THE JAMES COOK UNIVERSITY OF NORTH QUEENSLAND
CYCLONE STRUCTURAL TESTING STATION

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INVESTIGATION OF DIAPHRAGM ACTION OF CEILINGS

— PROGRESS REPORT 1 —

TECHNICAL REPORT No.10.

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DEPARTMENT OF CIVIL & SYSTEMS ENGINEERING
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George R. Walker
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Department of Civil and Systems Engineering,
James Cook University of North Queensland,
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PREFACE

It should be noted that this progress report is a summary of preliminary test results obtained in what is planned to be an extensive research programme. The authors believe that it is of benefit to the building industry to publish their findings in this manner, but stress that any conclusions drawn from these tests should be considered to be interim until the final report is published. Whilst it is unlikely that subsequent tests will cause any major changes in the conclusions expressed herein, they may cause the data to be reviewed in the light of some new finding or a more detailed analytical procedure. The analysis used for these results tends towards a lower limit of the strength of ceiling diaphragms. Where a high degree of continuity exists between bracing walls the ceiling strength may be significantly greater than concluded from the results of this report.

SYNOPSIS

The Department of Civil and Systems Engineering in conjunction with the James Cook Cyclone Structural Testing Station is currently engaged in a project in which the transmission of wind forces in domestic housing is being investigated. The project is being supported by the Australian Housing Research Council.

A major activity of this project is a study of the transmission of horizontal forces from the external walls through the roof and ceiling structure to the bracing walls. Initial work is being focussed on the diaphragm action of ceilings.

Three ceiling panels were tested using asbestos cement sheeting on timber battens, plaster board sheets on timber battens, and plaster board sheets on light gauge steel furring channels respectively.

The wide range of results obtained confirmed the need for a more detailed investigation and raised questions about the adequacy of some currently accepted systems of construction.

AUTHORS

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INVESTIGATION OF DIAPHRAGM ACTION OF CEILINGS - PROGRESS REPORT 1

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1. INTRODUCTION

Wind produces horizontal loads on buildings which must be transmitted through the structure to the foundation. In a large building these loads are often transmitted through a main structural frame. However, in the most common housing construction there is no frame in the normal structural sense. Loads are transmitted by a complex interaction between the walls, roof structure and floor structure (Walker, 1978).

The roof structure normally plays an important part in this action as most walls rely on support from the roof structure to prevent them blowing over. This is particularly true of typical stud frame wall construction where the major direction of load transmission of horizontal wind pressures within the walls is in the vertical direction to the roof and floor. The forces transmitted to the roof structure are then transferred through the roof to bracing walls which transmit them to the floor structure. They must then be transmitted to the ground through the lower storey, if one is present, and the foundation structure.

During recent years a considerable amount of work has been undertaken on the behaviour of bracing walls (e.g. Walker, 1980a) and the development of information for builders (Walker, 1980b; Smith and Adams, 1980; Queensland Government, 1981). However, very little information is available on the capacity of roof structures to transmit the wind pressure from the external walls to the bracing walls.

Nash and Boughton (1981) have demonstrated that well fixed corrugated iron can transmit considerable forces by diaphragm action and have indicated a method of calculating these. However, other types of metal cladding may not provide the same resistance and tile systems have no capacity for transmitting these forces. Consequently the ceilings are often relied upon to transmit these forces in conjunction generally with some diagonal roof bracing. The contribution of the latter in general is probably small due to difficulties of fixing and the low strength of the fixings normally employed.

As a consequence of the lack of information, current design requirements in regard to roof bracing, where they exist, tend to be rather arbitrary. The current Queensland Home Building Code (Queensland Government, 1981) effectively limits the spacing of bracing walls in timber framed construction to approximately 6 m for W42 construction and 9 m for W33 construction subject to the use of 'a conventional hardboard, asbestos cement, plasterboard, plywood, particle board or tongue and groove board ceiling or other material of equivalent stiffness securely fixed directly to the ceiling or roof structure or to battens which are in turn securely fixed to the ceiling or roof structure'. Compared with the other structural requirements of the Code it is a loose requirement open to a wide range of interpretations and it may well be the "Achilles heel" of the Code. It reflects the lack of information.

The present investigation at James Cook University is being directed at elucidating some of this lacking information in order to provide a basis for more rational design procedures and more soundly based building by-law requirements.

A survey of current ceiling construction indicated widespread differences, locally, regionally and nationally. Variations include batten spacing, type of battens, ceiling joist spacing, use of battens, use of glue and orientation of sheets in addition to the cladding material.

The three panels forming the subject of this report were based on 3 of the more common systems being used in the Townsville area. These are:

(1) Asbestos cement sheets nailed to timber battens and noggings with sheets laid parallel to direction of battens as depicted in Figure 1;

(2) Plasterboard sheets nailed to timber battens with sheets laid perpendicular to battens as depicted in Figure 2;

(3) Plasterboard sheets screwed to light gauge steel furring channels attached in turn to the timber joists by clips - see plate 1.

