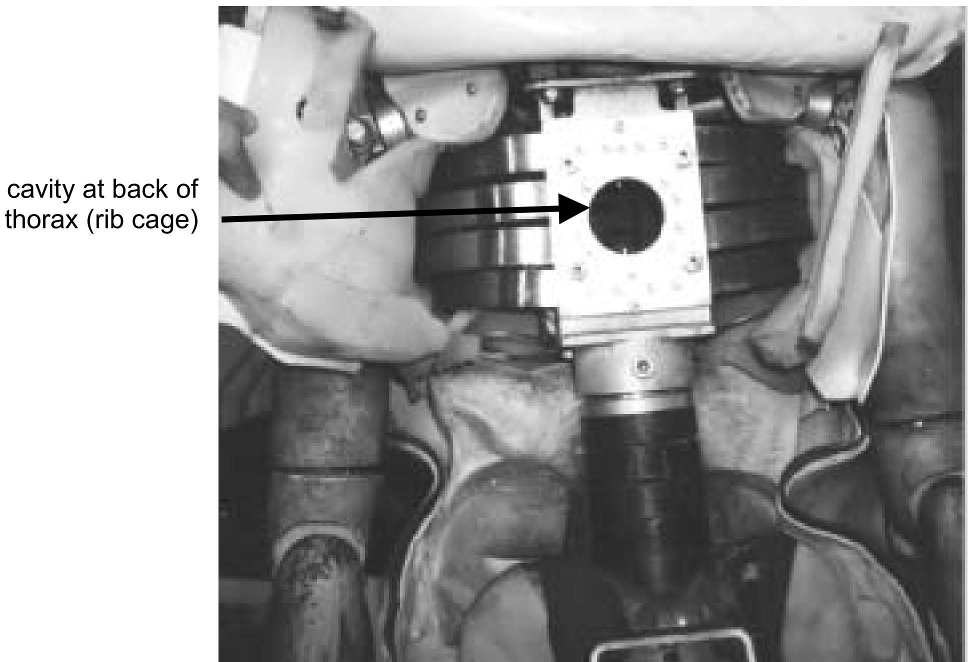

Figure 119 Tri-axial accelerometer location

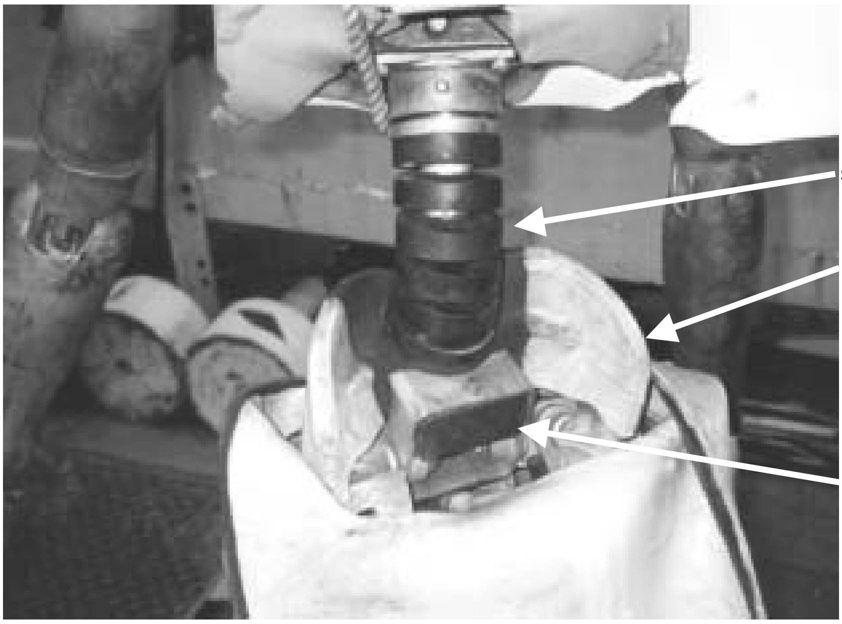

Figure 120 Articulation of lumbar spine and pelvis from front with viscera removed

