CI/SfB | | 08 | (J4)
Date August 1992

BRANZ

STUDY REPORT

NO. 41 (1992)

BEHAVIOUR OF ANNEALED GLASS UNDER SIMULATED HUMAN IMPACT

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The work reported here was jointly funded by the Building Research Levy, and the Foundation for Research, Science and Technology from the Public Good Science Fund

ISSN: 0113-3675

PREFACE

This study forms the first phase of an investigation undertaken by BRANZ into the impact behaviour of glass, to prepare suitable design information relating to accidental human impacts.

ACKNOWLEDGEMENTS

The authors thank Smith and Smith Glass for assistance in supplying glass, and Comalco, CHH Aluminium and Thermosash Aluminium for assistance in the supply of framing elements.

AUDIENCE

This report is intended for architects, design engineers, glass manufacturers, code writers, and other workers in the field of glass and structural engineering research.

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BRANZ Study Report SR 41 K.Y.S. Lim, A.B. King and S.J. Thurston

REFERENCE

Lim, K.Y.S; King, A.B. and Thurston S.J. 1992. Behaviour of Annealed Glass Under Simulated Human Impact. Building Research Association of New Zealand Study Report SR 41, Judgeford, New Zealand.

KEYWORDS

From the Construction Industry Thesaurus - BRANZ edition:
Annealed; Glass; Human Impact; Impact; Impact Loads; Impact Energy; Soft Body Testing.

ABSTRACT

The safety of building occupants when glass fails under accidental human impact is of great concern. This report investigates the effects of glass thickness, pane geometry and size, and the glass supporting frame, on the impact resistance of annealed glass. A soft body impact test specified in ISO 7892 (International Standards Organisation (ISO), 1988) was found to be suitable for simulating accidental human impact on glass.

The test results indicate that resistance to soft body impact is dependent primarily on glass thickness. Impact resistance did not appear to be a function of pane area. There were correlations between increased impact resistance and both reduced aspect ratio and reduced glass width. There was a strong correlation between glass deflection relative to the mullions and glass thickness at failure. Glass deflection was a linear function of the square root of impact energy whereas mullion deflection varied directly with impact energy.

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BEHAVIOUR OF ANNEALED GLASS UNDER SIMULATED HUMAN IMPACT

1.0 BACKGROUND

In response to public concern about the safety of building occupants in both domestic and high-rise buildings with glass facades, the Building Research Association of New Zealand (BRANZ) undertook a research programme to assess the behaviour of glass when subjected to accidental human impact. An information bulletin "Human impact on glass in high-rise buildings" (BRANZ Bulletin No. 270, 1990) was published. Codes surveyed during preparation of this bulletin revealed that emphasis is placed on designing glass and glazing systems to accommodate wind load, although designing for wind loads alone will generally provide insufficient protection against human impact. Interim guidelines and measures for reducing risks of accidental human impacts were recommended in the bulletin.

Safety glass (for use in hazardous locations) both in New Zealand and Australia is tested currently in accordance with AS 2208 (Standards Association of Australia (SAA), 1978). This standard specifies the size of pane to be tested (1900 mm x 860 mm), as well as the installation details. It does not require glass panes to be tested to destruction, although this is commonly carried out. It has not been possible to access glass manufacturers' test results, thus details of impact resistance and failure modes of glass panes that have been tested are not available. A local glass manufacturer supplied BRANZ with values of the impact strength of glass, derived from calculations using the "Modulus of Rupture" value obtained from wind face-load tests. Other assumptions made in deriving energy values included using simple bending theory on a simply supported span of 860 mm, and a person weighing 84 kg falling from a vertical height of 1.0 m. Interim impact strength values were included in Bulletin No. 270, with warnings about extrapolating pane sizes beyond those specified in AS 2208.

The literature survey and discussions with glass suppliers carried out during the preparation of the bulletin also revealed that there is little information on the effect of pane shape and size, installation details, glass type or thickness on the impact resistance of such glazing systems. Pane shape and size may be crucial because pane sizes greater than that specified in AS 2208 cannot be rated by extrapolation. Installation details are significant because the energy input to the system in an impact is shared between the glass and the support frame in an indeterminate manner; (Nilsson, 1976; Thorogood, 1978). Panel rigidity is in turn dependent on the rigidity of supporting framing members (Wade, 1990).

2.0 LITERATURE SURVEY

2.1 Types of Human Impacts on Glass

A survey of data on accidental human impacts on glass provided by the Accident Compensation Corporation of New Zealand (ACC), for the year from April 1989 to March 1990, revealed that 67% of such accidents (total number of 1070) occurred in the home. A further 10% occurred in commercial or service locations, with another 9% occurring in an industrial environment. Accidental human impacts on glass also occurred in schools, at recreation or sport places (4% each), and at other locations.

Nilsson (1976) and Toakley (1977) claimed that the injuries sustained through human impact with glass doors, panels and windows glazed with ordinary annealed glass, can be minimised by the use of safety glazing material such as toughened glass. Nilsson further added that in exterior locations, annealed glass is often more expensive to maintain than toughened glass.

A wide and varied range of activities cause human impact loads on glass. Some of the more frequent are:

(a) walking or running into glass;

(b) falling against glass, warding off with hands in the forward direction, or falling backwards;

(c) tripping, stumbling, slipping or skidding;

(d) kicking with foot (forward or backward), or knee;

(e) shouldering or elbowing;

(f) being thrown against glass: by people (while fighting); from object coming loose or from collision with object;

(g) leaning backwards against glass, or leaning chair backwards against glass. (Refer to Figure 1 for examples).

2.2 Simulation of Human Impact on Glass

Tests simulating human impact on glass should model the following human motion parameters.

For soft body impact (e.g. from a shoulder impact), the energy dissipated from the impact can be modelled by converting the potential energy of the test impactor into kinetic energy of the action. An example would be to vertically drop the test impactor from a certain height onto a horizontally mounted test specimen. Alternatively, a vertically hung test impactor could swing from a certain height to impact upon a vertically installed specimen. When modelling hard body impacts (such as a kick or a punch), Leicester and Datong (1991) claimed that the impact loading is transferred to the glass through absorption of impactor momentum and not of impactor energy.

The area of impact, which can be difficult to determine, also needs to be modelled. Consider the impact of a shoulder on a rigid pane of glass; the initial impact is transferred through the soft flesh around the shoulder and as the impact proceeds the harder "core" of the shoulder begins to act on the glass. Impact area increases as the flesh flattens but the load becomes more concentrated towards the end of the impact, i.e., the panel stiffness also increases at the end of the impact. The slope of the load-deflection graph is therefore non-linear.

In impacts from a hand, foot or more rigid part of the body, the impact area and mechanism of energy transferred would be different from that described for a shoulder impact on a flexible glass pane. During impact of a rigid body, impact area would remain almost constant throughout the impact, with impact energy being absorbed through deformation of the glass pane. To model soft bodies, bags filled with dry sand, small glass spheres or lead shot, are often used as test impactors as described below (section 2.2.2). To model effects such as a kick or punch, a much stiffer medium with a constant impact area is required (refer section 2.2.1).

Finally, the force-time relationship (impulse) of the impact needs to be considered. This varies with the type of impact, the stiffness of the material and its support, and the stiffness of the impactor. To model the true force-time relationship of an impact, shock absorbers have been specified in the test methods (Nilsson, 1976; 1980).

Thorogood (1978) stated that different impact test results are obtained by different researchers because various shape bags and contents are used. In addition, even when the bag and contents are specified, the specification is normally insufficient to allow satisfactory replication. The problem is particularly severe for sand filled bags since the proportion of energy transferred to the test pane is dependent on the extent to which the sand is compacted in the bag before impact. Although repeatability increases with reshaping the bag after each test, Thorogood maintained that different operators would achieve different results.

2.2.1 Concentrated soft body impact test

Nilsson (1976) conducted experimental tests on glass and other materials to determine the characteristics of human impacts, enabling standard test methods to be developed. Different types of human impact typical of those described in section 2.1 were conducted. The ratio of dynamic to static load (weight of person executing the impact), and the primary time of type (Figure 1b) of each material were measured. Values for glass alone are reproduced in Table 1. It was concluded that an increase in the rigidity of the panel tested resulted in a higher impact force, due to the reduction in the elastic impact absorption capability.

Although measured force varied for each material tested by Nilsson, it was considered that a test method modelling a particular human impact would represent the impact type being simulated, independent of the material being impacted upon. This was because people react in exactly the same way at the moment of contact for each impact type performed, independent of the material being impacted upon. This meant that the impact load (kinetic energy) would be the same for people as for the test prototype immediately before the moment of impact. They would also display the same behaviour as far as the impact surface is concerned, at the moment of impact, for all types of material being impacted upon.

Statistical analysis was used to determine a test load from the test data of human actions. In combination with modelling the contact area and the motion pattern's "primary time phase", a well defined force-time curve was obtained. Thus, the kinetic force was reproduced using a specific test model. Two test prototypes were developed, capable of reproducing human impact motions, based on the test load and the time of impact. The first method developed was a pendulum made of 60 mm diameter aluminium section, with its upper end fixed in a friction-free ball bearing suspension joint (Figure 2a). A special absorber was required to obtain a primary impact time equivalent to that obtained from the human impact motion data. The second method developed was a distributed soft body test described in section 2.2.2.

Nilsson (1980) used the above method to study the resistance of sheets of glass to simulated human impact loads. Amongst the variables studied were types of glass (annealed, laminated, toughened), older glass, presence of scratch in glass, patterned and sand blasted glass panes, size of the glass panes, and location of the impact points. It was concluded that when defects such as scratching, patterning, or sand blasting were present in the tension face of both annealed and laminated glass, there was almost zero resistance to impact loads. Toughened glass, however, behaved quite differently; defects when present reduced impact strength only slightly. Nilsson did not, however, tabulate impact resistance results in terms of energy.

Leicester et al (1991) reported an investigation which involved varying the vertical drop height of either a 63.5 mm (1.045 kg) or a 76.0 mm (1.805 kg) diameter steel ball impacting on a horizontally installed test specimen of size 600 x 600 x 3 mm thick. This impact test method simulates a human fist impacting on the specimen. Variables studied were fatigue effect of repeated impact, variability of glass impact strength, and difference in impact energy resistance from the choice of impact face. The study concluded that the glass impact energy resistance when the tin side was placed in compression, was five times that when the tin side was placed in tension. The tin side of a glass plate is the side that was in contact with the molten tin during the glass manufacturing process as opposed to the air side. Impurities were therefore present in the tin side, decreasing resistance of the glass. Also, a very large coefficient of variation of roughly 60% was observed in the impact energy resistance; both with the tension surface in the tin side as well as the air side.

2.2.2 Distributed soft body impact test

AS 2208 (Standards Association of Australia (SAA), 1978), BS 6206 (British Standards Institution (BSI), 1981) and ANSI Z97.1 (American National Standards Institute (ANSI), 1984) specify a distributed soft body impact test which sets out performance requirements for safety glazing materials for use in areas where human impact is likely. These codes both specify a pear shaped bag with a weight of 45 to 46 kg filled with lead shot (Figure 2b). They also stipulate a glass pane size of 1900 x 860 mm wide, with the glass pane being clamped to the test reaction frame using neoprene strips.

The test method was derived theoretically, on the assumption that a child weighing between 45 and 50 kg running at full speed (of 6.7 m/s) would produce kinetic energy of about 1000 J. Because of dispersion of energy at the time of impact, the codes acknowledged that test energies considerably below 1000 J would be adequate to represent the impact energy level imparted to the specimen. Three energy levels were therefore set at 135 J, 205 J and 540 J for situations ranging from a limited acceleration path, to that where acceleration is unlimited. It should be noted that not all the test energy specified is imparted to the specimen under the standard test because energy of the test impactor is also lost on impact. Toakley (1977) derived an expression whereby the amount of energy lost, and hence the amount of actual impactor energy transferred to the test specimen, could be determined. Using Toakley's method, the energy lost on impact for a 3.0 m x 1.2 m x 10 mm thick panel is calculated to be 55%. Similarly, the energy lost on impact for a 1.93 m x 0.86 m x 6 mm thick panel is 18%.

AS 2208 also sets a further energy level of 90 J for Grade B safety glazing material. This is equivalent to a child weighing 46 kg walking at a speed of 2 m/s. BRANZ Bulletin No. 270 recommends energy levels of 600 J, 425 J, and 250 J, respectively, for high, medium and low risk occupancies. These values are higher than those recommended by the above codes, and were based on a 110 kg person walking at 3.25 m/s and 2 m/s, in the high and low risk areas, respectively. BRANZ now considers that the value of 600 J recommended in Bulletin no. 270 for high risk occupancies is too high.

Two codes specifying a distributed soft body impact test for wall or vertical elements for any material are NT318 (Nordtest Method, 1987) and ISO 7892 (International Standards Organisation (ISO), 1988). Both codes specify a sphero-conical shaped bag weighing 50 kg filled with glass marbles (Figure 2c). The codes do not specify the panel size, or how the specimen is fixed to the test reaction frame. NT 318 requires that the point of impact is at the weakest area, or 1500 mm above the floor. ISO 7892 states that the large soft body impact test simulates a blow from a shoulder, and stipulates that the support points must be such that their displacements during impact is less than 0.1 mm. These standard test methods allow specimens representing "real" structures to be investigated, as there are no constraints on the pane size or the installation details. There is little difference between these two standard test methods and ISO 7892 is adopted for this experimental investigation.

ISO 7892 also specifies a small hard body impact test method for simulating impact from a fist or knee. The bag specified is a 100 mm diameter spherical bag filled with 3 kg of sand or lead shot.

Nilsson (1976) developed a test method using a 250 mm diameter sand filled cylindrical bag weighing either 30 or 40 kg, with a shock absorber. The bag was dropped vertically on a horizontally mounted element (Figure 2d). Nilsson (1980) carried out further tests on glass and other materials using a lead filled bag with specifications of ANSI Z97.1. It was concluded that this test model agreed with the test load obtained from human motion of the tests published in his 1976 publication.

Feldborg et al (1989) carried out distributed soft body comparison tests on various vertical and horizontal elements, enabling test methods for such elements to be recommended. Cylindrical, pear and sphero-conical shaped bags, filled with either sand or glass marbles, were used. Bag weight was also a variable considered. Observations indicated that a cylindrical bag produced a higher impact load than a pear shaped bag, which in turn had a higher impact load than the sphero-conical shaped bag. Moreover, the sand filled bag was stiffer than the glass marble filled bag. These results showed impact loads were a function of the stiffness of both the impact media and the glazed panes. Clearly, detailed specifications of the test method are necessary to ensure that test results from different laboratories can be compared.

Feldborg et al concluded that the time of impact of the 50 kg sphero-conical shaped glass marble filled bag represented the best fit to the recordings of Nilsson (1976, 1980). Because tests using a shock absorber are more difficult to perform, the sphero-conical shaped bag filled with glass marbles was recommended as the best test method for wall elements. Note that Feldborg et al did not carry out comparative tests between lead and glass marble filled bags, nor did they carry out comparative tests between pear and sphero-conical shaped bags filled with glass marbles, as used in tests specified in AS 2208, BS 6206 and ANSI Z97.1.

Wade (1990) conducted some soft body impact tests on an aluminium framed glass conservatory. The test method used a cylindrical impactor filled with 30 kg of sand; this was allowed to swing from a certain height to impact upon the vertically installed specimen. Results indicated that 1000 x 800 x 4 mm thick annealed glass failed at energy levels between 60 and 90 J, and the 5 mm thick panels at energy levels of between 120 and 150 J.

2.3 Analytical and Numerical Methods Determining Impact Resistance of Glass

Toakley's (1977) theoretical analysis method determined the impact resistance of glass. The model assumed that a moving mass M, with velocity V struck a stationery rectangular glass pane of dimensions (a by b), thickness (t), and mass (m) without rebounding (Figure 3a). The glass pane was assumed to be simply supported with no in-plane restraints at the edges, and the impact load was assumed to be over an area of 0.1 to 0.2 times the height and breadth of the pane. It was also assumed that after impact, the deflected shape of the pane corresponded to that resulting from static load. Examples of impact from a 45 kg body with kinetic energies of 136 J and 543 J were provided. The analysis indicated that:

(a) a large proportion of the impact energy is lost, when the mass to be impacted is large relative to the impacting mass.

(b) for a given pane thickness, the maximum stress depends significantly on the width of the panel;

(c) increasing the pane thickness reduces the maximum stress, almost linearly;

(d) for given pane dimensions and thickness, the maximum stress is proportional to the square root of the impact energy;

On the assumption of a glass breaking strength of 41.4 Mpa for a 0.1 second duration load, then Toakley's calculations indicated that annealed glass (both 6 and 10 mm) was potentially hazardous under an impact of 543 J. Toakley also stated that the stresses were sensitive to the loaded area, but the deflection was not.

Nilsson (1980) noted that design methods involving human impacts should consider both the probability of occurrence of the incident, as well as the probability of failure of the material being impacted upon. He noted that glass is a difficult material because the presence of flaws causes a significant reduction in its strength.

The number of claims paid by the Accident Compensation Corporation of New Zealand can be used to estimate a probability of injuries from accidental impact on glass. The number of claims of injuries from accidental glass impact in the year April 1989 to March 1990 was 1070. Therefore the probability of injuries (involving claims) is 1070 out of 3.5 million population = 30×10^{-5}. This value is not dissimilar from those mentioned by Toakley namely, 71×10^{-5} in the United Kingdom; 42×10^{-5} in Canada; 70×10^{-5} in Australia, and 90×10^{-5} in the United States.

Leicester and Datong (1991) conducted extensive numerical studies to examine the provisions of the Australian glass installation code, AS 1288 (SAA, 1979) in which the required glass thickness increases with increase in pane area. Further, the studies aimed to determine if (1) standard impact tests such as specified in AS 2208 (SAA, 1978) usefully model human impact and (2) if the standard tests correctly model prototype behaviour. An approximate method was developed for solving the non-linear lumped-mass model assumed in Leicester and Datong's studies (Figure 3b). Parametric studies were carried out on the effects of loaded areas on circular and rectangular plates, load location, plate area (aspect ratio) and thickness of glass, etc. The results were:

(a) there is no evidence that thicker glass is required for larger pane areas to resist human impact, as required in AS 1288;

(b) the impact loading of hard body impact was transferred to the glass through absorption of impact momentum. In soft body impact, the impact loading was usually transferred to the glass through absorption of impact energy;

(c) soft body impact tests are very sensitive to impactor stiffness, whereas hard body impact tests are very sensitive to variations in impactor mass and support stiffness. Thus these parameters must be correctly selected for a standard impact test to correctly simulate human impact events;

(d) a glass panel would have less resistance to an impact load if it is impacted near a corner than if it is impacted at the centre;

(e) the size of the loaded area has a minor influence on impact resistance:

3.0 EXPERIMENTAL PROGRAMME

A limited experimental programme was undertaken on annealed glass to determine the effects of the following parameters on its impact resistance, when subjected to soft body impact:

(a) glass thickness: 3 mm, 4 mm, 5 mm 6 mm, 8 mm or 10 mm. The 6 mm, 8 mm and 10 mm glass were float glass; the rest were sheet glass;

(b) glass geometry and size: square and rectangular panes of various aspect ratios;

(c) glass framing members: typical of those in multi-storey and in residential buildings.

Table 2 shows specimen dimensions and type of framing members studied. Five specimens of each category were tested.

3.1 Test Set-up and Instrumentation

The experimental work was conducted at the BRANZ Structural Engineering Laboratory between October 1990 and March 1991.

The test frame consisted of two vertical channel members (200 x 76 Channel) bolted to a 100 x 100 x 10 angle base member, which was in turn bolted to a strong floor. The channels were braced in two orthogonal directions by 100 x 100 x 10 mm structural steel angle members. One end of these angle members was bolted at to a base member. In the direction of impact, 100 x 100 x 10 angle members braced the main vertical channel member at a height of 2.5 m. In the other direction, a similar sized angle member was used to provide rigidity at a height of 1.5 m to the channel member (Figure 4a). The rig was designed to accommodate different glass width by moving the vertical channel members inwards or outwards.