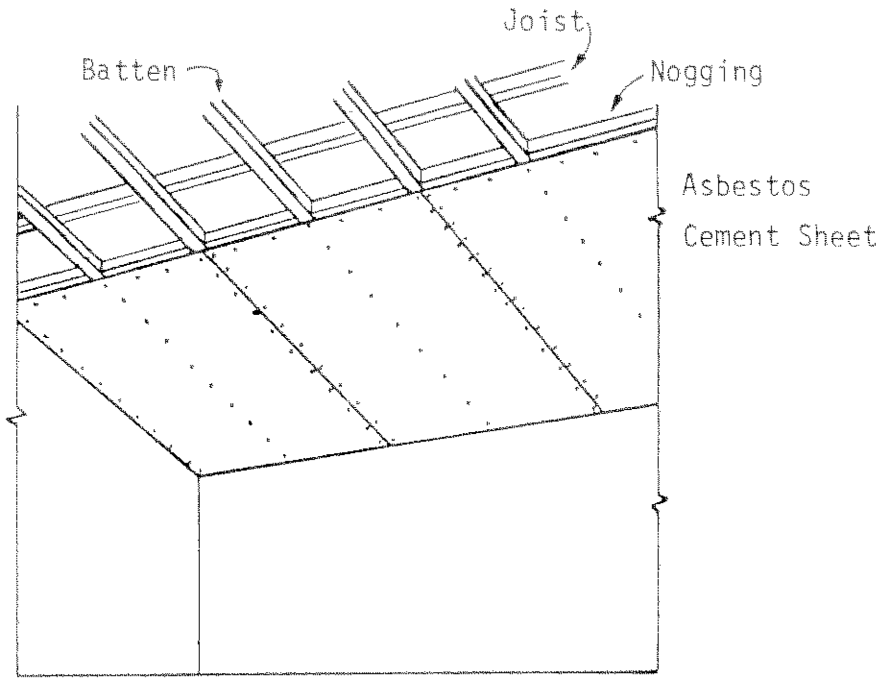

Figure 1. Fixing of Asbestos Cement Ceiling

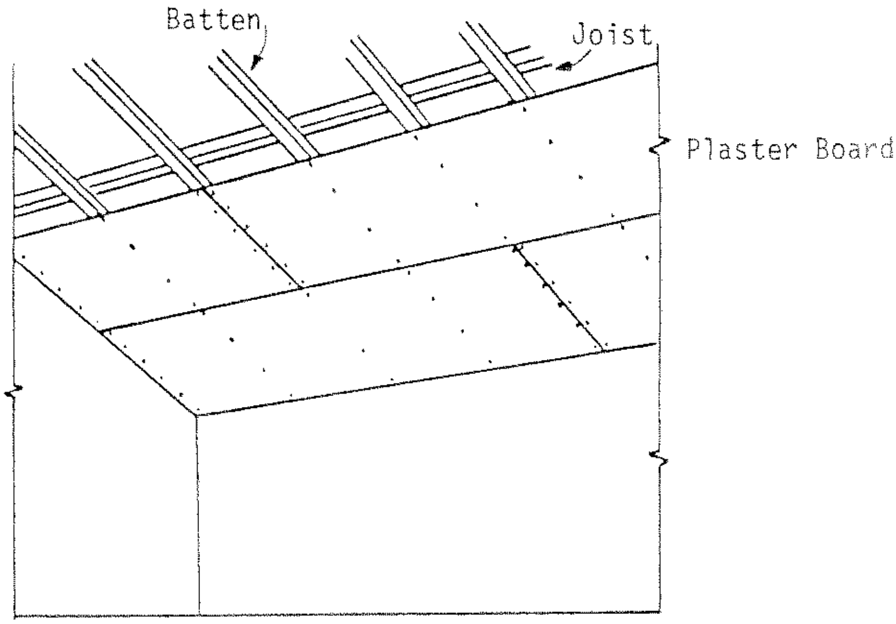

Figure 2. Fixing of Plaster Board Ceiling

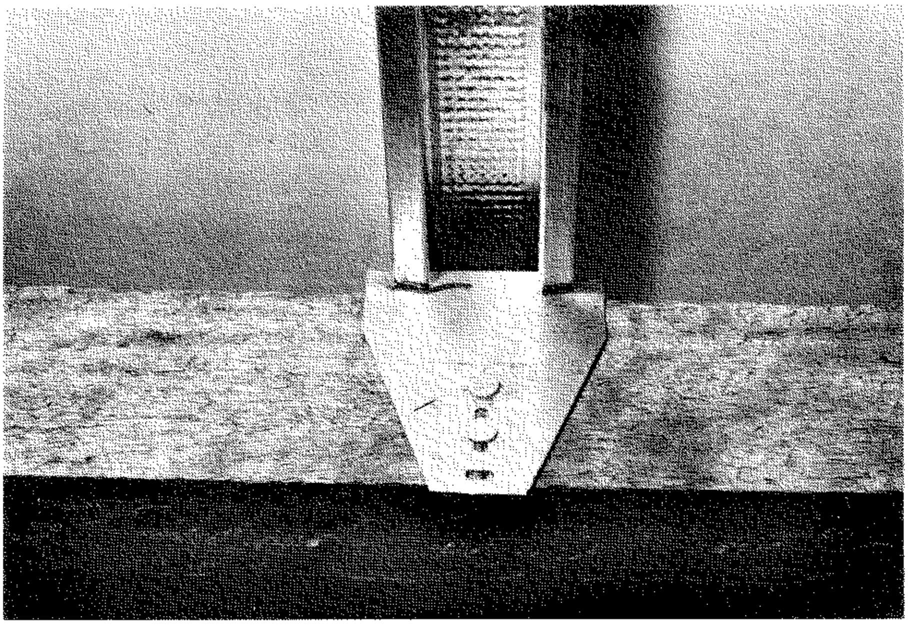

Plate 1 Furring Channel

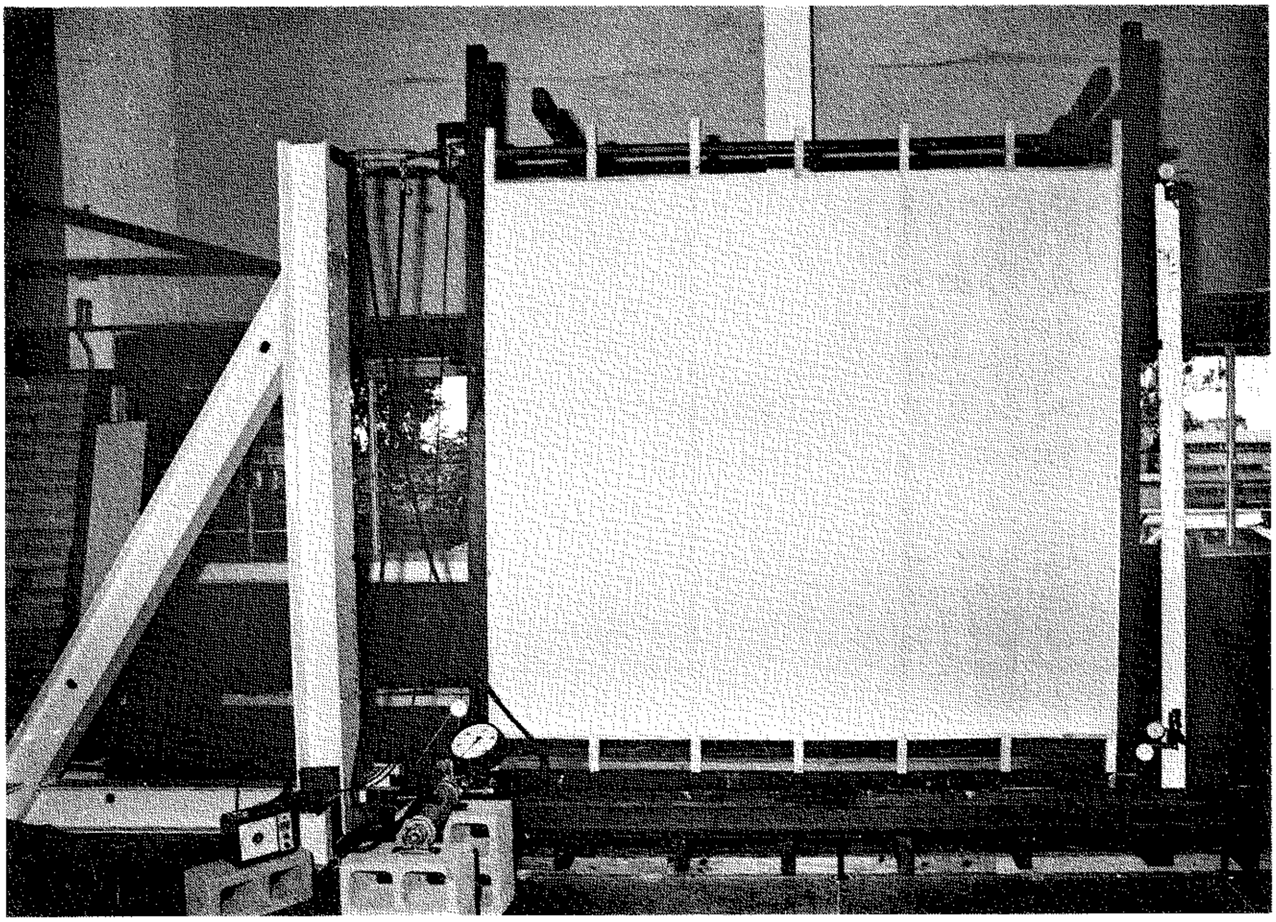

Plate 2 Ceiling Panel in Loading Rig

It is recognised that this is a very limited sample of the total range of ceiling systems used. Tests on other systems will be the subject of further reports.

2. TESTING ARRANGEMENT

Figure 3 gives a diagrammatic view of the testing arrangement in which the test panel was mounted vertically in the University's Wall Testing Machine and pushed at the top from one end.

Each test panel consisted of a framework comprising 70 x 70 mm spotted gum side members simulating the top plates connected by 70 x 36 mm spotted gum members on edge simulating the ceiling joists, to which were attached the ceiling battens or furring channels which supported the ceiling cladding material. Ceiling battens when used were 42 x 35 mm radiata pine battens on the flat.

The ceiling joist members were connected to the top plate members by bolted angle brackets as shown in Figure 4.

The panels were tied down to the laboratory floor by a pinned arrangement at the bottom of the 70 x 70 mm top plate members as shown in figure 5, and laterally restrained at the top to prevent transverse displacements and instability. The tie down and lateral restraint were designed to ensure that there was no restraint from the supporting system to the racking loads.

The racking load was measured by a load cell mounted at the loading point and deflections were measured by mechanical dial gauges mounted as shown in Figure 3.

Plate 2 is a photograph of a panel in the loading rig.