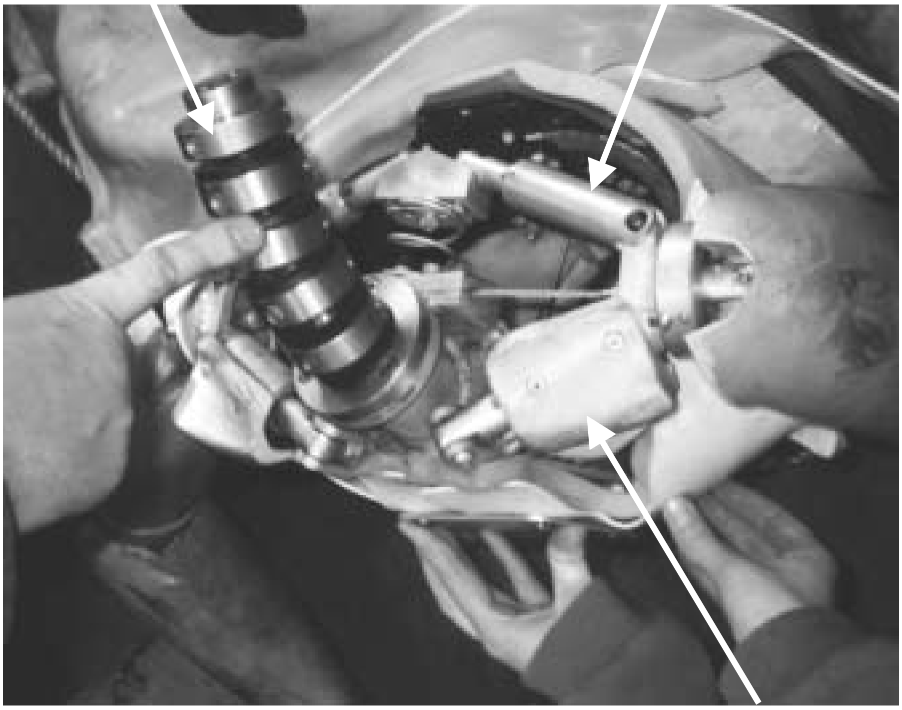

Figure 121 Articulation of cervical (neck) vertebrae and shoulder linkage detail

APPENDIX 4
ACCELERATION MEASUREMENT IN RESPECT OF THE HUMAN BODY'S NATURAL FREQUENCIES

A significant characteristic of some mechanical systems is their natural tendency to respond to a non-sinusoidal, brief force application with a sinusoidal[67] mechanical response at a fixed frequency, (e.g. a tuning fork). A system's mechanical response is called its natural or resonant frequency. If a system is subjected to sustained vibration at its natural frequency, it will respond at that frequency with increasing amplitude until mechanical failure occurs. The human body can be considered as a complex mechanical system with many resonant frequencies. These include resonant frequencies for its major structural elements, such as arms and legs, but also for other structures such as internal organs. Impacts applied to the body tend to excite all of the resonant frequencies. So it becomes important to be able to measure the dynamic response characteristics of the body and those frequencies which can cause injury, Brinkley and Raddin (1985), Sulowski and Brinkley (1991), Herbert et al (1996).

It is generally recognised through research that the frequency range of interest are all those frequencies up to and including 20 Hz, Sulowski (1995). In drop-testing, the chosen frequency range or bandwidth provides a force- or acceleration-time trace containing all events occurring at these frequencies. For this research a frequency bandwidth of 60 Hz was used, which is that used in the harmonised European test standard EN 364 (1992) for testing fall-arrest equipment. This represents a bandwidth three times greater than the 20 Hz band, to ensure that any relevant signal is not missed when measuring the arrest force or acceleration. In the 60 Hz case, this means that all frequencies from 0 to 60 Hz are measured. It should be noted however that different frequency bands are used worldwide, due to varying opinion and interpretation of medical data and human dynamic response investigation. In Canada and the U.S.A. a factor of safety of 5 has been applied to the 20 Hz frequency, so a frequency bandwidth of 100 Hz has been set, CSA-Z59.11-M92 (1992) and ANSI Z359.1 (1992). This means that all frequencies from 0 to 100 Hz are measured. In the UK, a bandwidth of 30 Hz is sometimes used, Hunter (2004).

The upper cut-off frequency heavily determines the peak amplitudes and phase change of the force- or acceleration-time trace. A test using 100 Hz may exhibit greater forces or accelerations than when using a 60 Hz filter, even if the tests are identical.

In order to demonstrate this effect, the acceleration time traces for test Nos 4 and 13 were selected for digital re-filtering at different cut-off frequencies in Excel software using Fourier transform techniques. The graphs in Figures 122 and 123 illustrate how some of the higher frequency peaks decrease in amplitude and smoothen out whilst lower frequency peaks become more prominent.