A 150 Universal Beam was bolted to the top of the channel members so the test impactor could be suspended. The impact energy level was determined from the product of the impactor weight (50 kg) and the vertical drop height. At each energy level, the impactor was set to the required height by using a crane to lift it, in conjunction with a "pulley" system. The impactor was released by using a rope set-up with a quick-release mechanism (Figure 4b).

To simulate glazing systems in multi-storey buildings, aluminium mullions and transoms of grade B6063-T5 and B6063-T6 alloy (AS 1664 SAA, 1979), respectively, were used. The 3.8 m high mullions were bolted at their ends to the vertical channel members at its ends (Figures 5a, 5b), and spaced at the width of glass to be investigated. The top and bottom channel simulates two floor levels in a multi-storey building. This particular configuration simulates a multi-storey building with an interstorey height of 3.8 m. At a height of 150 mm above the bottom fixing point of the mullion, a transom spanned between the mullions. The other transom was positioned at the top of the glass panel. The glass pane was installed with a 15 mm clearance all around the framing members and sealed using neoprene gaskets.

To study the framing members used in residential buildings, typical aluminium framing members were used. These were supplied as standard units by the manufacturer, with the aluminium members stapled to trimmer timber members. These timber members were connected to the test rig by nailing at 600 mm centres to equivalent wall studs, which were fixed to 100 mm x 50 mm timber members representing the top and bottom plates. The plates were supported by 200 x 76 mm Channel members, 1200 mm apart (Figure 6a). This simulated roof trusses at 1200 mm centres supporting the top plate under face loading of the wall.

Deflections were measured at the mid-height of the mullions after each impact. (i.e., midway between the mullion connection points to the vertical channels). The glass deflection of the reverse face to the point of impact and the mullion deflection at the level of impact, were also measured. All deflections were measured relative to the ground. This was done by measuring the movement of a stainless steel rod housed in a "plate". The rods were attached to steel brackets which were clamped to the vertical channels (Figure 6b). There was sufficient friction between the "plate" and the rod to allow only movement caused by the initial impact to be recorded. Because the impactor was left free after the initial impact, subsequent impacts occurred on the glass. However, the movement caused by the subsequent impacts did not alter the deflection of either the glass or the mullions, because the impactor movement after the initial impact was damped by friction and air resistance.

Some impacts were also recorded with a video camera.

3.2 Procedure

The literature survey revealed that the most appropriate test method for assessing the impact resistance of glass to soft body impact is that specified in ISO 7892 (1988). This test method uses a sphero-conical bag filled with 50 kg of glass spheres. It is highly repeatable. It allows for modelling of different pane sizes and the complete installation details of the glass system as used in actual structures. This test method was therefore adopted for the current series of testing.

To simulate accidental human impact in a multi-storey building the glass was subjected to the simulated impact test from inside the building.

Because the strength of float glass has been identified as five times greater with the tin side in compression than with it in tension (Leicester et al, 1991) the glass panes were installed with the tin side in tension (i.e., impact on the "air" side. In normal practice there is no way of knowing which side of the glass will be impacted upon. This procedure provides lower bound results. To identify which side of a glass pane was the tin side, a Mineralight lamp (emitting ultraviolet light) was shone on the edges of the glass pane. The tin side fluoresced when the lamp shone on it. However, sheet glass has no tin or air side due to its manufacturing process, and therefore no specific installation method was applied.

For panels taller than 1200 mm, the impact point was set at 1000 mm above the bottom fixing point of the mullion, i.e., at a height equivalent to 1000 mm above the equivalent floor level. This height was considered to be the likely point of accidental child impact. A more typical impact height for adults is 1.5 m. For glass shorter than 1200 mm, the point of impact was set at mid-height.

Beginning at 15 J, the energy impact was increased by 15 J increments (i.e., 30 mm x 50 kg) to failure. In thinner sheet glass (3 mm, 4 mm and 5 mm), the incremental energy level was set at 10 J (20 mm x 50 kg). At each height, one impact was carried out before increasing the impactor suspended height to the next scheduled height. It is debateable whether previous impacts have any influence on the final glass failure strength. It is conceivable that cracks and tension stresses could develop during the lower impact energies, which may have lead to premature failure. It would be useful to carry out a single impact on a new control sample once break energy was found by the incremental approach. This was not done for this testing.

4.0 OBSERVATIONS AND RESULTS

Figure 7a shows the typical failure of glass when framed with multi-storey framing members. Failure occurred when the impactor crashed through the glass pane. This resulted in a hole of approximately 300 mm diameter, with radial cracks spreading from the hole to the four edges of the glass. Figure 7b shows typical failure with glass framed with members commonly used in residential construction.

Results of glass impact resistance is shown in Table 3. Of most significance is the average of the impact energies of each pane size just before failure. The results indicated that the maximum resisted impact energies (or impact resistance) within some pane sizes (3000 x 1200 x 10 mm, 2400 x 1200 x 10 mm, 1800 x 1200 x 6 mm) were in very close agreement with each other while others (1200 x 1200 x 6 mm, 2400 x 1200 x 6 mm) varied considerably.

The mean of the impact energies was used arbitrarily here to indicate the likely impact resistance of the glass tested. The probability of failure from accidental human impact on glass in New Zealand is about 30 x 10^{-5} per person per year (refer section 2.3). Because a lower bound result was obtained through testing with the tin side placed in tension, adopting the mean value impact resistance characteristics may be justified, but such an assumption is beyond the scope of this work.

Glass deflection at point of impact of the different glass sizes and geometry is tabulated in Table 4a. Tables 4b and 4c tabulate mullion deflections at the height of impact and at mid-height of the mullion.

5.0 DISCUSSION

5.1 Glass and Mullion Deflections

The plot of glass deflection at the point of impact, against the square root of impact energy, (Figure 8a), showed a near linear relationship. As the square root of the energy is proportional to the momentum (for constant mass), the glass deflection is therefore proportional to the momentum of the impact bag. (Note that the glass deflection was measured relative to the ground and thus includes the movement of the mullions.) Mullion deflections have a linear relationship, with impact energy (Figure 8b). This trend agrees with results of numerical studies undertaken by Leicester and Datong (1991), on a simply supported 1700 x 850 x 10 mm glass pane, with a loaded area of 170 x 85 mm. They observed that the glass deflection was proportional to the square root of the impact energy (Figure 8a).

A comparison of experimental glass deflections of the 1930 x 860 x 10 mm thick specimen with the computed deflections for the 1700 x 850 x 10 mm thick specimen in Figure 8a, shows that the slope of the deflection plot for the former is steeper than that for the numerical studies. This is mainly due to different boundary conditions, as the tested glass deflections include movement of the aluminium mullions supporting the glass panel; the numerical studies, however, assumed simple support conditions on all four edges of the panel. Another reason could be the difference in characteristics of the impactor used, including the loaded area modelled in the numerical studies.

Figures 8a, 8b and 9 indicate, that for the same framing members, glass deflection at the point of impact for a given energy level reduced with an increase in glass thickness. However, from Table 4b and Figure 9, there were neglegible differences in mullion deflection at the point of impact for panels of the same size but with different glass thicknesses (2400 x 1200 x 6 mm and 2400 x 1200 x 10 mm); (1930 x 860 x 6 mm, 1930 x 860 x 8 mm and 1930 x 860 x 10 mm). A similar observation can be made for deflections at mid-height of the mullion from Table 4c.

Figure 8a shows that glass deflection at the point of impact of the narrower specimen (860 mm width) was less than that of the 1200 mm width. This deflection ratio was 1.2 for the 1800 x 1200 x 6 mm compared to the 1930 x 860 x 6 mm specimen; and 1.25 for the 2400 x 1200 x 10 mm compared to the 1930 x 860 x 10 mm specimen. Thus, reducing glass width caused a slightly less than proportional decrease in glass plus mullion deflection.

The glass deflections of the 2400 x 1200 x 6 mm and 1800 x 1200 x 6 mm glass panes were similar (as were deflections of 2400 x 1200 x 10 mm and the 3000 x 1200 x 10 mm glass panes) (Figure 8a). The deflection at the point of impact of the 1200 x 1200 x 6 mm specimen was on average, about 15% smaller than the 2400 x 1200 x 6 mm specimen (Table 4a). These indicated that once a certain height of glass pane was reached that glass deflections of panes with a specified width were independent of pane height. Thus, for a glass pane of width 1200 mm, if the glass heights were no less than 1800 mm and 2400 mm for 6 and 10 mm thick glass, respectively, then glass deflection under impact was independent of pane height. That is, for 6 mm thick glass with a width of 1200 mm, all heights greater than 1800 mm would produce the same glass deflection under impact. Therefore, the aspect ratios for glass of 1200 mm width, for the glass deflection under impact to remain the same, were 1.5 (i.e., 1800/1200) for 6 mm thick glass and 2.0 (i.e., 2400/1200) for 10 mm glass.

Glass deflection just before breakage is plotted in Figure 10. There is a general trend (with the high rise framing) of increased deflections as glass thickness reduces. There is a slight reversal of this trend with residential framing. The scatter of data is not large.

Mullion deflections have been deducted from Figure 10 to produce Figure 11, which is therefore the deflection of the glazing relative to the mullions. There is very little scatter of data in this graph, with a well defined relationship between glass deflection and glass thickness. This shows that glass breakage is a direct function of glass deflection.

5.2 Impact Energy

In section 1.0, it was mentioned that the amount of energy transferred by the impactor, and absorbed by the glass panel, is dependent on rigidity of the glass pane and the rigidity of the supporting framing members. This latter point is supported by the behaviour of the 1930 x 860 x 5 mm specimen, which required a higher impact energy to cause it to fail when framed with the more flexible residential framed members (Figure 12 and Table 3).

Figure 12 plots the relationship between maximum impact energy before failure and glass thickness. This shows that the ability of the glazing to absorb energy increases with increases in glass thickness. The rate of increase is greater with residential than high rise framing. Figure 13 plots the same data as Figure 12 but the ordinates are momentum rather than energy values. This provides an fairly good linear relationship between momentum and glass thickness for glass thicknesses between 3 and 8 mm. The results for the 10 mm glass are lower than the general trend.

Figures 14 and 15 show the energy and momentum (respectively) before failure plotted against glass aspect ratio. There appears to be a trend of greater energy (or momentum) for lower aspect ratios, although the higher values for the 1930 x 860 x 6 mm glass (aspect ratio 2.24) are against this trend. The trend would otherwise indicate that decreasing the aspect ratio from 2 to 1 would provide an average increase of energy of 100 Joules or momentum of 45 Kg m/sec^2.

Figure 16 plots the energy before impact against the glass width (for 6 and 10 mm glass). There is too much scatter of the data, and the range of glass widths investigated was too small, for a trend to be defined with confidence. However, there appears to be a small increase in impact resistance with reduction in pane width.

Figure 17 shows the relationship between the total applied impact energy and glass area. There is no evidence that an increase in glass area increases impact resistance. This vindicates recommendations in AS 2208 and other test standards to test a standard size of 1930 x 860 mm. Assuming that the impact energy is independent of area for panes with areas less than 3.0 m^2, the mean impact resistance for 6 mm thick annealed glass was 168 J with a standard deviation of 75 J. Similarly, the 10 mm thick annealed glass has a mean impact resistance of 185 J with a standard deviation of 50 J.

The Draft New Zealand Human Impact Safety Requirements (NZS 4223 SANZ 1990) have been added to a code comparison provided by Sage (1991; pers. comm.) to produce Figure 18. This shows that the draft provisions of the New Zealand standard follow closely the AS 1288 (SAA, 1989) code. The code relationships in Figure 18 which also includes BS 6262 (BSI, 1982) all imply a close relationship between impact resistance and glass area, plotted in Figure 19. A comparison of the code requirements and the BRANZ test data (also plotted in Figure 19) did not show a good agreement.

Appendix A calculates the energy absorbed by mullions, as a ratio of the total impact energy using the mullion deflections in Table 4b and the measured mullion stiffness. These ratios were 10% for the 2.4 x 1.2 m panel and 6% for the 1.93 x 0.86 m panel. Thus, energy absorbed by mullions themselves was not very significant. However, the mullion flexibility would have resulted in more of the impact force being transmitted to the top and bottom transoms, as against being directly transmitted to the mullions, thus giving a more uniform resistance path across the area of glass (which may have enhanced the pane's impact resistance). To study the influence of mullion flexibility, it would be useful to compare impact tests, with the results in this report, on panels with the mullions restrained.

The mullion deflection at the height of impact for the 1930 x 860 x 3, 4 or 5 mm thick specimens, framed with residential framing members, increased slightly with increased glass thickness. The glass and mullion deflections of the residential framed panel of the 1930 x 860 x 5 mm specimen were also higher than those of the multi-storey framed panel (Figure 8b, 9, Tables 4a, 4b). This is because residential framing members are more flexible than multi-storey framing members.

6.0 CONCLUSIONS

(1) The proportion of energy absorbed by the mullions was small relative to the imposed impact energy. However, the mullion flexibility would have resulted in more of the impact force being transmitted to the top and bottom transoms, as against being directly transmitted to the mullions. This would give a more uniform resistance path across the area of glass, which may have enhanced its impact resistance.

(2) Glass deflection at the point of simulated human impact decreased, but the failure impact energy increased, with increased glass thickness. Glass deflection and average failure impact energy were higher when the specimen was framed with residential framing members.

(3) Glass deflection has a linear relationship with the square root of the impact energy, suggesting that glass deflection is a linear function of the impacting bodies momentum.

(4) Glass deflection of the 860 mm wide specimen was smaller than the 1200 mm wide specimen, but by less than the ratio of widths. There was no strong correlation between glass width and impact resistance, and the parameters tested did not test this aspect well. However, impact resistance did appear to increase slightly with reduced glass width.

(5) With panels of the same size, mullion deflection at the same impact energy was equal for 6, 8 and 10 mm thick glass, when framed with multi-storey framing members. Mullion deflections of the 3, 4 and 5 mm thick glass increased slightly with increased glass thickness when framed with residential framing members.

(6) The maximum aspect ratio beyond which there was no increase in glass deflection (at the point of impact) for a 1200 mm pane width is 1.5

for 6 mm thick and 2.0 for 10 mm thick glass. Although there was only a moderate correlation between aspect ratio and impact resistance, reducing the aspect ratio from 2 to 1 appeared to increase the resistance by 100 Joules (energy) or 45 Kgm/sec^2 (momentum).

(7) The limited testing suggested that impact resistance is independent of pane area for the pane sizes tested, although there was a reasonable correlation for the 6 mm float glass. Generally, codes relate allowable glass area to the glass thickness (Figure 18), and this is often for reasons other than impact resistance. However, it was only with the 6 mm glass that a trend of impact resistance reducing significantly with increased glass area was seen. This should be investigated further.

(8) Glass deflection was strongly correlated with mullion and glass thickness at the maximum energy level before failure. This indicated that glass failure was purely a function of glass deflection.

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APPENDIX A: CALCULATION OF ENERGY ABSORBED BY DEFLECTING MULLION

A.1 Energy Directly Absorbed By the Mullions

A simply supported length of mullion of length L (Figure A.1) was test loaded to determine it's stiffness K. The stiffness "EI" of the mullion was calculated from:

$$EI = KL^3/48 = 1515 \times (1400)^3 / 48 = 86.6 \times 10^9 \text{ Nmm}^2$$

Note that as the manufacturer's data provided the Moment-of-Inertia (I) as 2.986 mm^4, then the aluminium Youngs Modulus (E) can be calculated as 29 GPa which is only 41% of the usually assumed value.

The mullions used in the impact test were simply supported over a length of 3.8 m and are taken as loaded with a point load from the impact 1.0 m from one end. It is appreciated that this is somewhat simplistic as some load spread will occur. The stiffness, K1, for the above configurationis given by:

$K1 = 1.45 \times 10^{-9}$ EI = 125.9 N/mm using the value of EI deduced above.

The energy, E, absorbed by the deflecting mullions is given by:

$E = K1 \times D^2/2$ where D = mullion deflection

The 2.4 x 1.2 m panels had an average deflection (6 mm and 10 mm panel) of 12 mm at 180 Joules from Table 4b. Thus the energy absorbed by the two mullions:

$E = 2 \times 125.9 \times 122/^2 \times 10^{-3} = 18.1$ J or 10% of the total input energy.

Similarly, average deflection of the 1.93 x 0.86 panels (6 mm, 8 mm and 10 mm) was 9.4 mm at 180 J giving the energy absorbed by the mullions as 11.2 J or 6.2% of the total energy.

Note that the calculated bending moment in the mullions at 12 mm deflection was only 32% of the moment before the test beam became non-linear so the assumption of linear behaviour in the above calculations is justified.

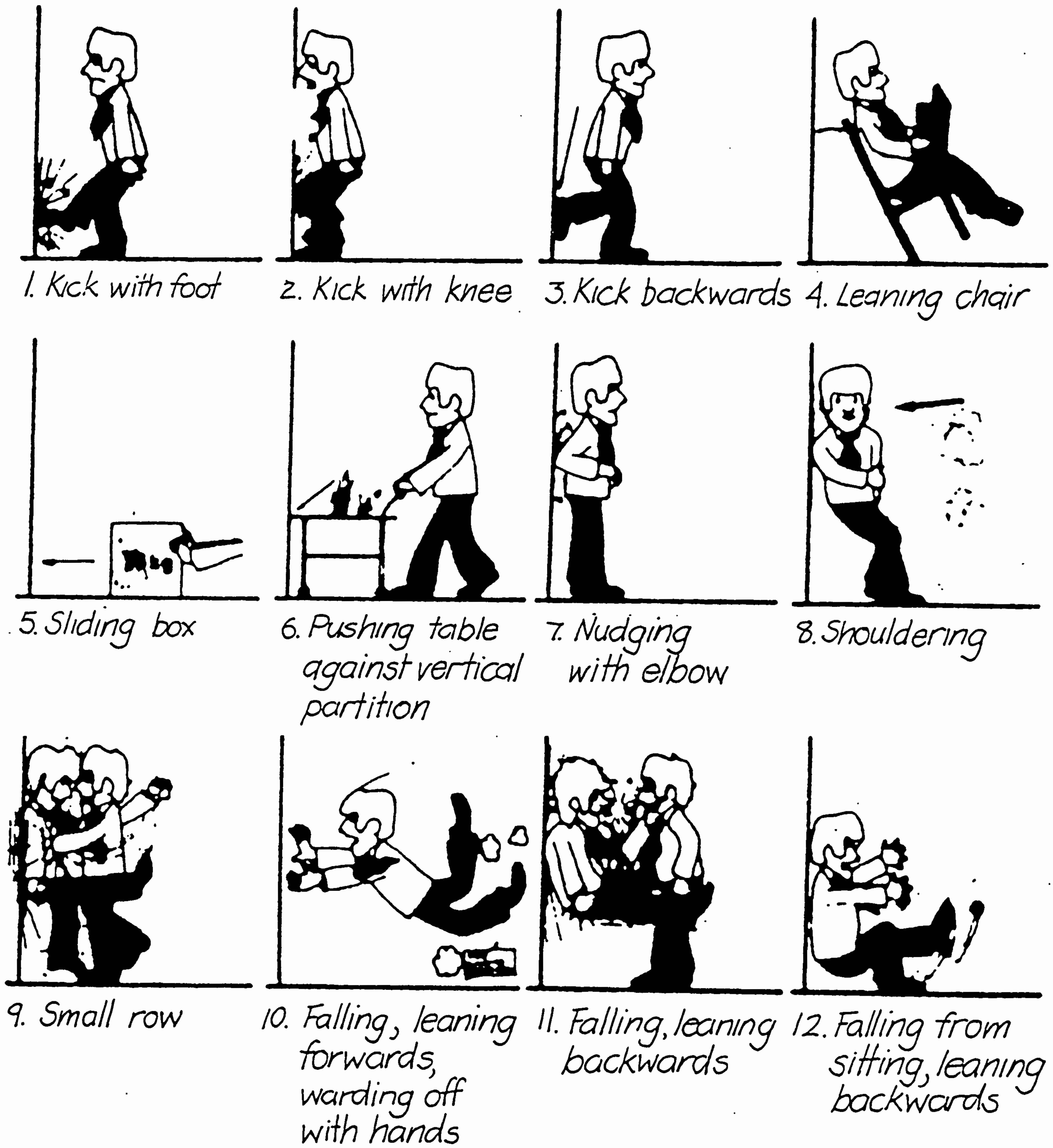

Figure 1a : Illustration of the motion patterns performed on walls from Nilsson (1976)