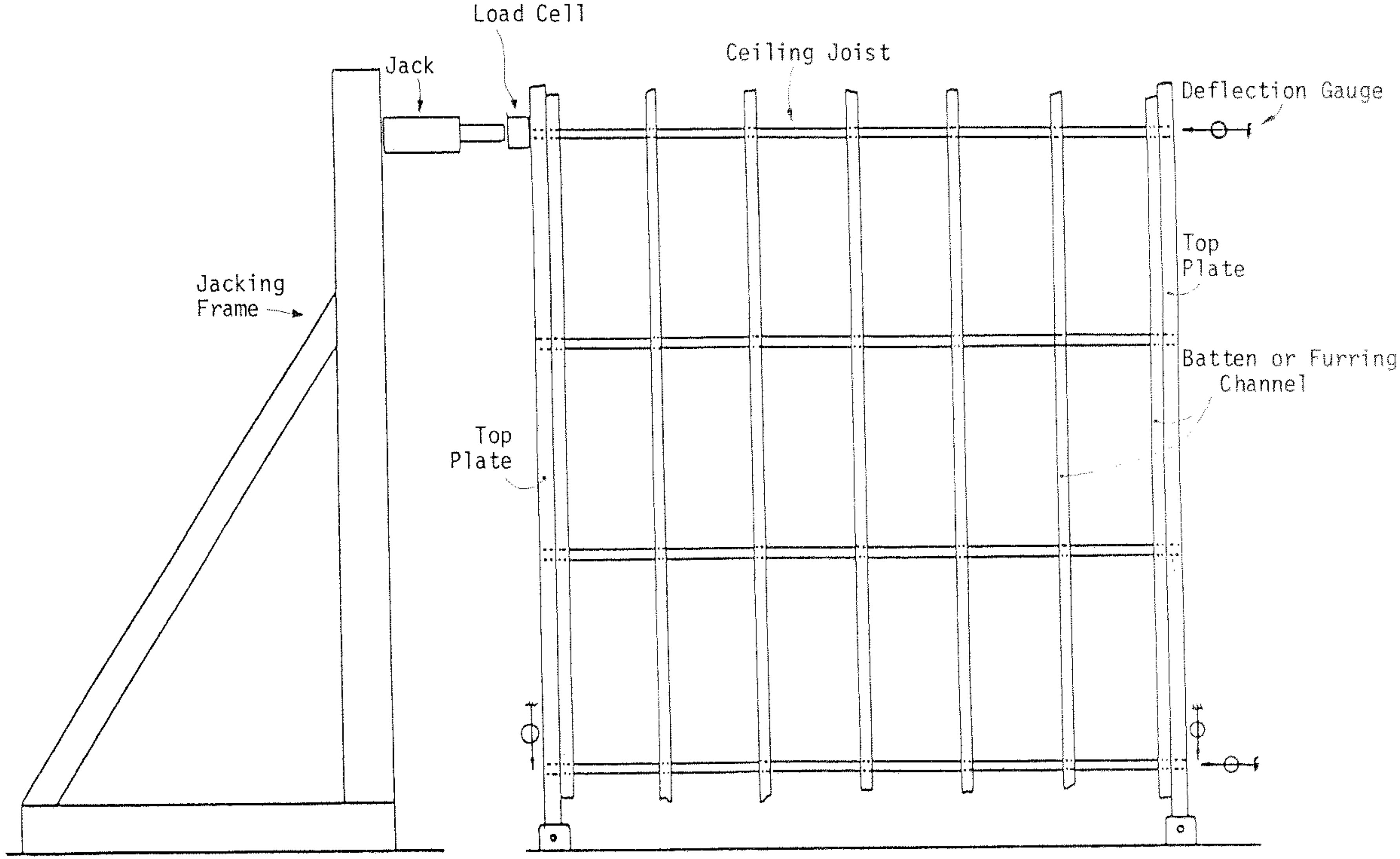

Figure 3 Testing Arrangement

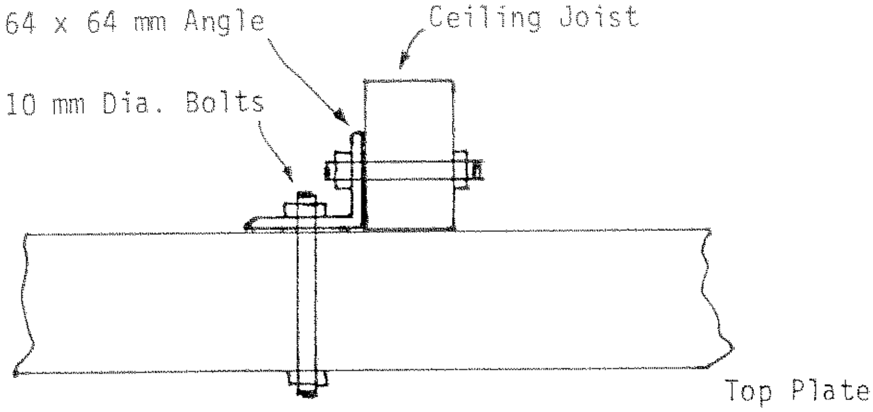

Figure 4. Fixing of Ceiling Joist Members to Top Plate Members.