The graph in Figure 122 shows the peak acceleration in test No 4 for the z axis only, reducing and changing phase as the filter level decreases. At 60 Hz the peak acceleration is -23.42g deceasing to -17.4g at 44 Hz, to -8.13g at 29.3 Hz and to 1.54g at 9.8 Hz. Filtering at 9.8 Hz is too slow to measure any of the transients in the overall main event.

[67] *Having a magnitude that varies as a sine curve. Vibration is a typical example of a sinusoidal mechanical response.*

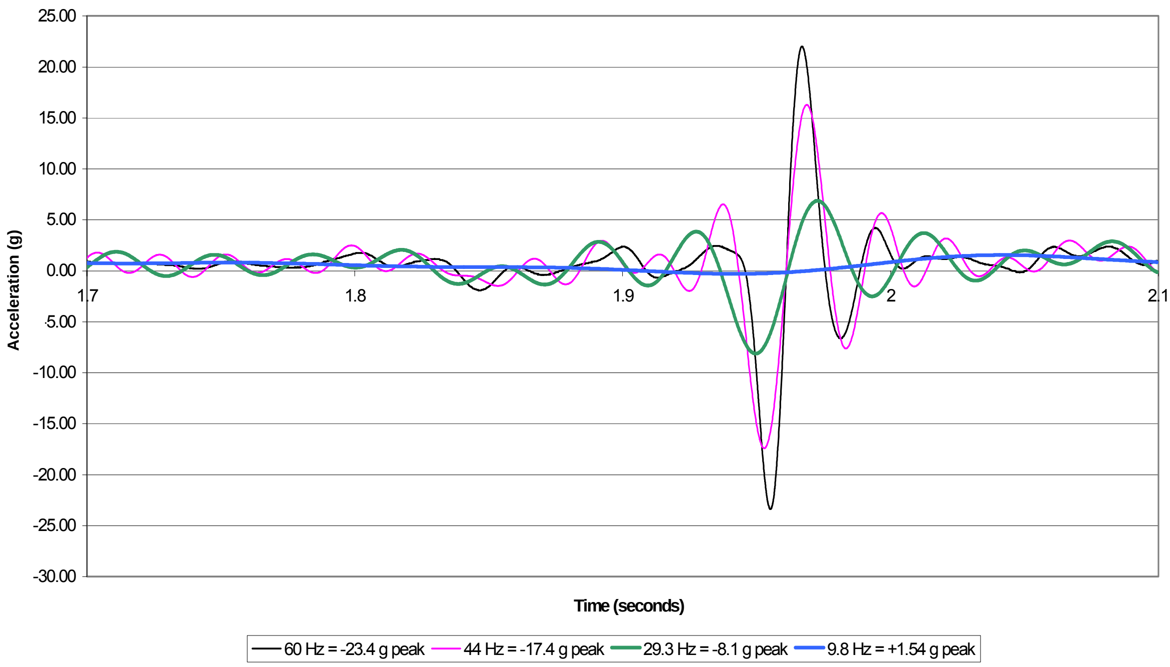

Figure 122 Acceleration – time trace for test 4 (z axis only) filtered at different frequencies

The graph in Figure 123 (below) shows the peak acceleration in test No 13 for the x axis only. Re-filtering test No 13 gives peak acceleration measurements of 12.7g at 60 Hz, 11.3g at 44 Hz, 9.36g at 29.3 Hz and 3.54g at 9.8 Hz.