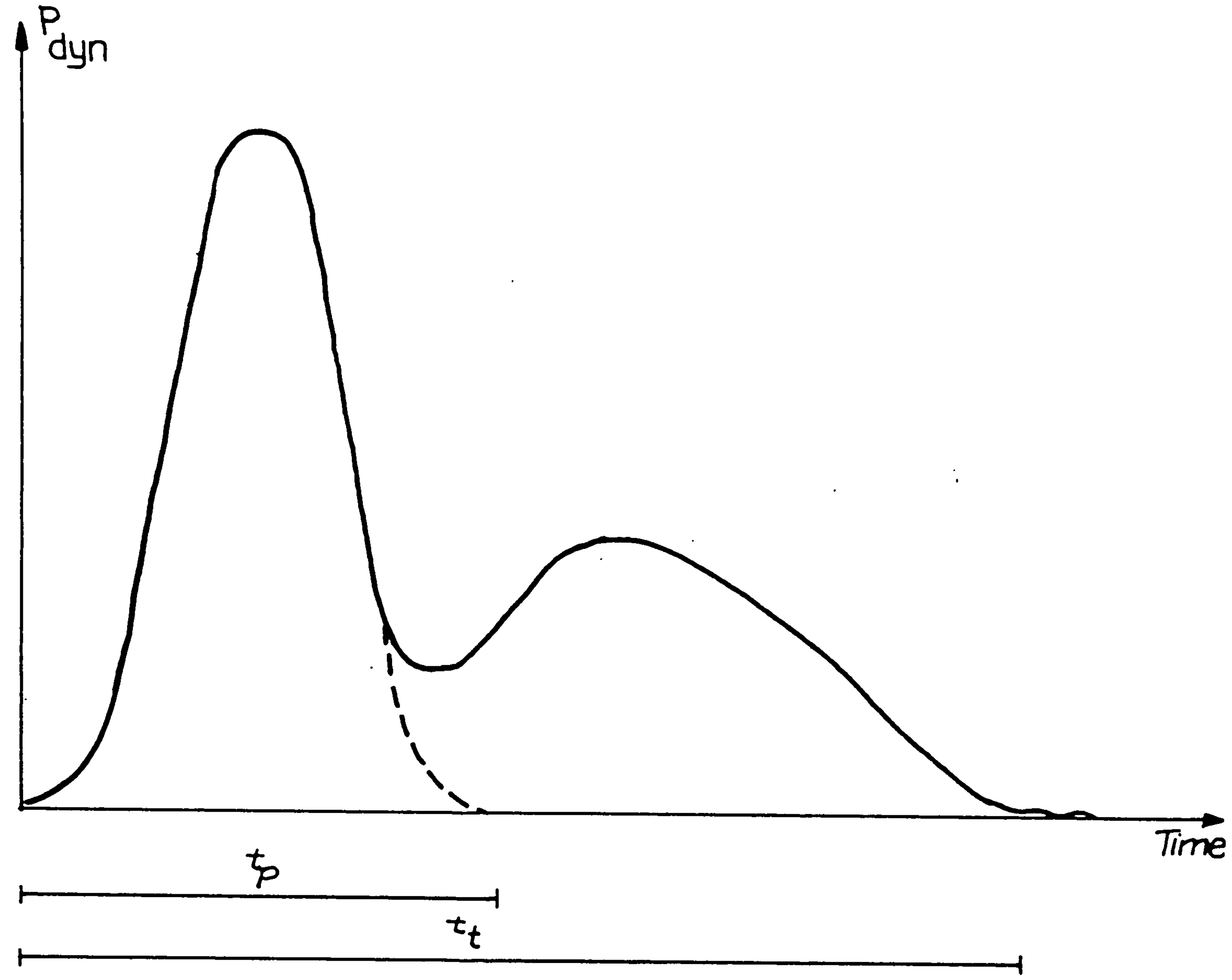

Figure 1b : Characteristic force-time relation of human impact from Nilsson (1976)

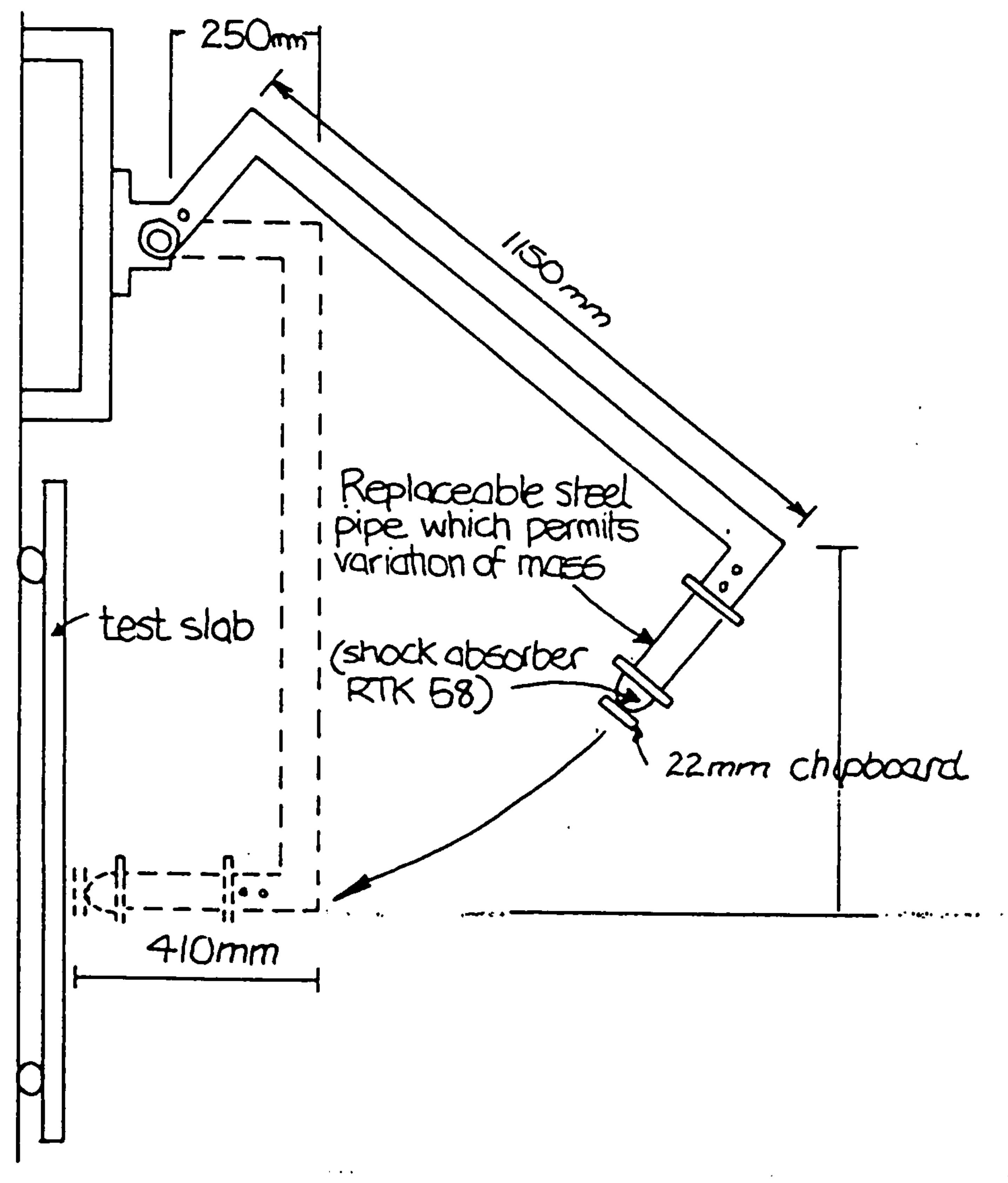

Figure 2a : Pendulum impactor from Nilsson (1976)

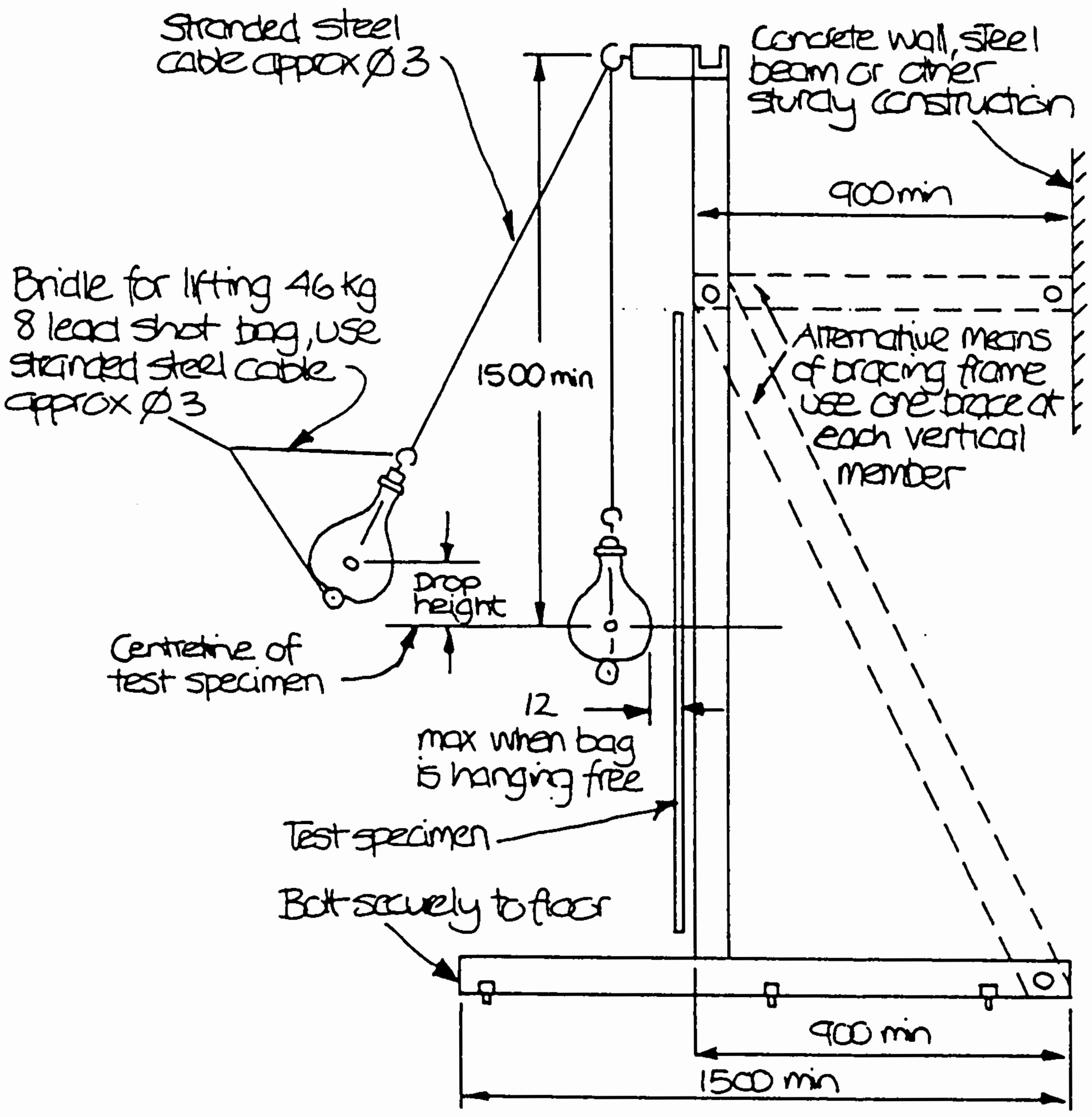

Figure 2b : Pear-shaped bag from AS 2208 (1978)

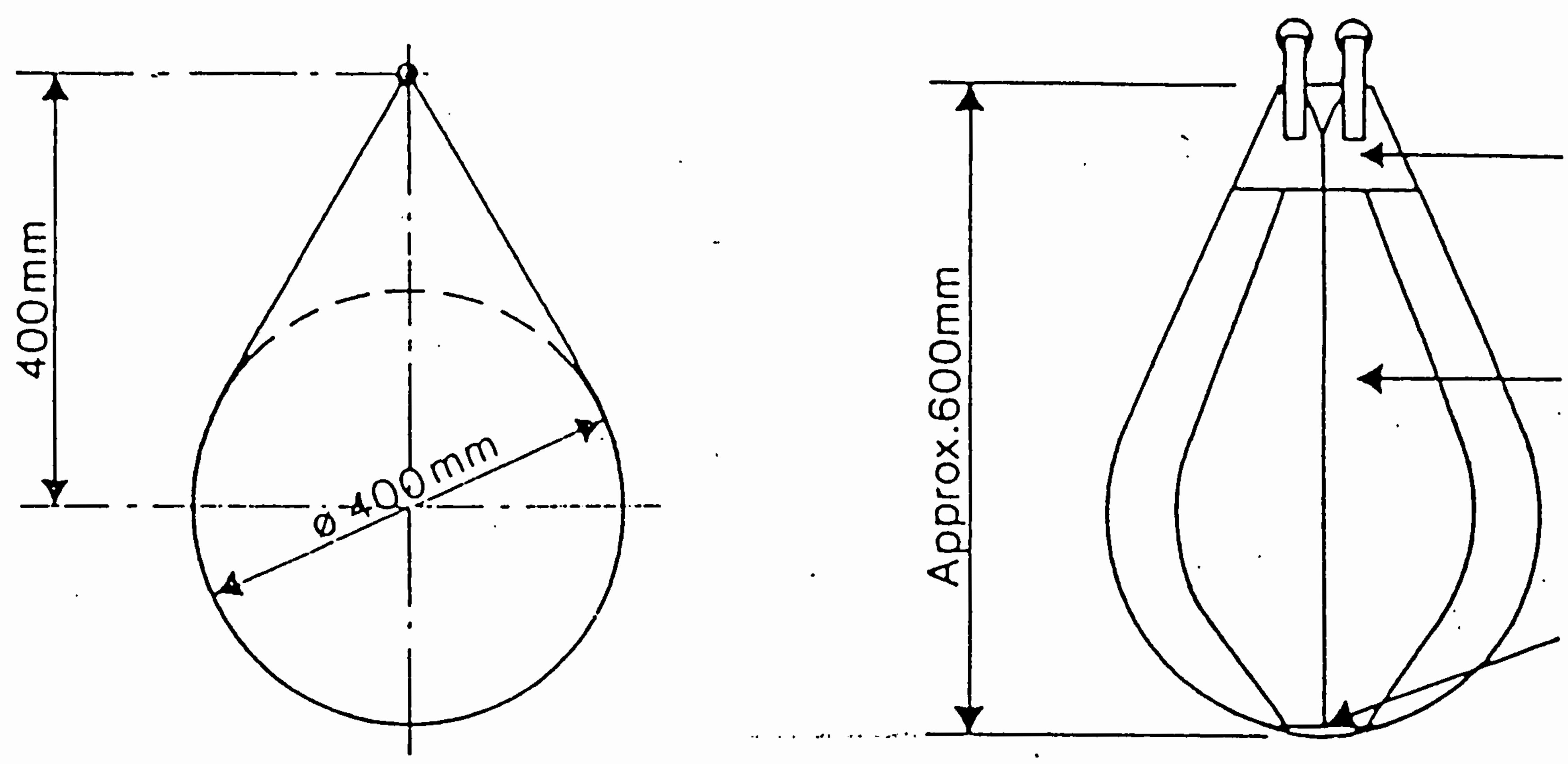

Figure 2c : Spheroconical bag from ISO 7892 (1988)

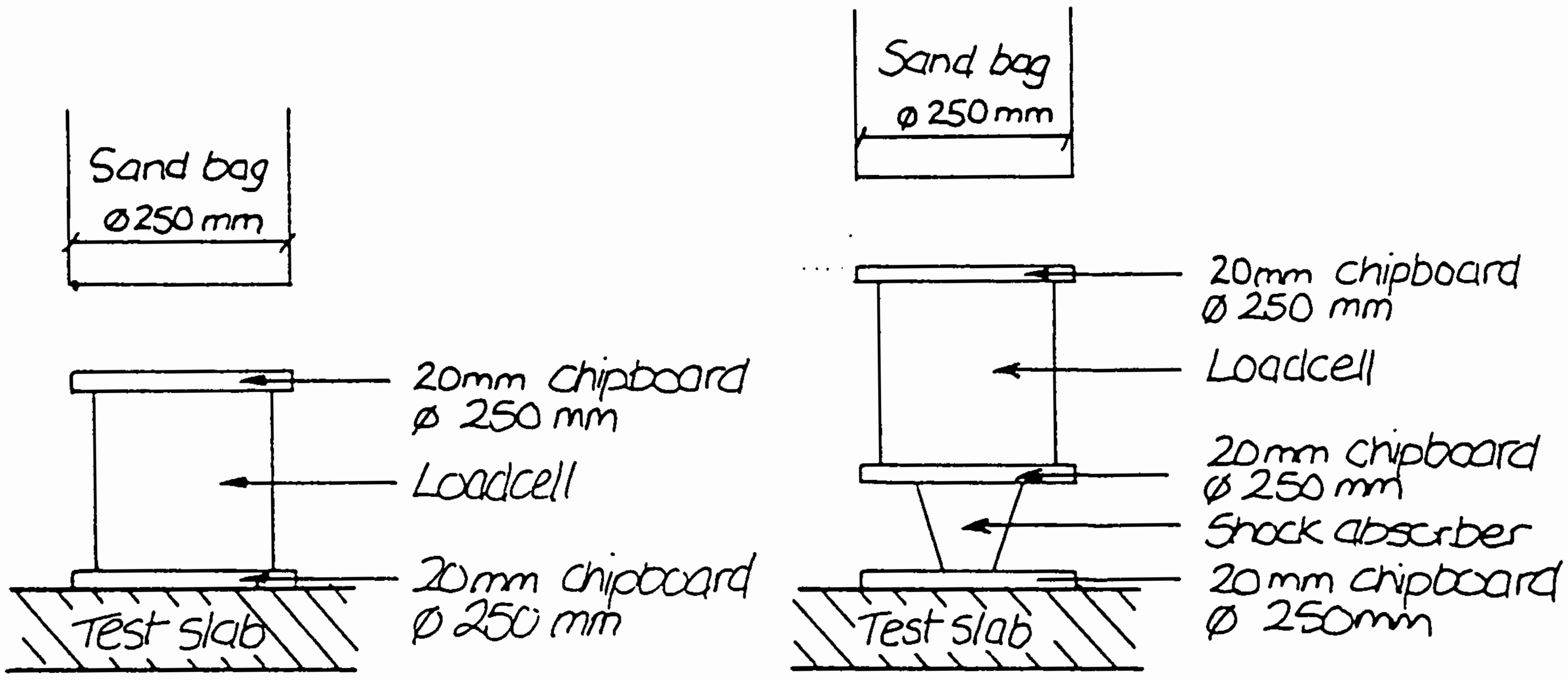

Figure 2d : Cylindrical bag on horizontal elements from Nilsson (1976)