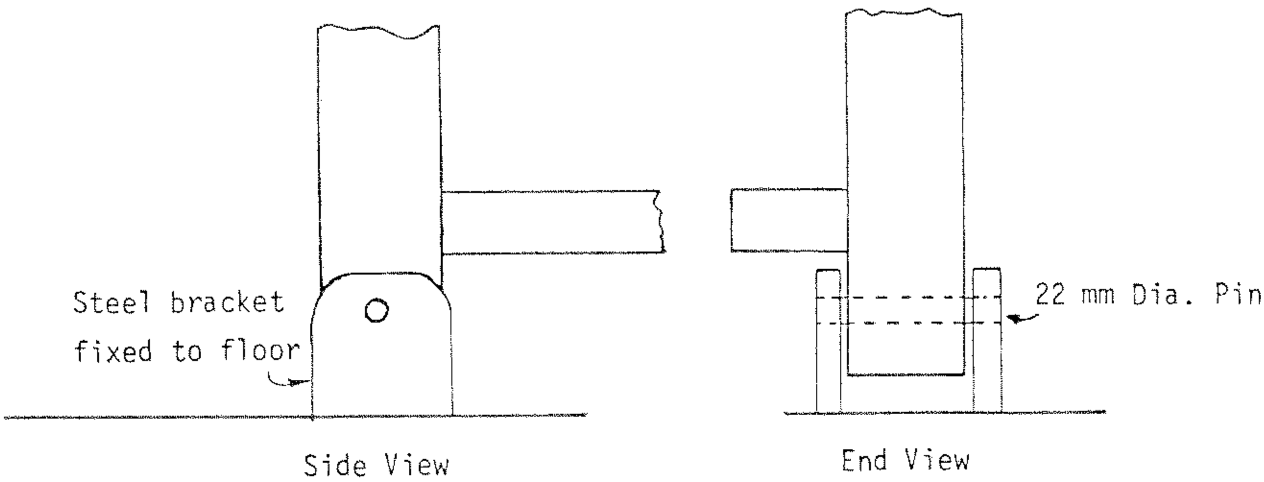

Figure 5. Tie Down Arrangement

3. DESCRIPTION OF TESTS

3.1 Asbestos Cement on Timber Battens

3.1.1 Test Panel

The panel geometry used in this test was:

spacing of top plate members:	2815 mm
spacing of ceiling joist members:	900 mm
spacing of timber battens:	450 mm

The timber battens were nailed to the ceiling-joist members by one 75 x 3.75 mm plain nail. The edge battens were not nailed to the top plate members. Nogging between the battens was used at ends of the asbestos cement sheets. The nogging was of the same material as the battens and skew nailed with two 50 x 2.8 mm plain nails at each end to them.

The cladding consisted of three 2400 x 900 x 4.5 mm 'Versilux' sheets manufactured and supplied by James Hardie Pty. Ltd. laid in the same direction as the battens. The sheets were fastened to the battens and noggings using 25 x 1.8 mm Flex Sheet nails at 150 mm spacings around the perimeter of each sheet and at 200 mm along the centre batten.

3.1.2 Test Procedure

The panel was loaded in increments of the order of 0.6 - 0.7 kN up to 7.7 kN, unloaded, reloaded in slightly larger increments to 10.1 kN, unloaded and reloaded in increments of the order of 1 kN to failure.

3.1.3 Test Results

The observed load deflection behaviour of the panel is shown in Figure 6. The deflection refers to the racking deflection of the panel frame over a height of 2400 mm.

Failure occurred at 12.0 kN by the cladding fasteners pulling through the cladding material.