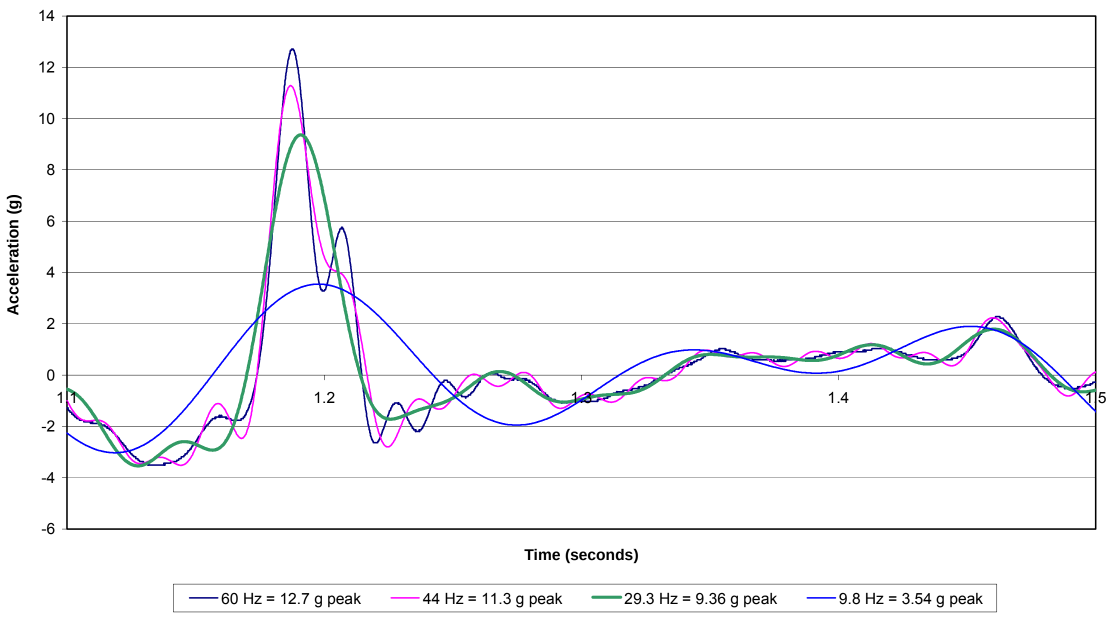

Figure 123 Acceleration – time trace for test 13 (x axis only) filtered at different frequencies

Although the peak acceleration reduces in amplitude, the change in phase during the smoothening out effect can increase the time duration spent above certain thresholds. This can be seen using the 29.3 Hz filter, whereby peak acceleration decreases but the ATD is subjected to a deceleration above 6g for a longer period of time than that measured when the 60 Hz or 44 Hz filters were used.

The cut-off frequencies selected can significantly change the outcome of test results. The selection of the frequency should be reviewed in future work to ensure that the current 60 Hz figure is still appropriate and to investigate / recommend other alternatives as appropriate.

APPENDIX 5
NETHERLANDS SAFETY WARNING IN RESPECT OF EN 353-1

Warning for the use of EN 353 products

Guided type fall arresters with a fixed or flexible anchorage line

A recent accident of a window cleaner using a EN 353-1 product showed that the application of this standard may be dissuaded in certain special circumstances when the safety of the user is not fully covered.

This is the case when a vertical steel wire or rail system is being applied as a fall arrest system on a ladder, and when a ladder is equipped with an integrated rail system or stick ladder.

The standards have always been drawn up from the position that the user goes up and that the ladder starts safely at the ground, or on a stable platform. This is not always the case, for example:

- Rail system attached on a permanent suspension ladder for window cleaning and surface maintenance

- Steel wire / rail systems on ladders that start from some point above the ground for other safety reasons (unauthorized access prevention) This is the case with advertising and communication masts, electricity pylons, etc.

The bottom stop of abovementioned systems has not been calculated, and is not tested for forces that occur during a fall. A fall just above the bottom stop, which is not being blocked for various reasons, can run through the bottom stop, resulting in a derailing of the guided fall arrester and the fall of the user as a consequence.

Therefore, before use, the safety and stability of the basis of a ladder combined with fall arrest systems must be assessed. The safety may be expected when a *platform, roof surface, where the rail / steel wire starts, and which has a size that is sufficiently stable when a user, in case he comes loose from the rail / steel wire, can under no circumstance fall any further than the mentioned platform or roof surface.*

The use of vertical fall arrest systems in conformity with EN 353-1 and EN 353-2, which do not start at a safe and stable basis, the following additional requirements are essential:

1) Rail/steel wire must continue until the surface of a sound and stable platform. This must not give way if the user falls onto the platform from a limited height (impact force ca. 6 kN);
The space between the platform and the start of the rail/steel wire must be restrained to a minimum (max. ca. 100 mm).

2) At the access to the rail/steel wire, a clear warning must be affixed stating that the fall arrest system is not intended to be used for stabilizing or positioning whilst performing other tasks. These systems are solely intended as a safeguarding of the vertical access to a work place, unless if stated otherwise by the manufacturer of the equipment. For stabilizing and positioning, a separate lanyard or hook is required.

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