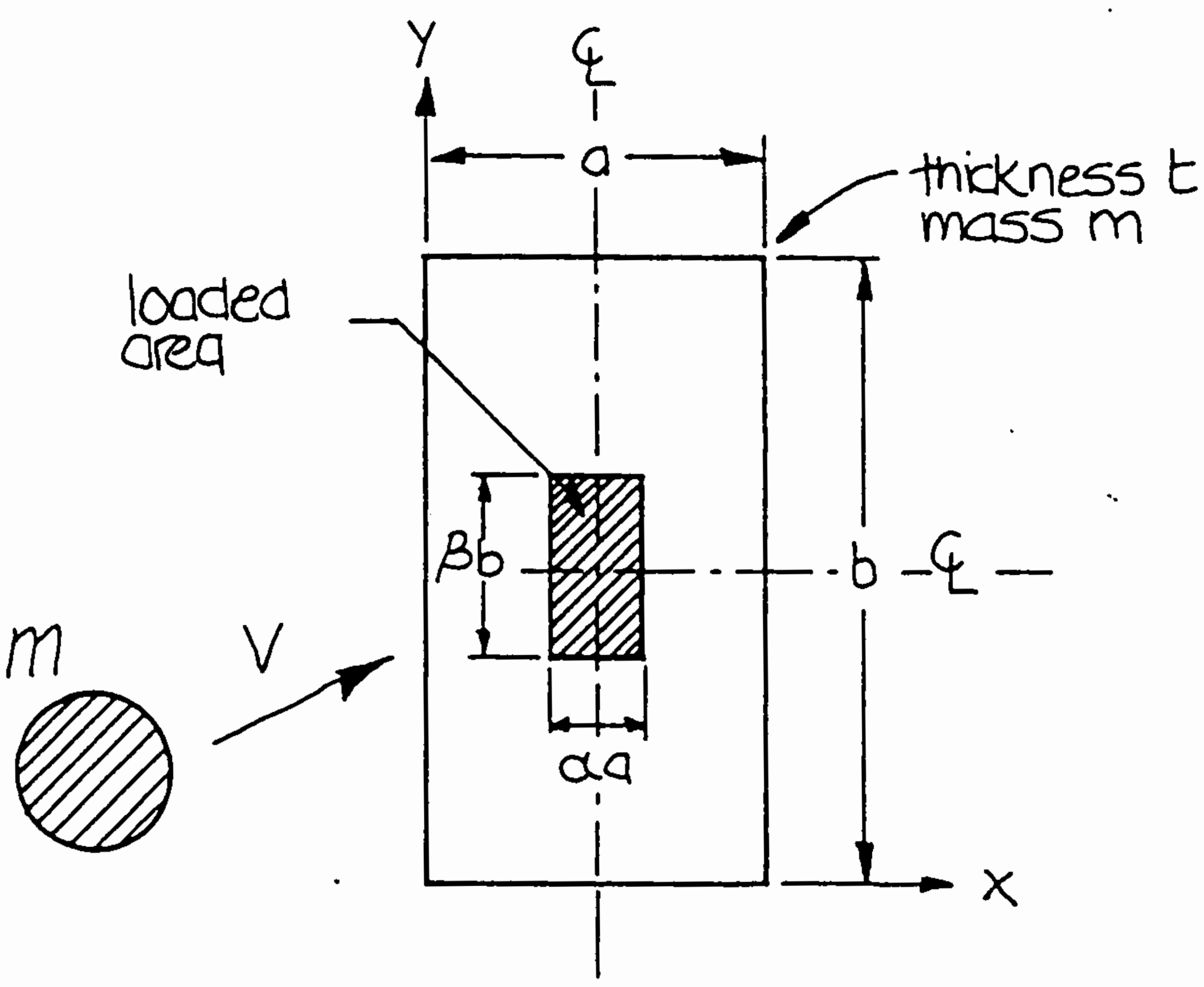

Figure 3a : Details of glass panel and loaded area from Toakley (1977)

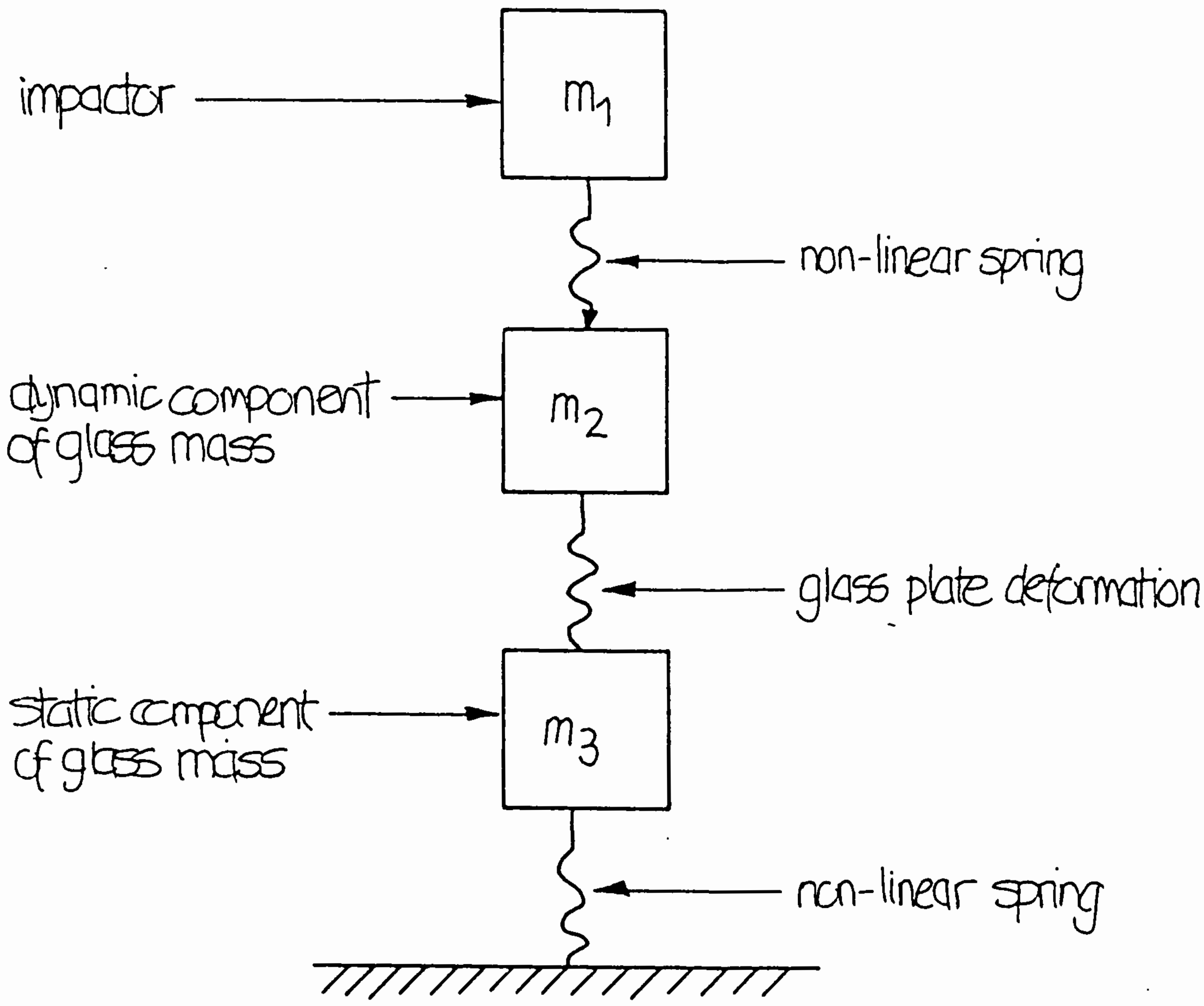

Figure 3b : Idealised lumped mass approximation from Leicester and Datong (1991)