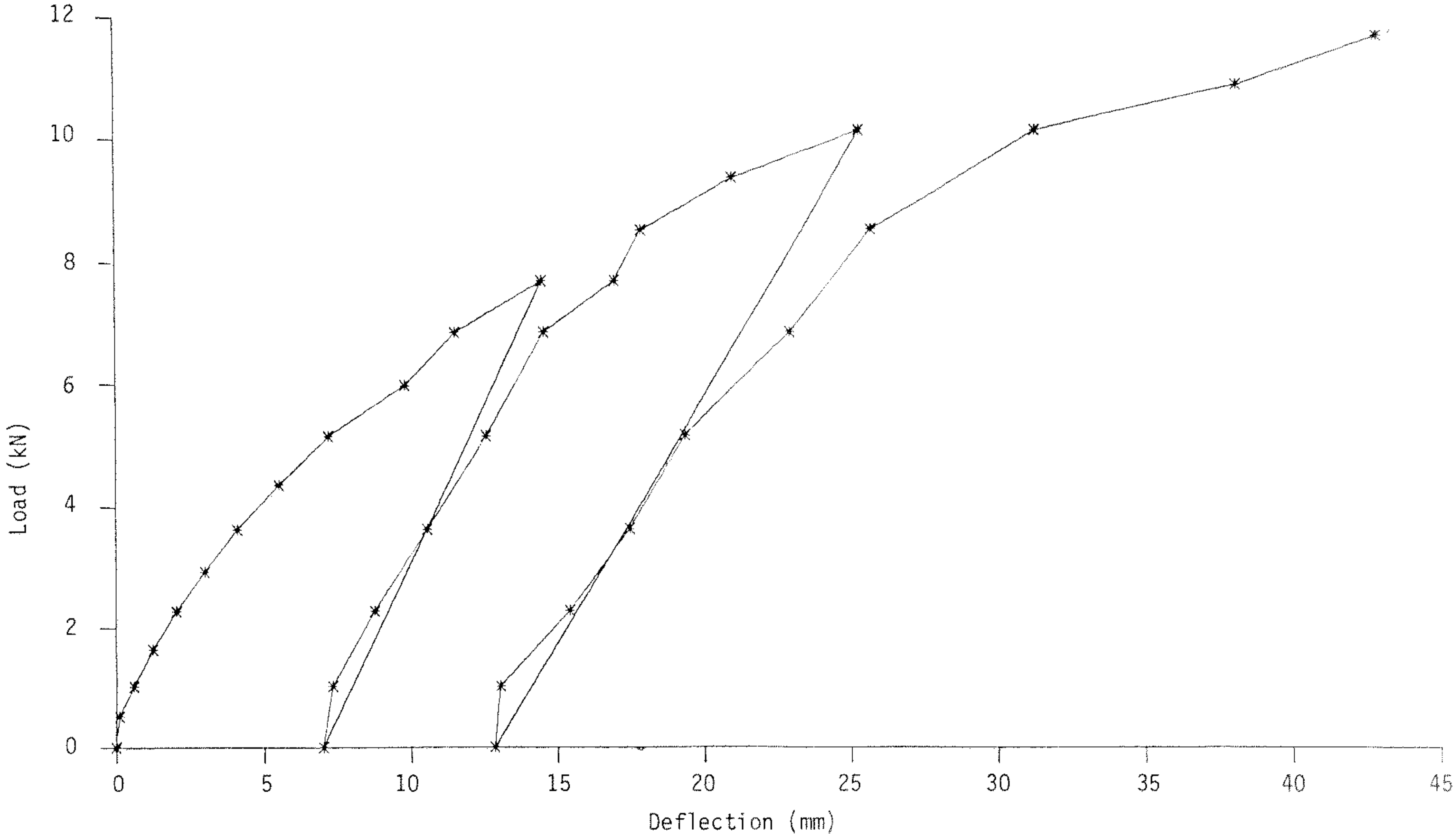

Figure 6 Load-Deflection Curve - Test 1

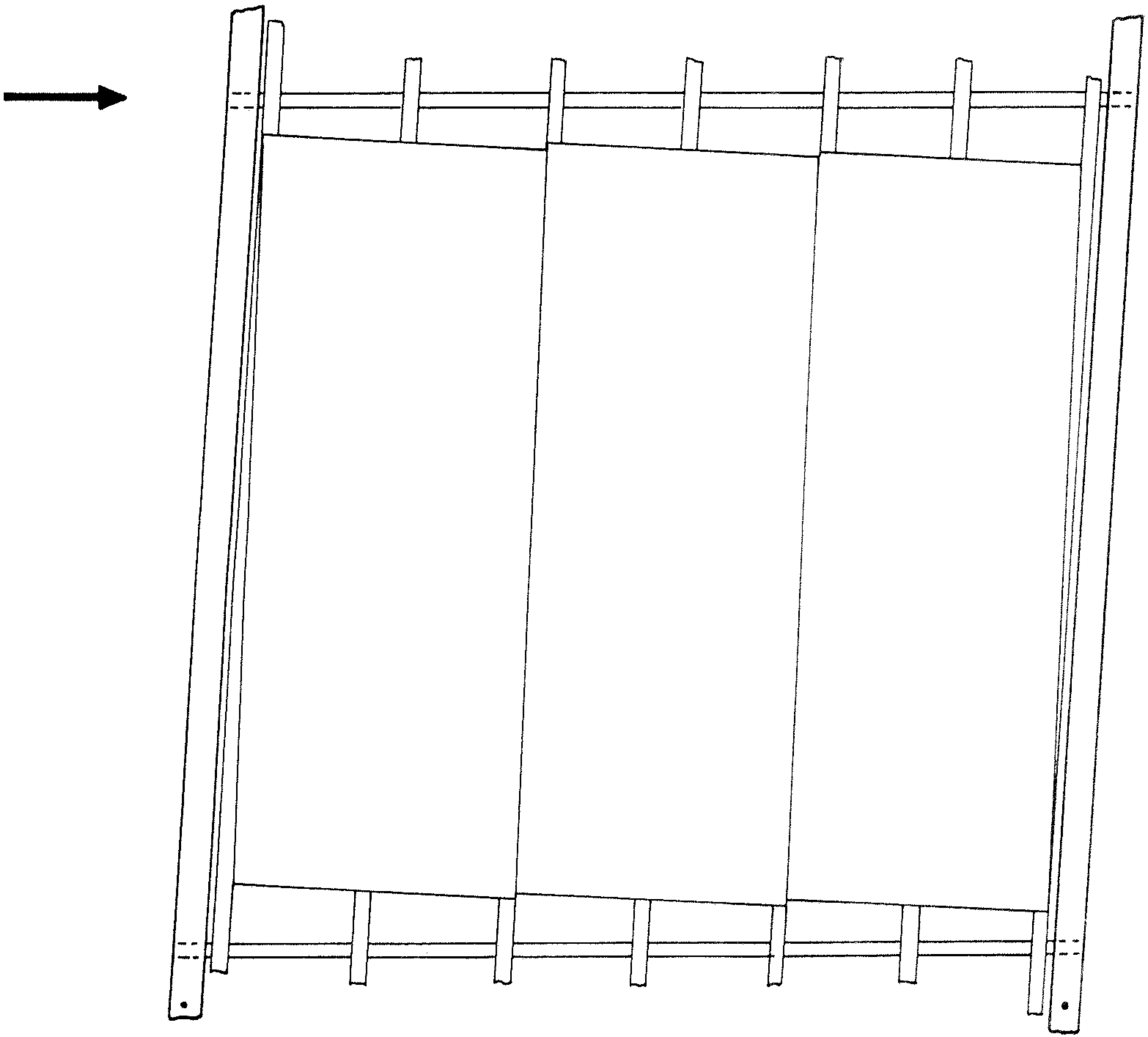

Figure 7. Deformed Pattern of Failure - Test 1

Figure 7 indicates the form of the deformed panel just prior to failure. Rotation of each of the panels relative to each other had occurred and rotation of the overall cladding system had occurred due to a relatively large displacement (approximately 25 mm) of the right hand batten relative to the ceiling joist members to which it was attached. There was also a noticeable curvature of the ends of battens due to an inconsistency between the overall area of the cladding and the spacing of the ceiling joists.

3.1.4 Comments

The general behaviour and ultimate load of the panel compared very closely with results obtained on wall panels of similar material and fastening configuration. This is not surprising as with end nogging the systems are very similar.

One significant difference between walls and ceilings is that in the latter the attachment of the edge battens can be critical. The large displacement of the right hand batten in this test indicated that this limit was close to being reached. Indeed in the final stages it is possible that friction between this edge batten and the adjacent top plate member may have been all that prevented complete failure of the batten-joist connections. Because of the individual rotation of the panel elements the resultant forces on the battens are only significant for the edge battens as the forces balance out in the interior ones. This failure mode could be effectively prevented by increasing the number of fasteners and fastening the battens directly to the top plate.