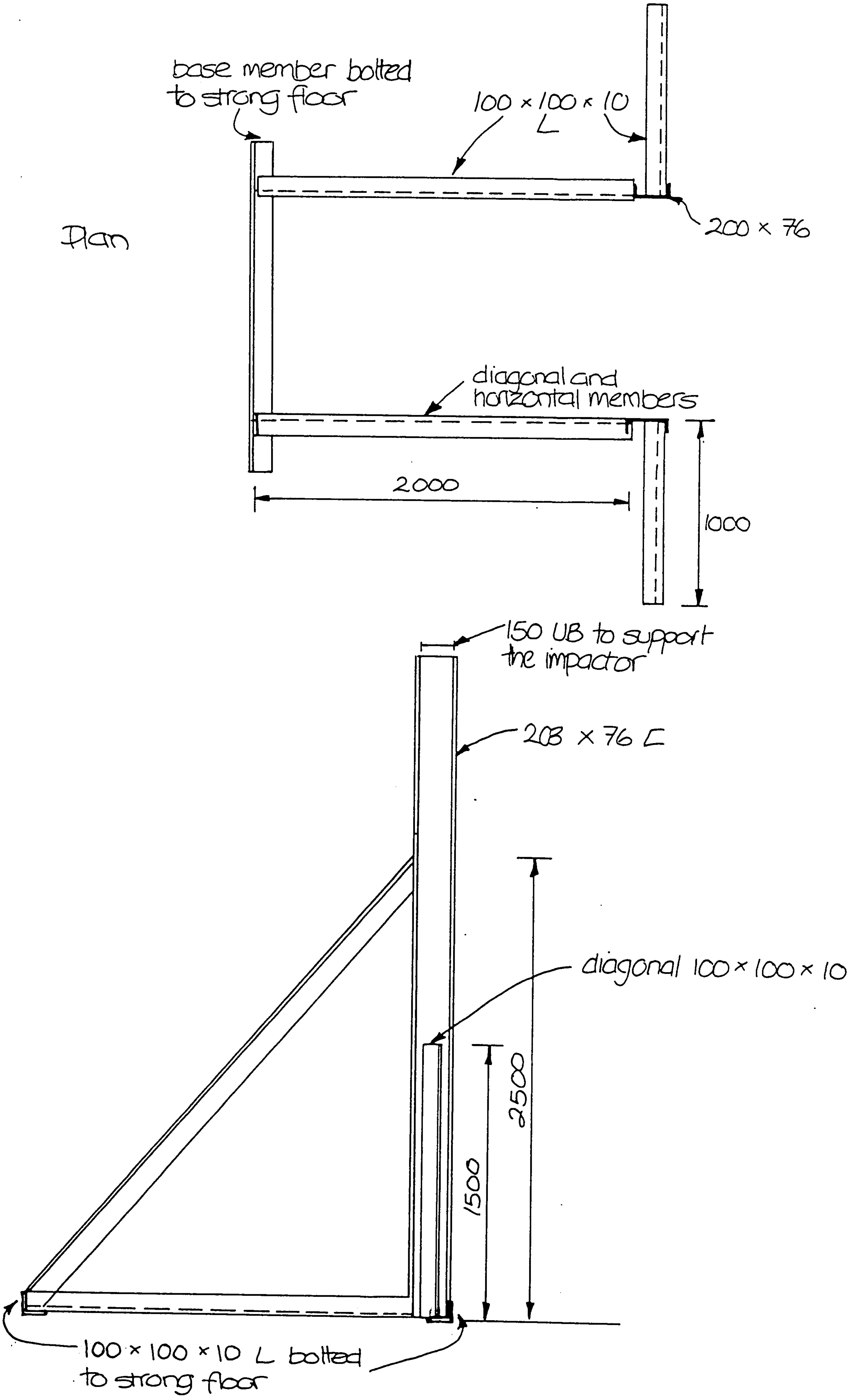

Figure 4a : Test rig

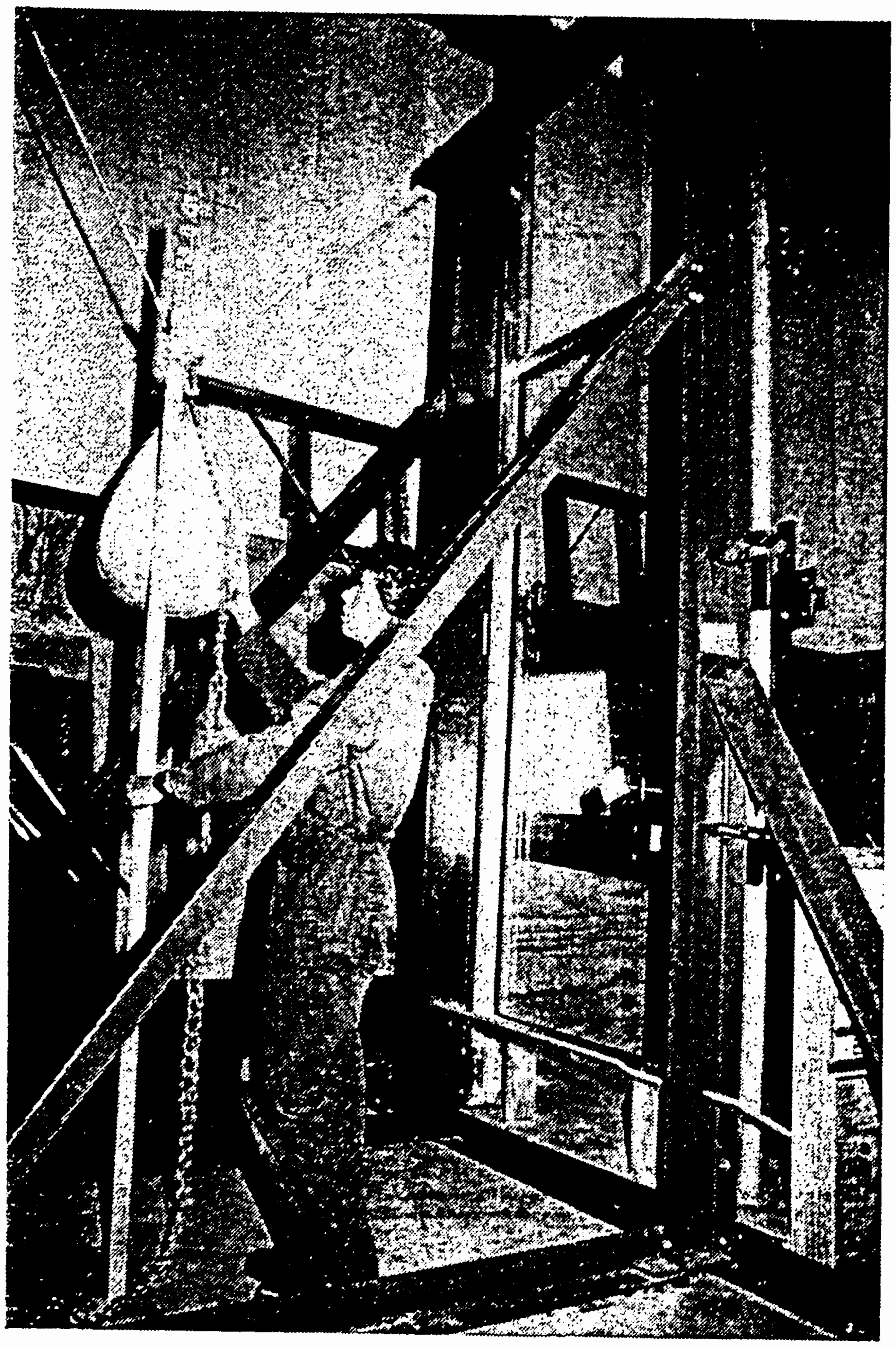

Figure 4b : Impactor attachment details

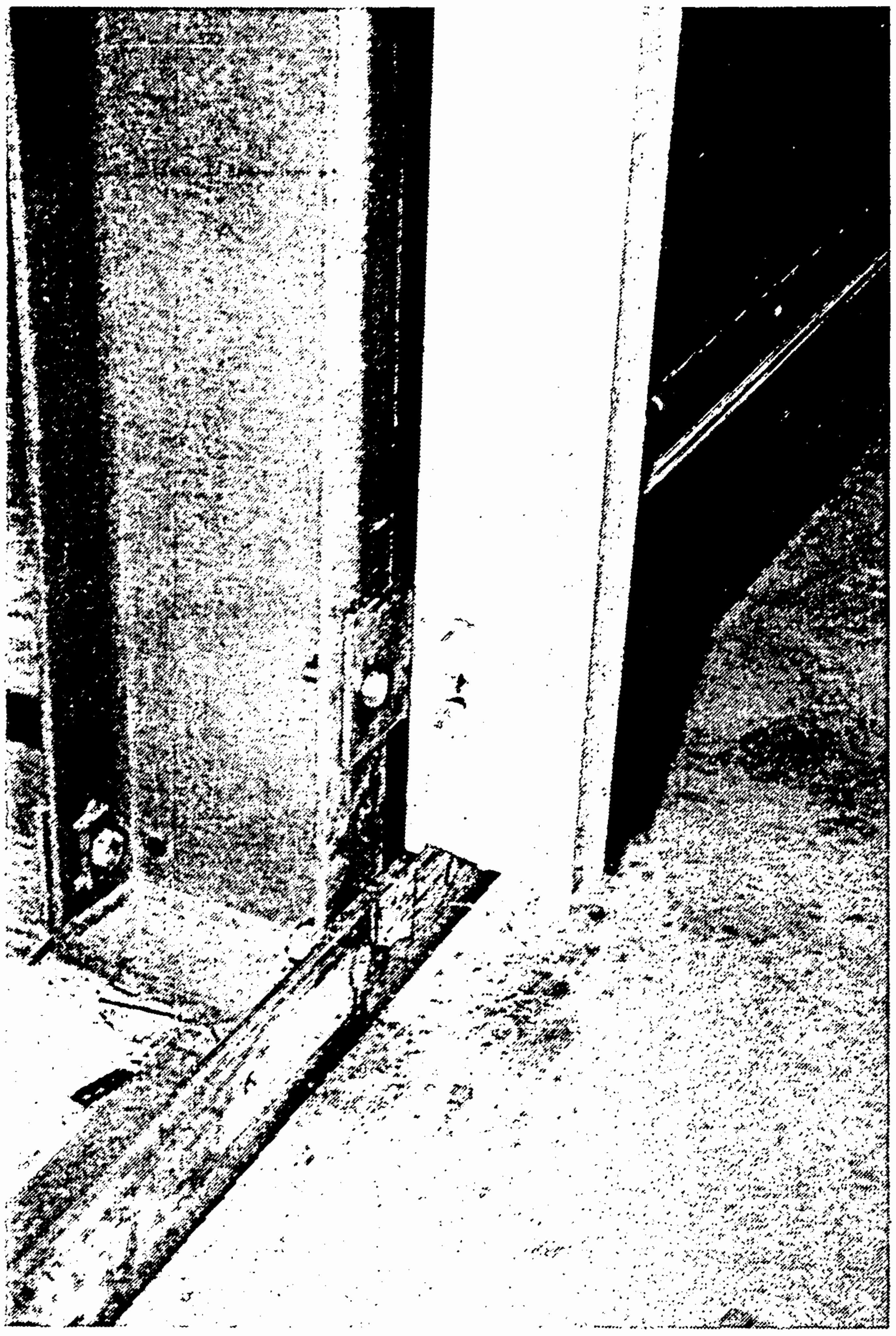

Figure 5a : Fixing of mullion to channel as viewed from the exterior

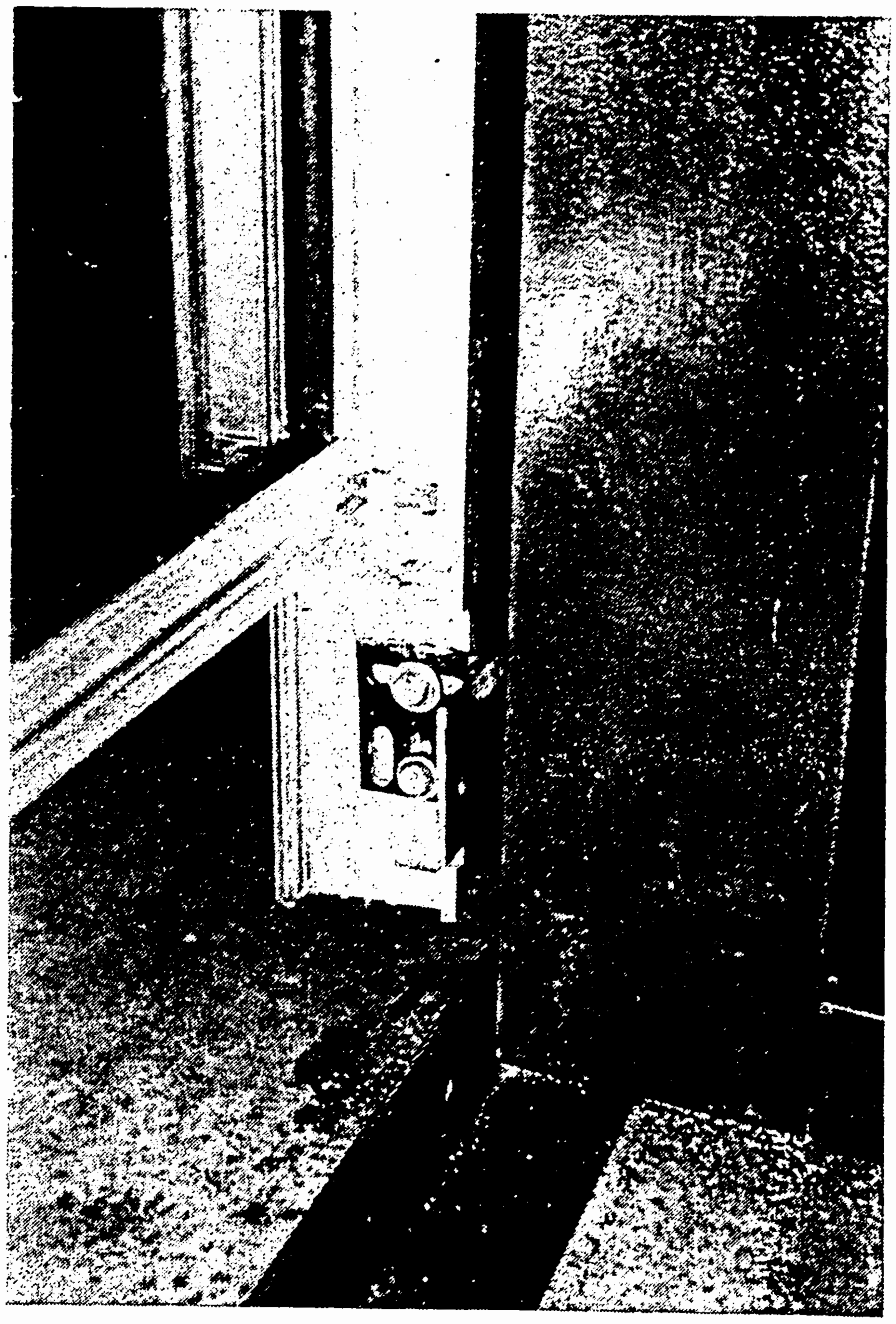

Figure 5b : Fixing of mullion to channel as viewed from the interior

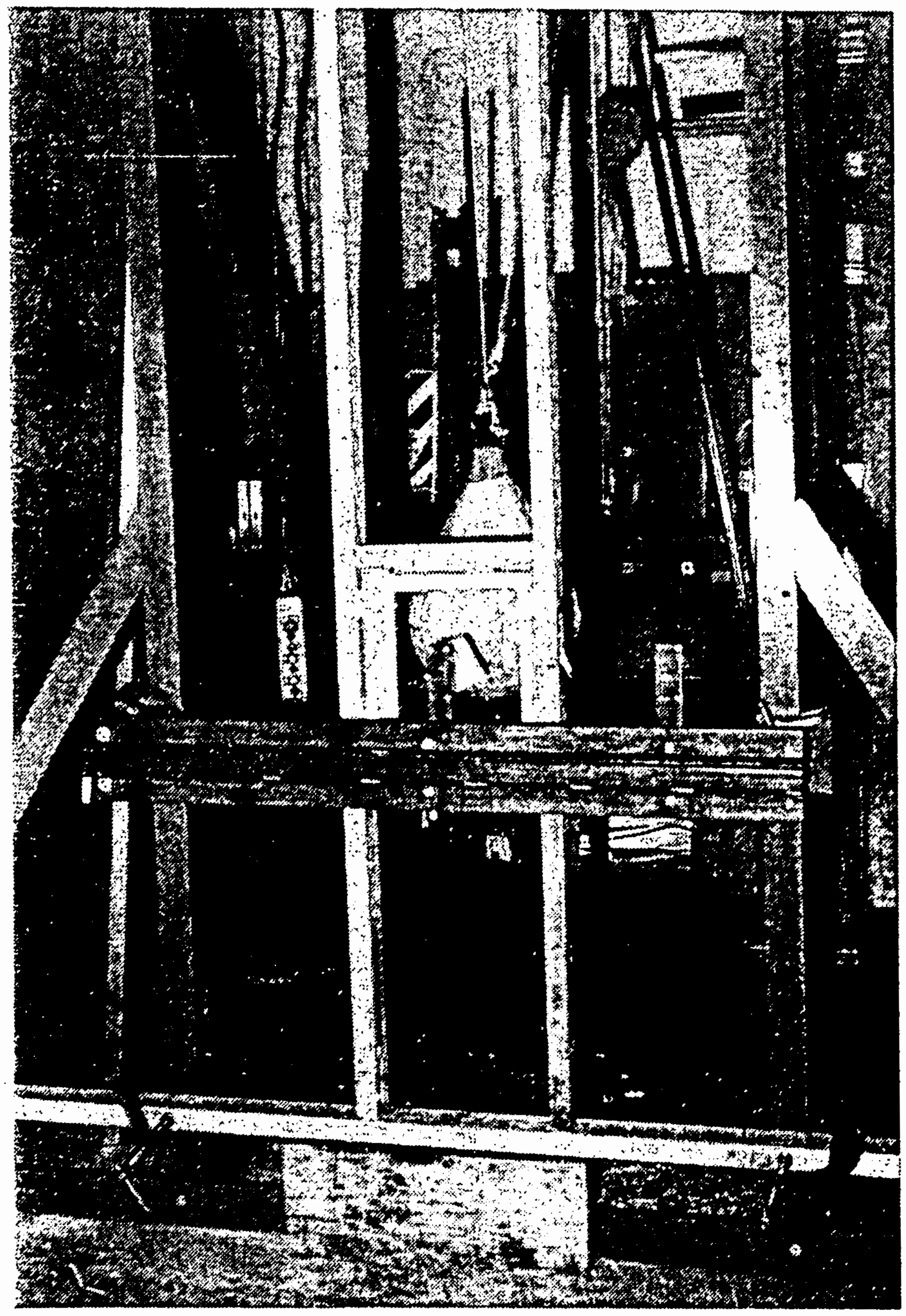

Figure 6a : Installation detail to simulate residential construction of a 550 x 550 mm pane size

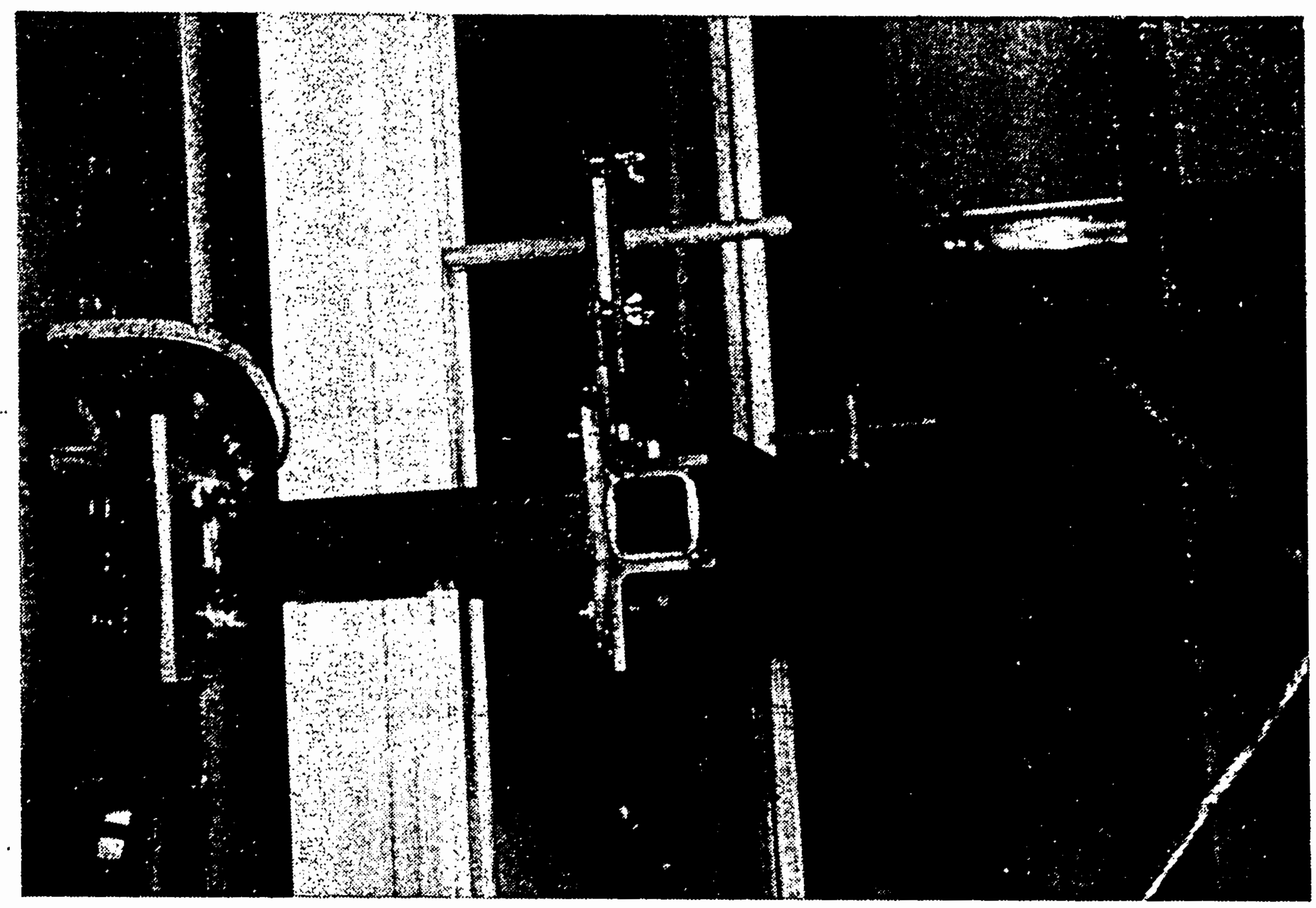

Figure 6b : View of deflection measuring system

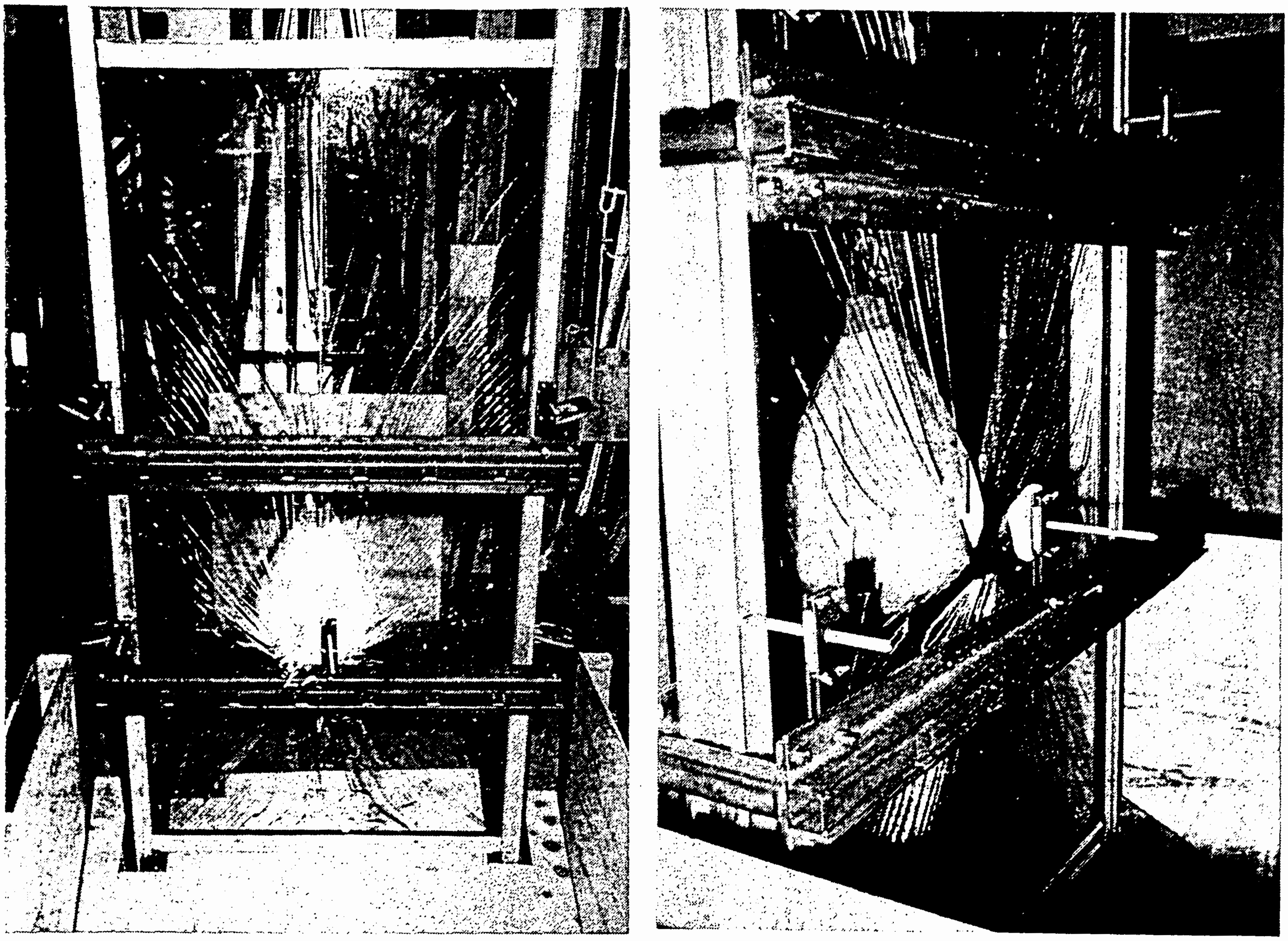

Figure 7a : Typical failure state using multi-storey framing members

Figure 7b : Failure of a 550 x 550 mm pane with residential framing members

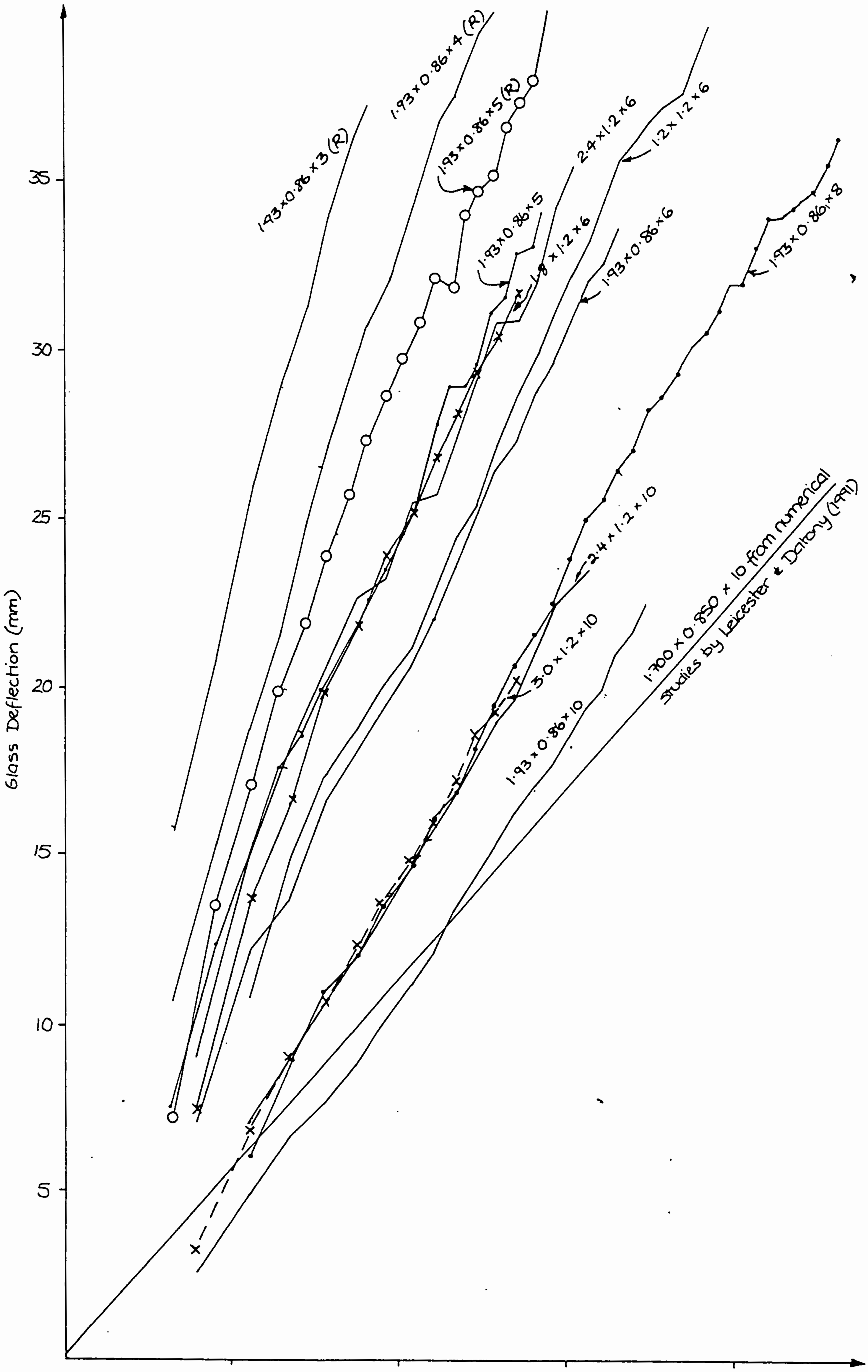

Figure 8a : Plot of glass deflection at the point of impact against the square root of impact energy

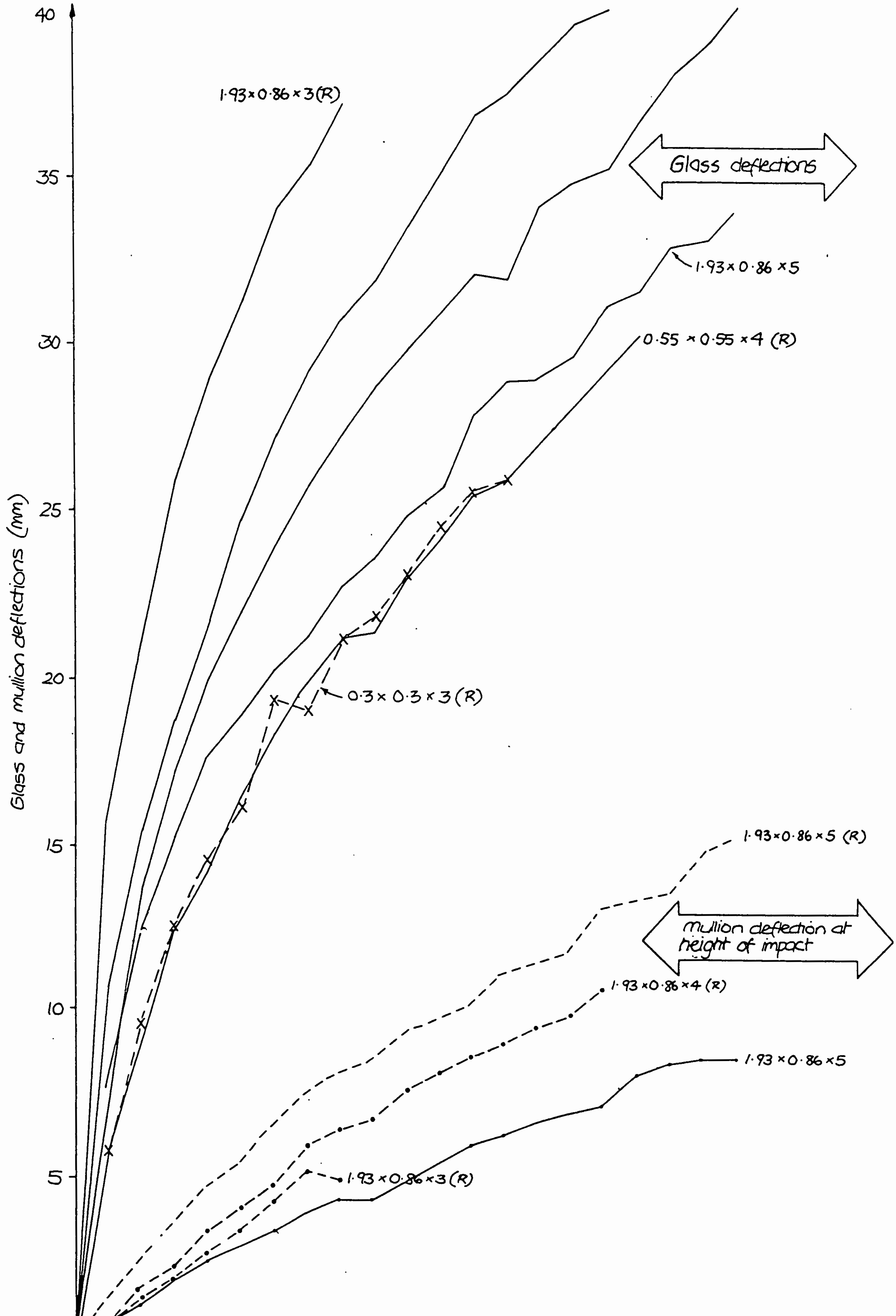

Figure 8b : Plot of glass and mullion deflections of the 3, 4 and 5 mm thick glass against impact energy

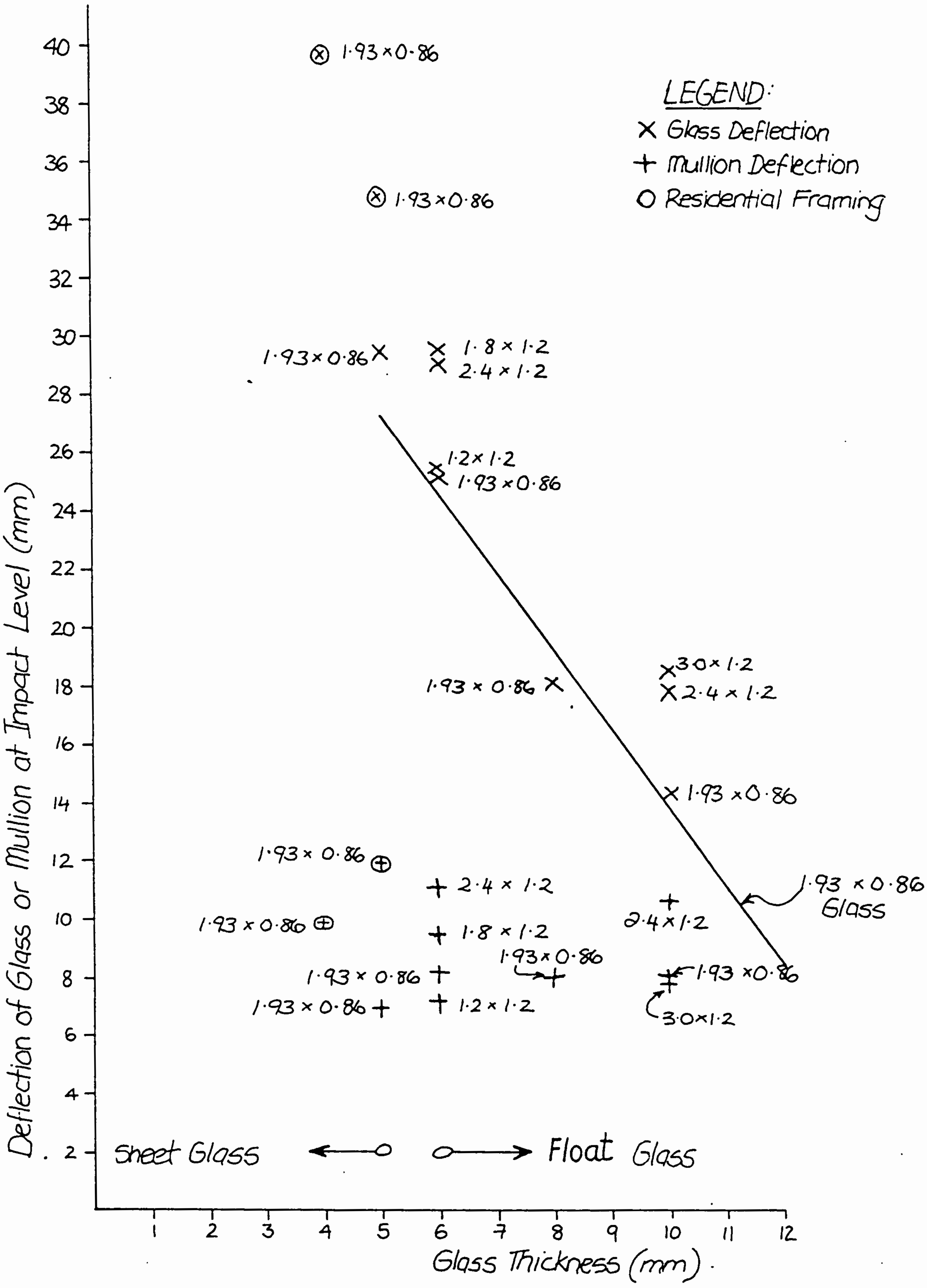

Figure 9 : Average deflections at impact energy of 150 Joules

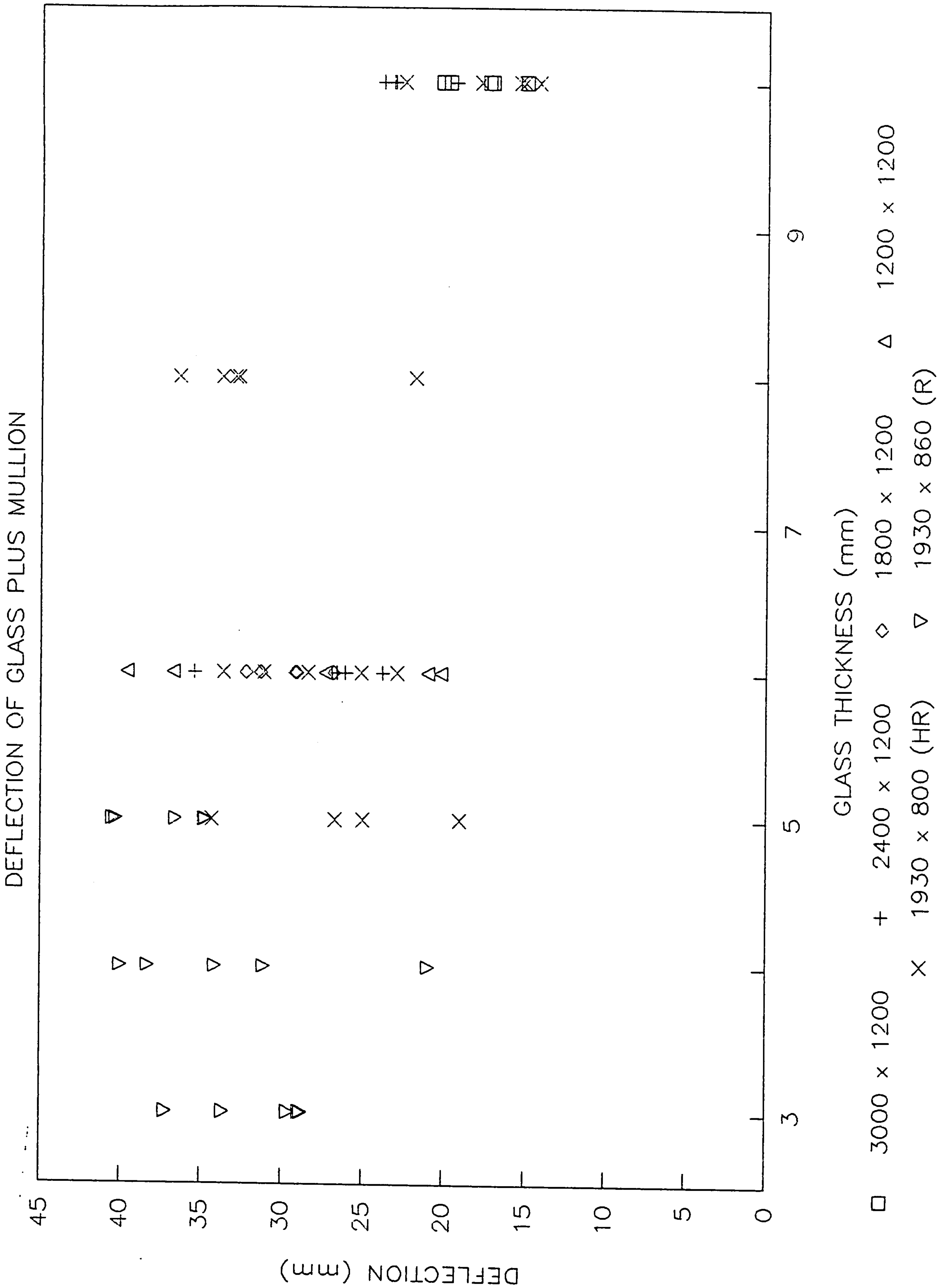

Figure 10 : Plot of maximum glass total deflection preceding failure

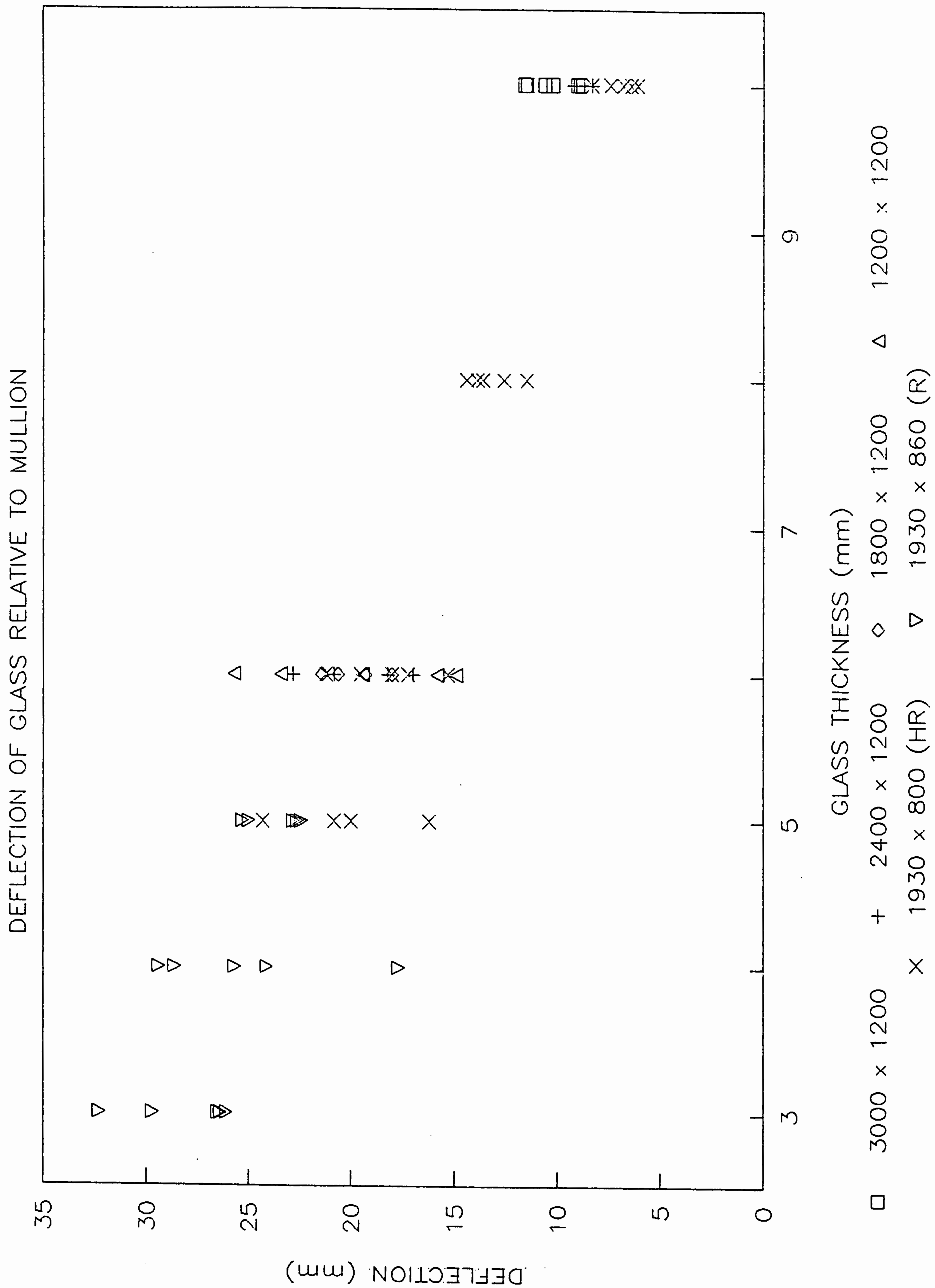

Figure 11 : Plot of maximum glass deflection minus mullion deflection preceding failure