The stiffness indicated by the test - i.e. the initial slope of load deflection curve in Figure 6 - is lower than would be expected in practice due to the distortion obtained at the ends of battens which would not normally occur.

3.2 Plaster Board on Timber Battens

3.2.1 Test Panel

The panel geometry and fixing of the timber battens to the ceiling joist members was the same as that used for the asbestos cement clad panel. However, nogging between the battens was not used.

The cladding consisted of two 2700 x 1200 x 10 mm recessed 'Gyprock' sheets manufactured and supplied by C.S.R. Pty Ltd laid across the battens. The sheets were fastened to the battens by Gypsum 8 x 30 mm Hi-Lo Type S power drive screws at 300 mm centres along each batten. The recessed joint between the sheets and the screw head depressions were cemented using the Gyprock GB100 system with GBRM and paper tape as supplied by the manufacturers.

3.2.2 Test Procedure

The panel was loaded in increments of approximately 0.6 kN to 2.9 kN, unloaded, and reloaded to failure in similar increments.

3.2.3 Test Results

The observed load-deflection behaviour of the panel is shown in figure 8. Failure occurred at a load of 3.6 kN as a result of the fasteners pulling through the cladding.

Figure 9 indicates the form of the deformed panel just prior to failure. In contrast to the previous test no relative movement occurred between individual sheets, the entire cladding rotating as a single unit. No significant relative displacement between the battens and the ceiling joist members was observed.

3.2.4 Comments

The general behaviour was similar to previous wall tests using plaster board cladding in respect of the maintenance of continuity across the joint between the sheets causing the cladding to rotate as a single unit.

The ultimate load was lower than obtained in wall tests, but consistent with the lesser number of fasteners used in the ceiling panel as a result of the fasteners being restricted to the batten lines only.

The lack of any appreciable relative displacement between the battens and ceiling joists, particularly at the ends can be attributed to the relatively low failure load compared with the previous test.