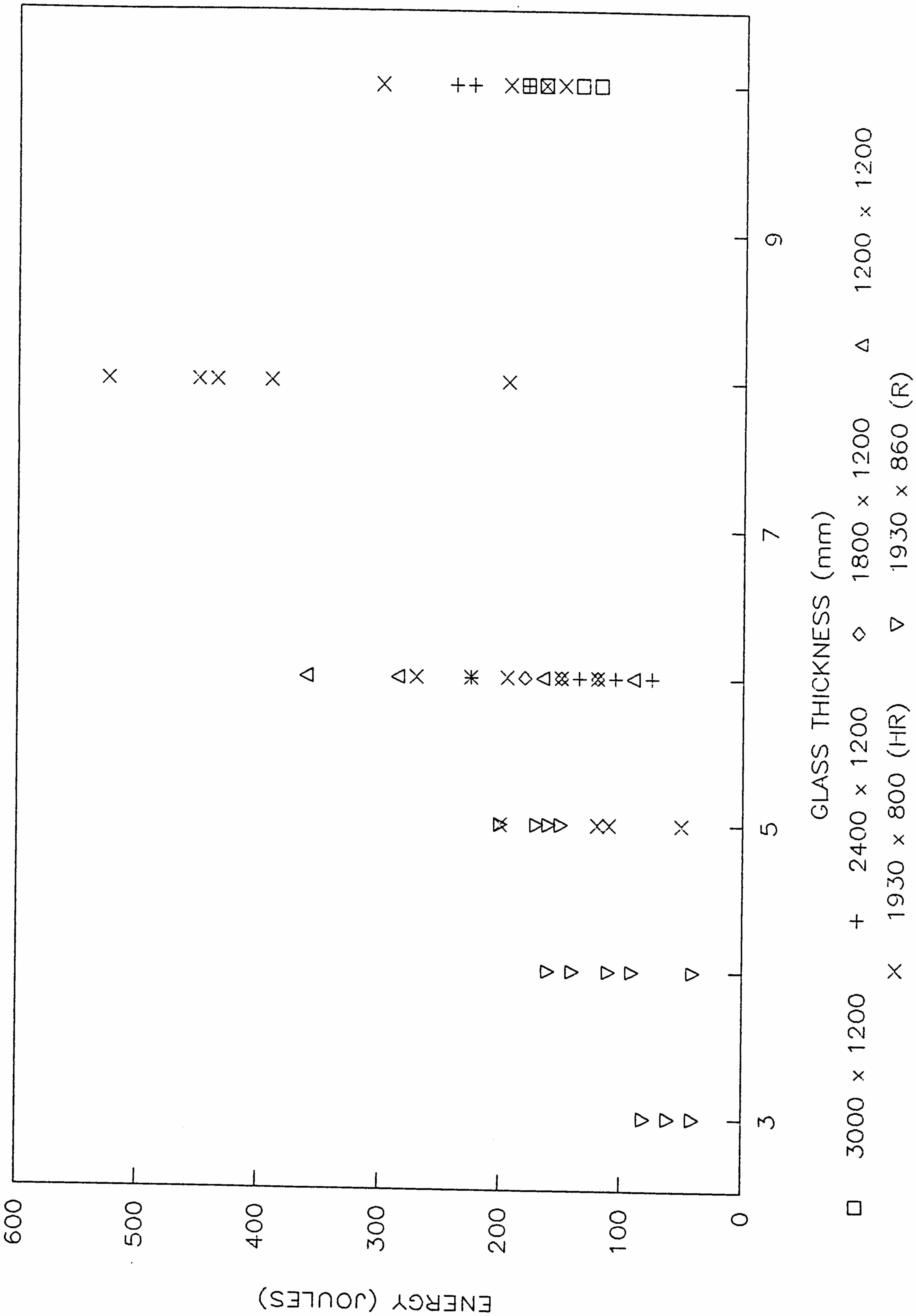

Figure 12 : Plot of energy level preceeding failure versus glass thickness

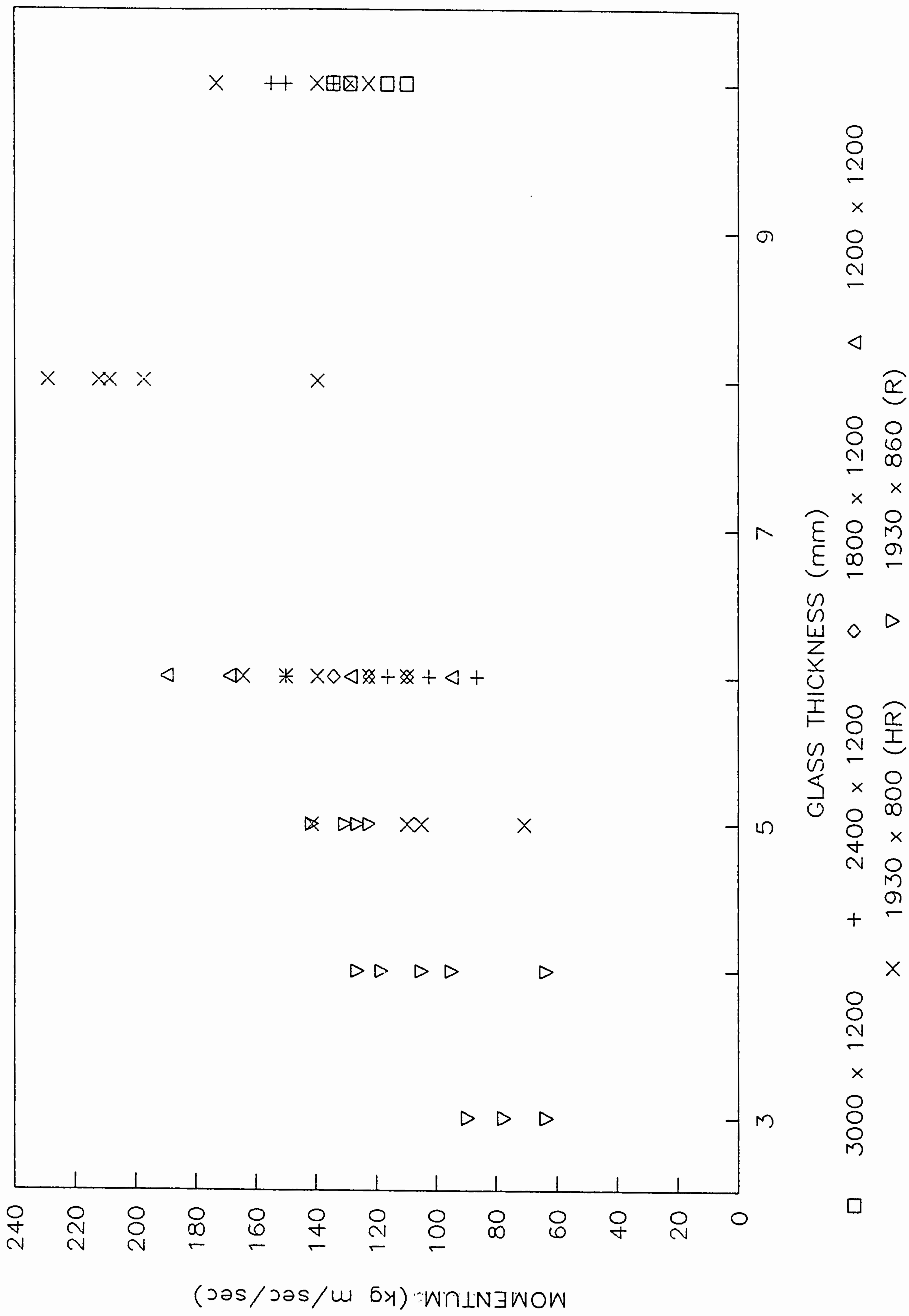

Figure 13 : Plot of momentum preceeding failure versus glass thickness

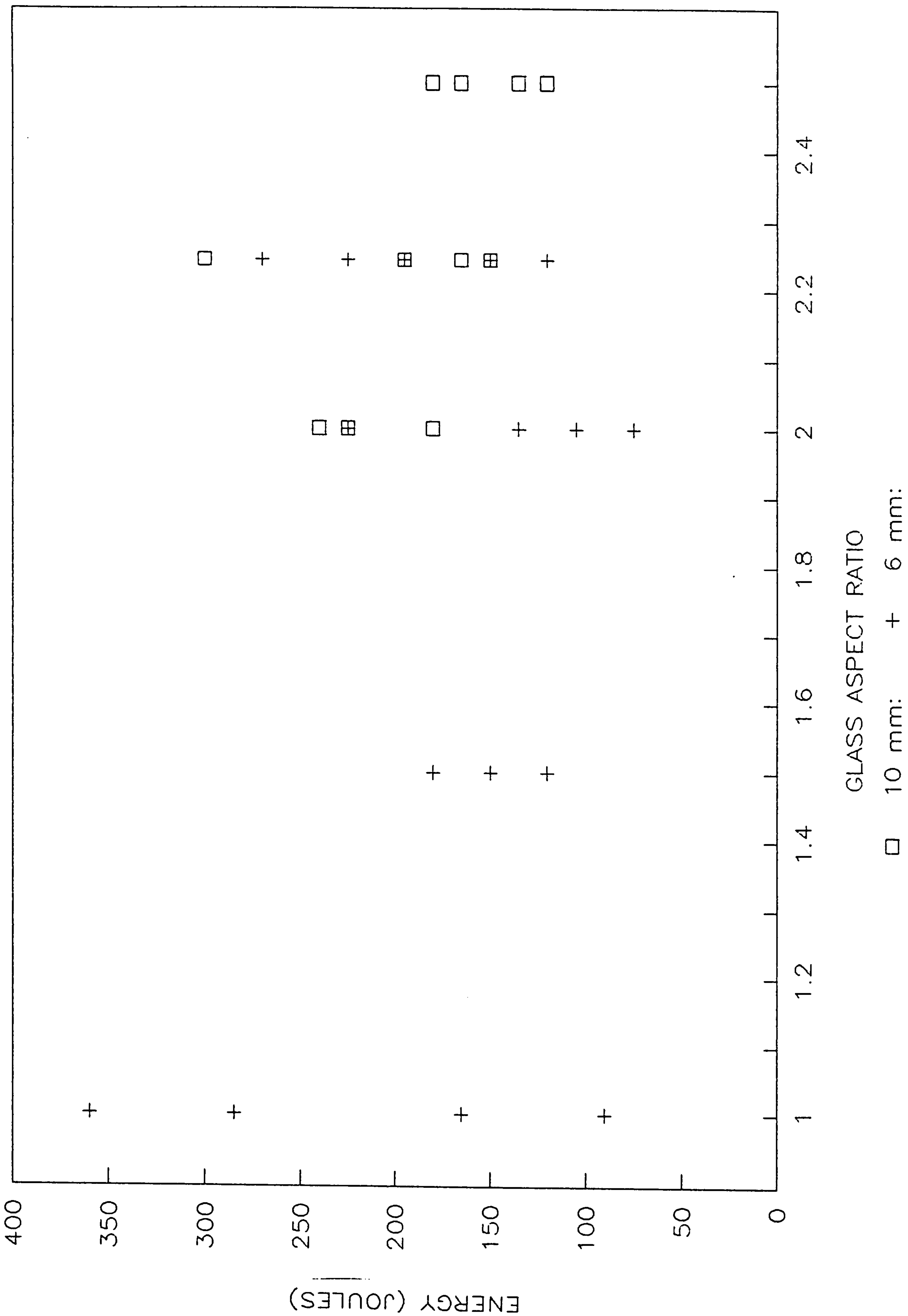

Figure 14 : Plot of energy level preceeding failure versus aspect ratio

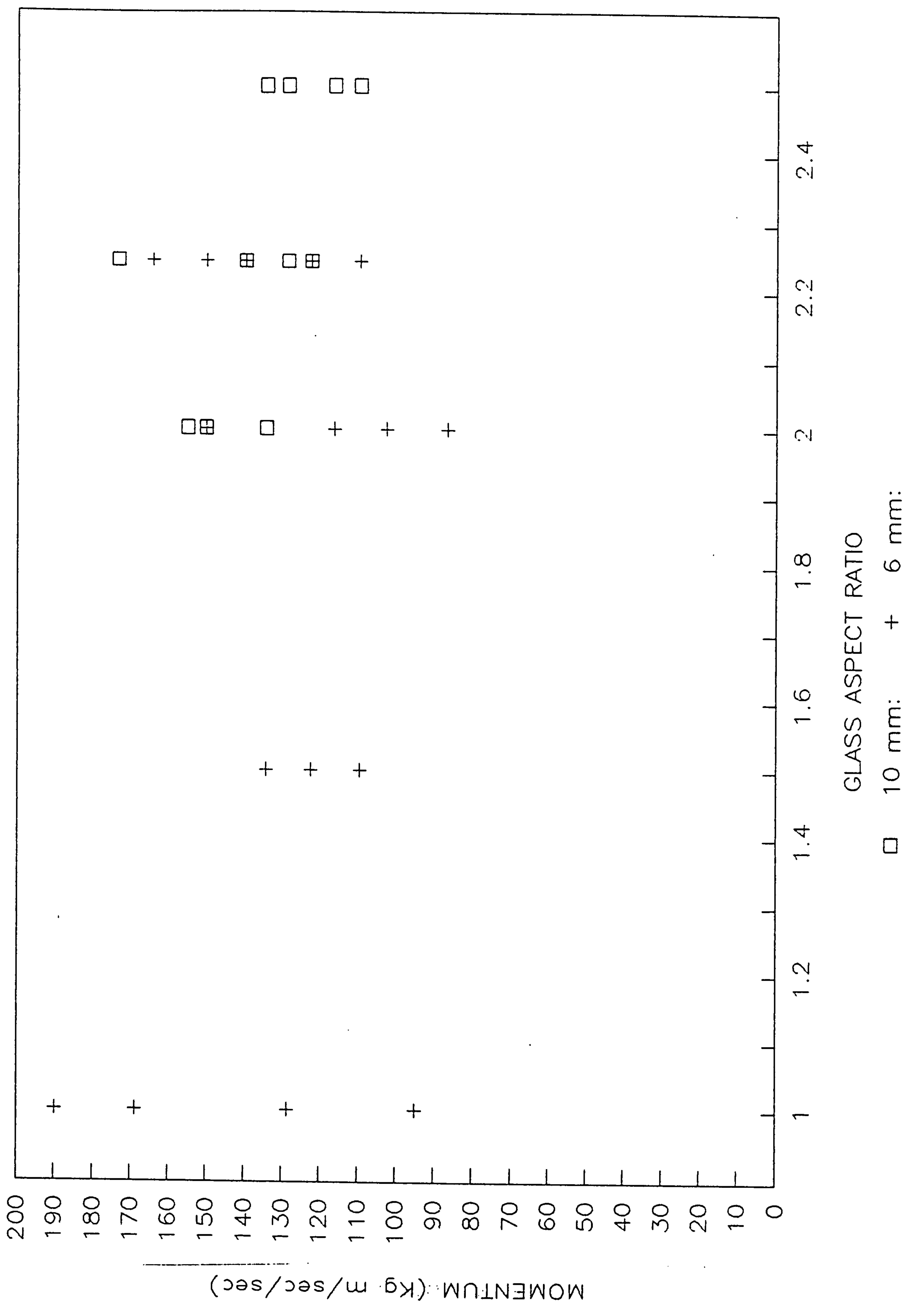

Figure 15 : Plot of momentum preceeding failure versus aspect ratio

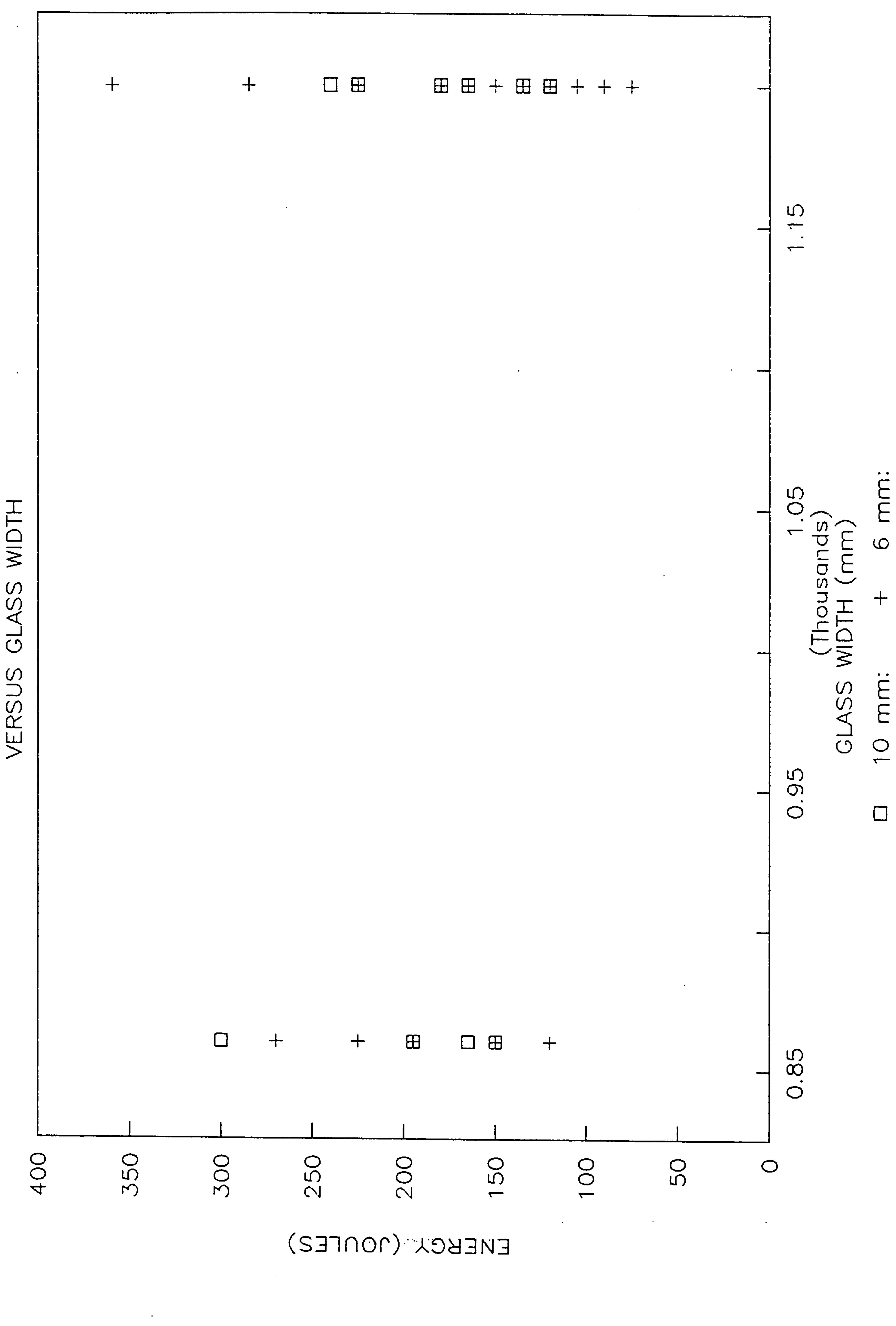

Figure 16 : Plot of energy level preceeding failure versus glass width

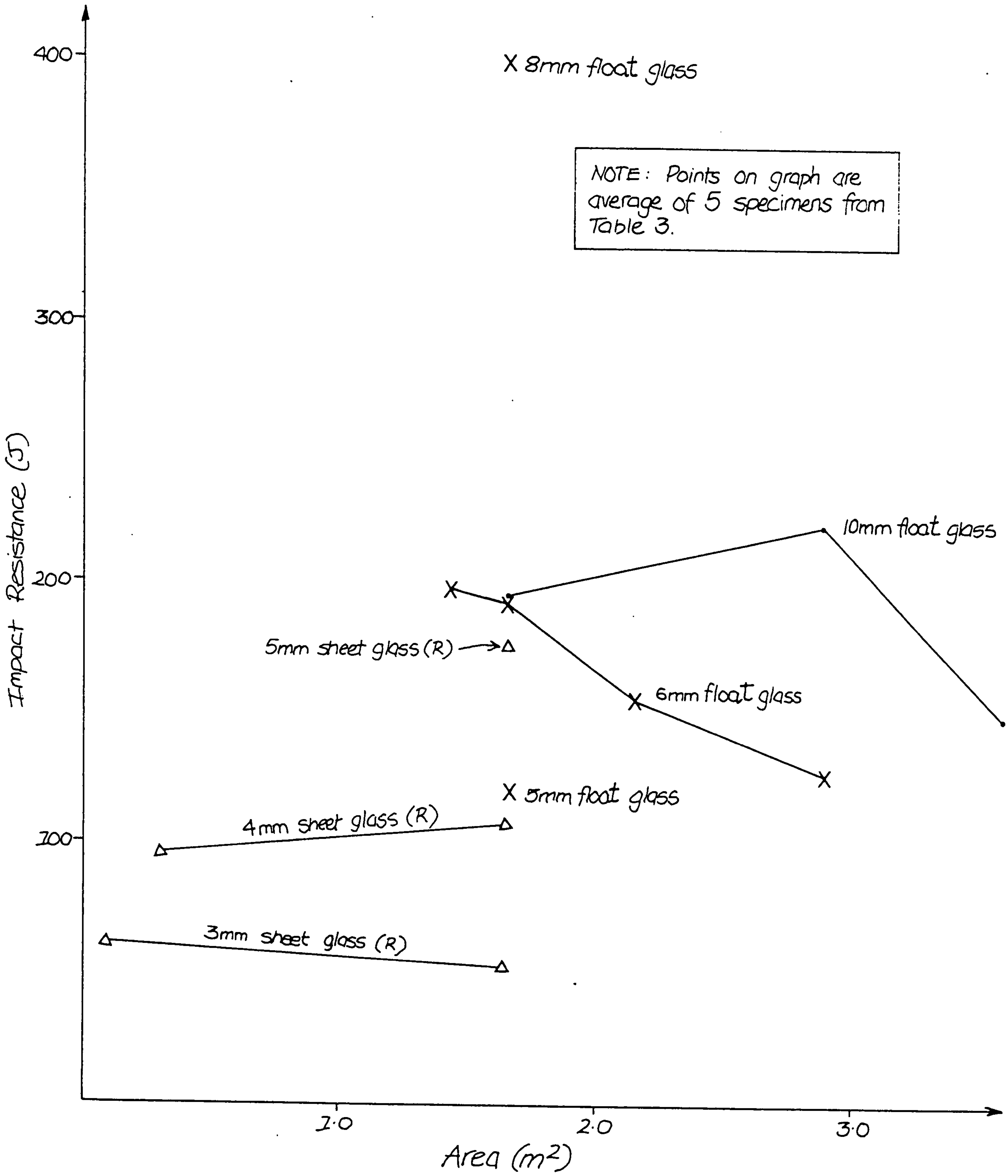

Figure 17 : Plot of impact resistance against glass area

STANDARD COMPARISON CHART

Maximum Area of Ordinary Annealed Glass for Fully Framed Glazing

Glass Thickness	NZS 4223 1985	NZS 4223 Revision 1990	AS 1288: 1979		AS 1288 1989	BS 6262 1982
			Domestic	Non-Domestic		
3	0.1	0.1	0.2	0.1	0.1	-
4	0.3	0.3	0.5	0.3	0.3	0.2
5	1.6	0.5	0.7	0.5	0.5	0.8
5.5	1.9	0.7	-	-	-	-
6	2.2	0.9	1.1	0.9	0.9	1.8*
8	3.7	1.8	2.0	1.8	1.8	-
10	5.6	2.7	3.0	2.7	2.7	3.3
12	7.7	4.5	5.0	4.5	4.5	5.0
15	6.3	6.3	1.0	6.3	6.3	-
19	-	8.5	-	-	8.5	-
25	-	12.0	-	-	12.0	-

* Minimum required for doors and side panels unless pane size less than 0.02 m^2, then 4 mm glass thickness is the minimum required.

MAXIMUM AREA FOR I.G.U

Glass Thickness	BS 6262:1982	AS 1288:1989	NZS 4223 Revision
4 + 4	0.6	0.45	
5 + 5	1.2	0.75	
6 + 6	2.5	1.35	
10 + 10	5.0	4.05	

Figure 18 : Comparison of various Code Requirements For glass thickness from Sage (1991)

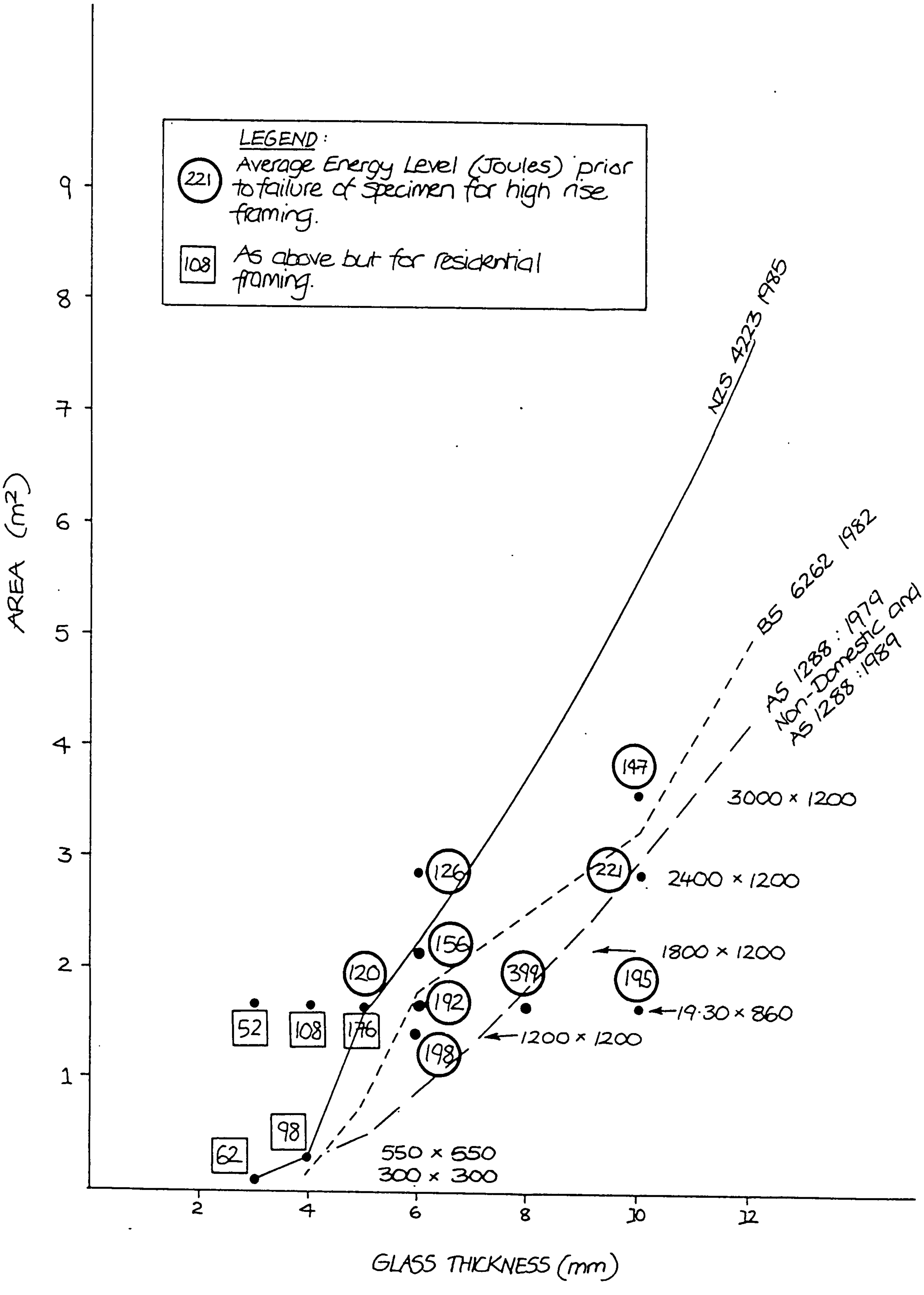

Figure 19 : Area versus glass thickness for annealled glass

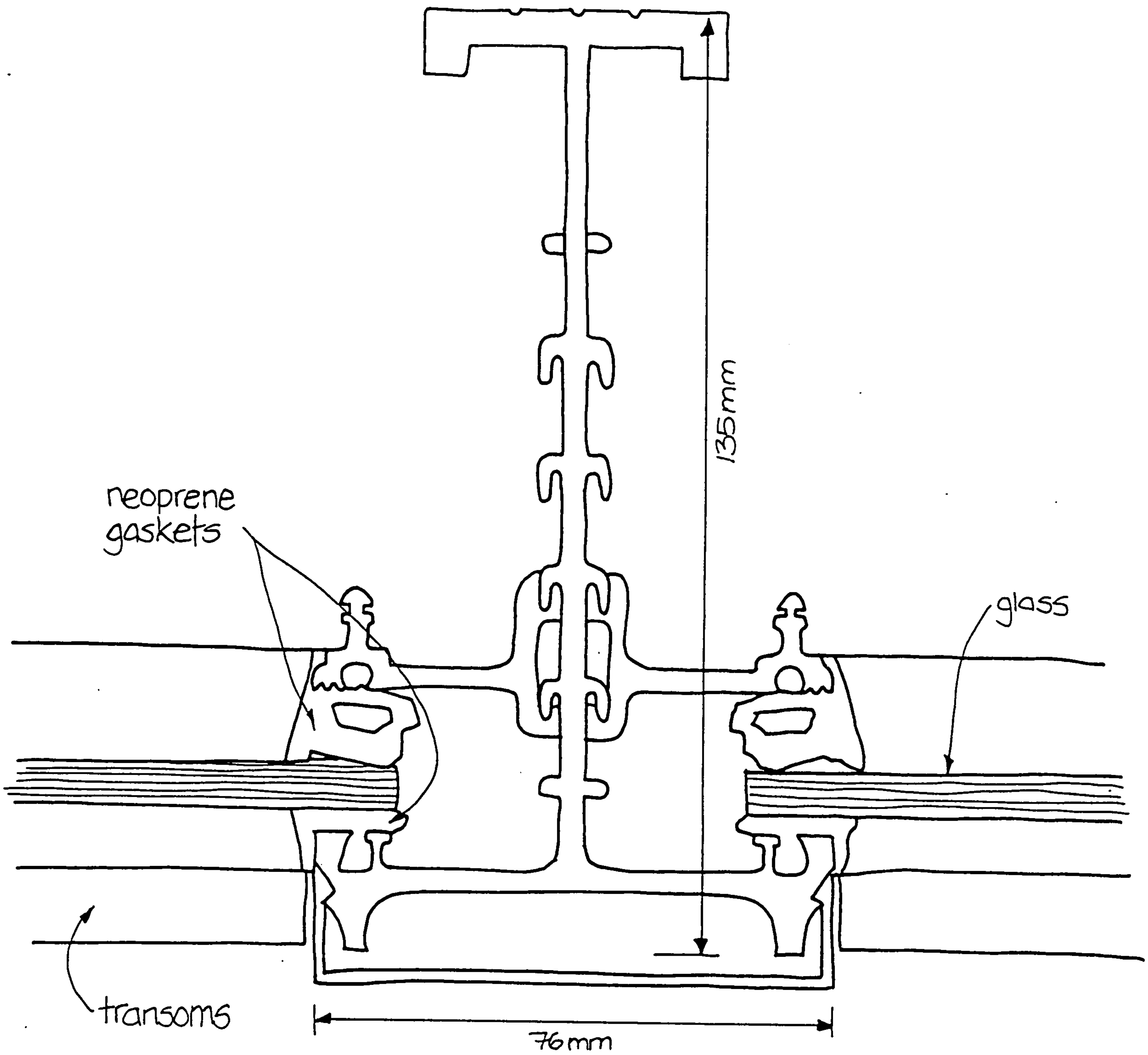

Figure A.1 : Vertical section through a mullion

Motion pattern	No. of recorded responses	P_{dyn}/P_{stat}				t_p (10^{-2} s)	deflection (mm)		
		mean	max	min			mean	max	min
1	36	0.83	1.42	0.47	0.22	3	0.4	1.2	0.1
2	32	1.10	1.81	0.55	0.37	3	1.0	1.8	0.4
3	31	1.35	2.13	0.79	0.36	3	0.8	2.0	0.1
4	36	0.91	1.95	0.27	0.47	14	1.3	2.6	0.4
5	39	5.15	9.60	1.76	2.00	7	0.4	1.0	0.1
6	25	1072	1960	400	399	3	1.4	2.6	0.2
7	38	0.96	1.49	0.39	0.26	3	1.2	2.0	0.6
8	39	1.36	2.24	0.51	0.45	8	2.5	3.8	1.2
9	34	2.06	3.84	0.92	0.80	7	3.5	7.4	1.6
10	37	2.10	3.90	0.65	0.90	5	3.2	5.8	1.2
11	37	2.53	5.08	1.14	0.82	6	4.1	6.4	1.2
12	34	2.20	3.41	1.01	0.64	7	1.3	2.4	0.4

Table 1 : Characteristics, basic values and other quantities compiled from the experiments involving a study of impact loads generated by human motion on a vertical test screen of 10 mm toughened glass used for walls from Nilsson (1976)

Glass Thickness mm	Glass Size mm x mm	Framing Members	Glass Type
6	2400 x 1200	multi-storey	float
10	2400 x 1200	multi-storey	float
6	1800 x 1200	multi-storey	float
6	1200 x 1200	multi-storey	float
10	3000 x 1200	multi-storey	float
10	1930 x 860	multi-storey	float
8	1930 x 860	multi-storey	float
6	1930 x 860	multi-storey	float
5	1930 x 860	multi-storey	sheet
5	1930 x 860	residential	sheet
4	1930 x 860	residential	sheet
3	1930 x 860	residential	sheet
4	550 x 550	residential	sheet
3	300 x 300	residential	sheet

Table 2 : Schedule of Specimens

	At the energy level prior to failure							
Glass size mm	Glass deflection		Mullion mid-height deflection	Mullion deflection at level of impact	Energy survived	Failure Energy		C.O.V
	mm	mean			J	J	mean	
3000 x 1200 x 10	15.0 17.1 17.3 19.7 20.2	17.9	7.7 8.9 9.2 10.7 11.0	6.0 6.5 7.1 8.1 8.7	120 135 135 165 180	135 150 150 180 195	162	0.15
2400 x 1200 x 10	• 19.3 23.1 23.2 23.8	22.4	13.5 17.6 17.1 17.6	11.0 14.4 14.1 14.6	180 240 225 240	195 255 240 255	236	0.12
2400 x 1200 x 6	- 26.1 26.6 23.8 35.4	28.0	- 2.6 10.0 8.2 16.6	- 3.3 8.4 6.8 14.6	90 135 105 75 225	120 150 120 90 250	166	0.42
1800 x 1200 x 6	26.8 29.2 31.3 32.2 29.1	29.7	10.2 11.8 12.8 13.7 12.0	8.8 9.9 9.9 11.6 9.8	120 150 180 180 150	135 165 195 195 165	171	0.15
1200 x 1200 x 6	39.6 21.0 20.2 27.3 36.7	29.0	19.3 7.0 7.1 11.1 17.9	13.9 5.2 5.3 7.9 13.3	360 90 90 165 285	375 105 105 180 300	213	0.57
1930 x 860 x 10	15.1 17.8 15.4 22.5 14.2	17.0	9.6 11.8 10.1 15.6 8.8	8.7 10.4 8.6 14.2 8.1	165 195 165 300 150	180 210 180 315 165	210	0.29
1930 x 860 x 8	21.8 32.7 33.7 36.4 32.9	31.5	10.7 22.3 22.0 24.8 23.2	10.3 18.8 20.1 22.0 20.3	195 390 450 525 435	210 405 465 540 450	414	0.30
1930 x 860 x 6	28.4 25.1 31.1 33.6 22.9	28.2	10.6 8.0 12.0 12.8 7.2	10.4 7.9 11.6 12.4 7.6	195 150 225 270 120	210 165 240 285 135	207	0.29
1930 x 860 x 5	• 25.0 34.3 19.0 26.7	21.0	7.2 11.7 4.4 8.2	5.0 10.0 2.8 5.9		120 210 60 130	130	0.47
1930 x 860 x 5 (R)	34.7 40.3 40.5 34.8 36.6	37.4	- - - - -	12.1 15.3 15.2 12.0 14.2	160 200 200 150 170	170 210 210 160 180	180	0.12
1930 x 860 x 4 (R)	20.9 34.1 31.1 40.0 38.3	32.9	- - - - -	3.2 8.4 7.0 10.6 9.7	40 110 90 160 140	50 120 100 170 150	112	0.39
1930 x 860 x 3 (R)	28.8 28.9 37.2 33.6 29.6	31.6	- - - - -	2.4 2.8 4.9 3.9 3.1	40 40 80 60 40	50 50 90 70 50	62	0.29
550 x 550 x 4 (R)	30.3 25.6 18.5 18.7 21.3	22.9	- - - - -	- - - - -	170 120 60 60 80	180 130 70 70 90	168	0.44
300 x 300 x 3 (R)	15.9 14.1 15.2 16.1 25.9	17.4	- - - - -	- - - - -	50 40 40 50 130	60 50 50 60 140	72	0.53

R = residential framing members   C.O.V = coefficient of variation-standard deviation/mean   • = accidental failure of specimen

Table 3 : Measured Parameters at Glass Pane Failure

Average (mm)												
Impact Energy (J)	2.4 x 1.2 x 6	1.8 x 1.2 x 6	1.2 x 1.2 x 6	3.0 x 1.2 x 10	3.0 x 1.2 x 10	1.93 x 0.86 x						
						10	8	6	5	5 (R)	4 (R)	3 (R)
10									7.5	7.2	10.6	15.7
15	9.0	7.4	-	-	3.3	2.6	3.5	7.0				
20									12.3	13.6	15.3	20.9
30	15.0	13.7	10.8	6.0	6.8	4.9	7.0	11.2	15.2	17.1	18.8	25.9
40									17.6	19.9	21.6	29.0
45	18.3	16.6	15.0	8.8	9.0	6.6	8.9	13.7				
50									18.8	21.9	24.8	31.3***
60	20.5	19.8	17.4	10.6	10.6	7.8	10.9	16.6	20.2*	23.9	27.2	34.1
70									21.2	25.7	29.2	36.3*
75	22.7	21.8	18.8	12.2	12.3	8.8	12.0	18.2				
80									22.7	27.3	30.8	37.2
90	23.2*	23.9	20.1	13.4	13.5	10.0	13.5	19.4	23.5	28.7	31.9	*
100									24.9	29.8	33.6	
105	25.5	25.2	21.2**	14.7	14.8	11.1	14.7	20.7				
110									25.6	30.9	35.2*	
120	25.7**	26.9	23.0	15.8	15.9	12.1	16.1	22.1	27.9*	32.1	36.9*	
130									28.9*	31.9	37.5	
135	27.4	28.1*	24.4	16.9	17.2*	13.4	16.9	23.7*				
140									28.9	34.1	38.5	
150	29.0*	29.4	25.4	17.9	18.6**	14.3	18.1	25.1	29.6	34.8	39.6*	
160									31.1	35.2*	40.0	
165	30.9	30.5**	27.2	19.0	19.3	15.2*	19.5	26.6*			*	
170									31.6	36.7*		
180	30.9	31.8	28.7	19.7	20.2*	16.3**	20.7	27.3	32.9	38.1*		
190									33.1	39.0		
195	32.1	**	30.0	21.3*	*	17.1	21.6	28.9				
200									34.3	40.4		
210	34.3		31.0	22.5		17.7*	22.4*	29.7*	*	**		
225	35.4		32.3	22.9		18.5	23.9	30.9				
240	*		33.2	23.5*		19.4	25.0	32.1*				
255			34.4	**		19.9	25.6	32.7				
270			35.8			21.1	26.5	33.6				
285			36.3			21.7	27.1	*				
300			36.9*			22.5	28.3					
315			37.3			*	28.6					
330			37.6				29.4					
345			38.8				30.2					
360			39.6				30.6					
375			*				31.3					
390							32.0					
405							32.0*					
420							33.1					
435							34.0					
450							34.0*					
465							34.3*					
480							34.6					
495							34.8					
510							35.6					
525							36.4					
540							*					

* - failure occurred in a specimen
(R) - residential framing members

Table 4a : Glass Deflection at Point of Impact Prior to Failure

Average (mm)												
Impact Energy (J)	2.4 x 1.2 x 6	1.8 x 1.2 x 6	1.2 x 1.2 x 6	2.4 x 1.2 x 10	3.0 x 1.2 x 10	1.93 x 0.86 x 10	1.93 x 0.86 x 6	1.93 x 0.86 x 5	1.93 x 0.86 x 5 (R)	1.93 x 0.86 x 3 (R)	1.93 x 0.86 x 4 (R)	1.93 x 0.86 x 3 (R)
10									0.5	1.3	0.5	0.5
15	-	1.0	-	-	1.0	1.0	0.9	1.2				
20									1.1	2.7	1.6	1.3
30	4.2	2.6	2.0	3.2	2.1	2.1	2.1	2.0	1.9	3.6	2.3	1.9
40									2.4	4.7	3.3	2.7
45	5.1	3.9	2.9	4.4	3.0	2.8	2.9	3.0				
50									2.9	5.4	4.0*	3.3***
60	5.7	5.3	3.7	5.6	3.9	3.6	3.8	4.2	3.3*	6.6	4.7	4.2
70									3.9	7.5	5.9	5.1*
75	6.9	6.4	4.3	6.5	4.5	4.2	4.1	4.7				
80									4.3	8.2	6.4	4.9
90	7.6*	7.1	5.0	7.5	5.1	5.0	5.1	5.5	4.3	8.5	6.7*	*
100									4.9	9.4	6.6	
105	8.6	8.0	5.3**	8.2	5.8	5.9	5.7	6.2				
110									5.3	9.7	8.1	
120	9.5**	8.8	6.2	9.1	6.4	6.6	6.4	7.0	6.0*	10.2	8.6*	
130									6.2*	11.1	9.0	
135	10.6	9.4*	6.7	10.2	7.1*	7.3	7.3	7.4*				
140									6.6	11.4	9.5	
150	11.1*	9.5	7.2	10.6	7.8**	8.0	8.0	8.1	6.98	11.9	9.8*	
160									7.1	13.0	10.6	
165	12.6	10.5**	7.9	11.2	8.1*	8.5*	8.5	9.0*			*	
170									8.0	13,4**		
180	12.3	10.7	8.1*	11.7	8.7	9.2**	9.6	9.4	8.4	13.5*		
190									8.5	14.7		
195	13.5	**	9.3	12.8*	*	10.5	10.4	10.0				
200									8.5	15.2		
210	13.9		9.7	13.3		10.5*	11.9*	11.0*	*	**		
225	14.6		10.4	13.9		11.1	12.4	11.8				
240	*		11.0	14.1*		12.0	13.0	11.3*				
255			11.7	**		12.5	13.8	11.1				
270			11.9			13.3	14.3	12.4				
285			12.8			13.9	14.9	*				
300			13.0*			14.2	15.2					
315			12.4			*	16.3					
330			12.7				15.9					
345			13.8				17.5					
360			13.9				17.2					
375			*				18.3					
390							18.7					
405							19.9*					
420							20.0					
435							21.0					
450							20.4*					
465							21.1*					
480							21.5					
495							22.4					
510							21.8					
525							22.0					
540							*					

* - failure occurred in a specimen (R) - residential framing members

Table 4b : Mullion Deflection at Height of Impact Prior to Failure

Impact Energy (J)	Average (mm) 2.4 x 1.2 x 6	1.8 x 1.2 x 6	1.2 x 1.2 x 6	2.4 x 1.2 x 10	3.0 x 1.2 x 10	1.93 x 0.86 x 10	1.93 x 0.86 x 8	1.93 x 0.86 x 6	1.93 x 0.86 x 5 (R)
10									0.9
15	-	1.4	-	-	0.9	1.1	0.9	1.0	
20									2.0
30	4.7	3.0	2.7	3.4	2.5	2.2	2.2	2.1	2.9
40									3.6
45	6.0	4.3	4.2	5.2	3.7	3.1	2.9	2.9	
50									4.2
60	6.7	6.0	5.1	6.7	5.0	4.1	3.7	4.0	4.7*
70									5.2
75	8.1	7.2	5.7	7.6	5.6	4.8	4.8	4.5	
80									6.0
90	8.9**	8.4	6.8	8.8	6.5	5.7	5.6	5.3	6.0
100									6.9
105	10.1	9.3	7.6**	9.7	7.4	6.6	6.4	6.1	
110									7.4
120	11.2**	10.1	8.5	10.9	8.4	7.4	7.0	7.0	8.5*
130									8.7*
135	12.6	10.7*	9.6	12.2	9.2*	8.2	7.9	7.6*	
140									9.2
150	13.3*	11.6	9.7	12.7	10.1**	8.7	8.7	8.1	9.4
160									9.9
165	14.6	12.3**	10.7	13.5	10.5*	9.6*	9.5	9.1*	
170									10.6
180	14.1	13.3	11.5*	14.1	11.0	10.4**	10.5	9.6	11.5
190									11.6
195	15.6	**	13.2	15.4*	*	11.3	11.3	10.4	
200									11.7
210	16.1		13.5	16.0		11.3*	13.4*	11.2*	*
225	16.6		14.1	16.8		12.2	13.9	12.1	
240	*		15.0	17.6*		13.0	14.6	11.7	
255			17.8	**		13.5	15.5	11.3	
270			18.9			14.5	15.9	12.8	
285			18.2			14.9	16.4	*	
300			17.6*			15.6	17.0		
315			18.0			*	17.9		
330			17.6				17.8		
345			18.8				19.5		
360			19.3				18.9		
375			*				20.3		
390							21.4		
405							22.2*		
420							22.4		
435							23.9		
450							22.9*		
465							23.8*		
480							23.9		
495							25.1		
510							24.3		
525							24.8		
540							*		

* - failure of a specimen

Table 4c : Mid-height Mullion Deflection Prior to Failure

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