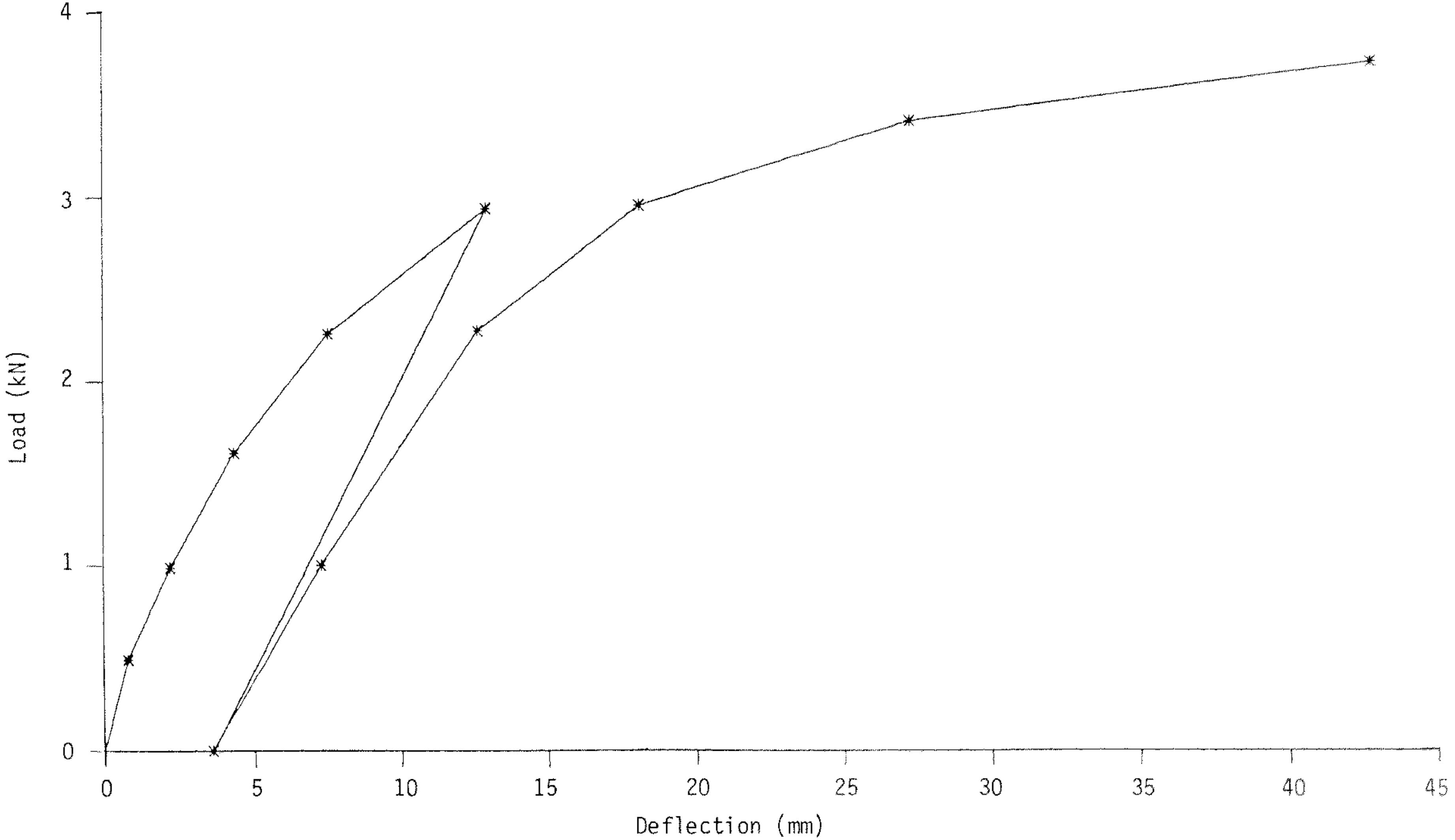

Figure 8 Load-Deflection Curve - Test 2

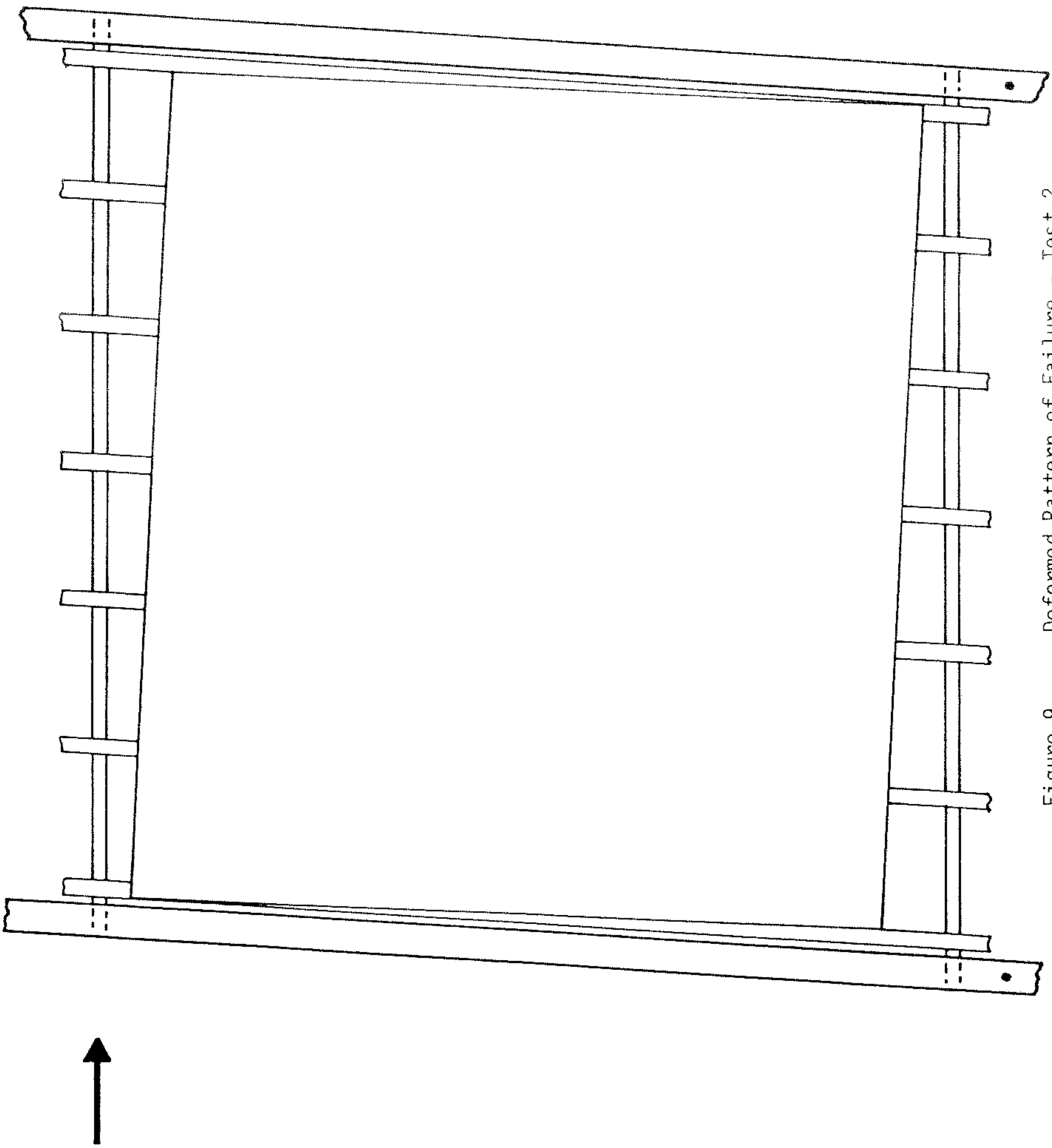

Figure 9. Deformed Pattern of Failure - Test 2

3.3 Plaster Board on Furring Channels

3.3.1 Test Panel

In this panel the spacing of the ceiling joist members was reduced to 800 mm so that the full test area was covered by the cladding. The spacing of the top plate members remained the same as for the previous tests at 2815 mm.

In place of the timber battens used in the previous two tests, CSR Rondo furring channels at 450 mm centres were used. These were fixed to the ceiling joist members with 'direct fixing clips' according to the manufacturer's instructions.

The plaster board cladding and cementing of the joint and over the screws was the same as for the panel using plaster board on timber battens. The plaster board was fixed to the furring channels using Gypsum 6 x 25 mm Bugle Head Tek power driven screws at 300 mm spacings along the furring channels.

3.3.2 Test Procedure

The panel was loaded in increments of the order of 0.2 - 0.3 kN to failure.

3.3.3 Test Results

The observed load deflection behaviour is shown in figure 10.

Initial failure occurred at approximately 1 kN when the furring channels began to slide relative to the ceiling joists. The panels continued to take an increase in load beyond this point but this was associated with a large increase in deflection as the furring channels moved longitudinally and the fixing clips were twisted laterally allowing the cladding to rotate.

The rotation of the plaster board continued until it came in contact with the top plate members as shown in figure 11. At this stage the load was approximately 2.5 kN and the deflection approximately 100 mm. From this point on there was a dramatic increase in stiffness. Ultimate failure finally occurred at a load of 5.1 kN as a result of crushing of the plaster board against the top plate member.

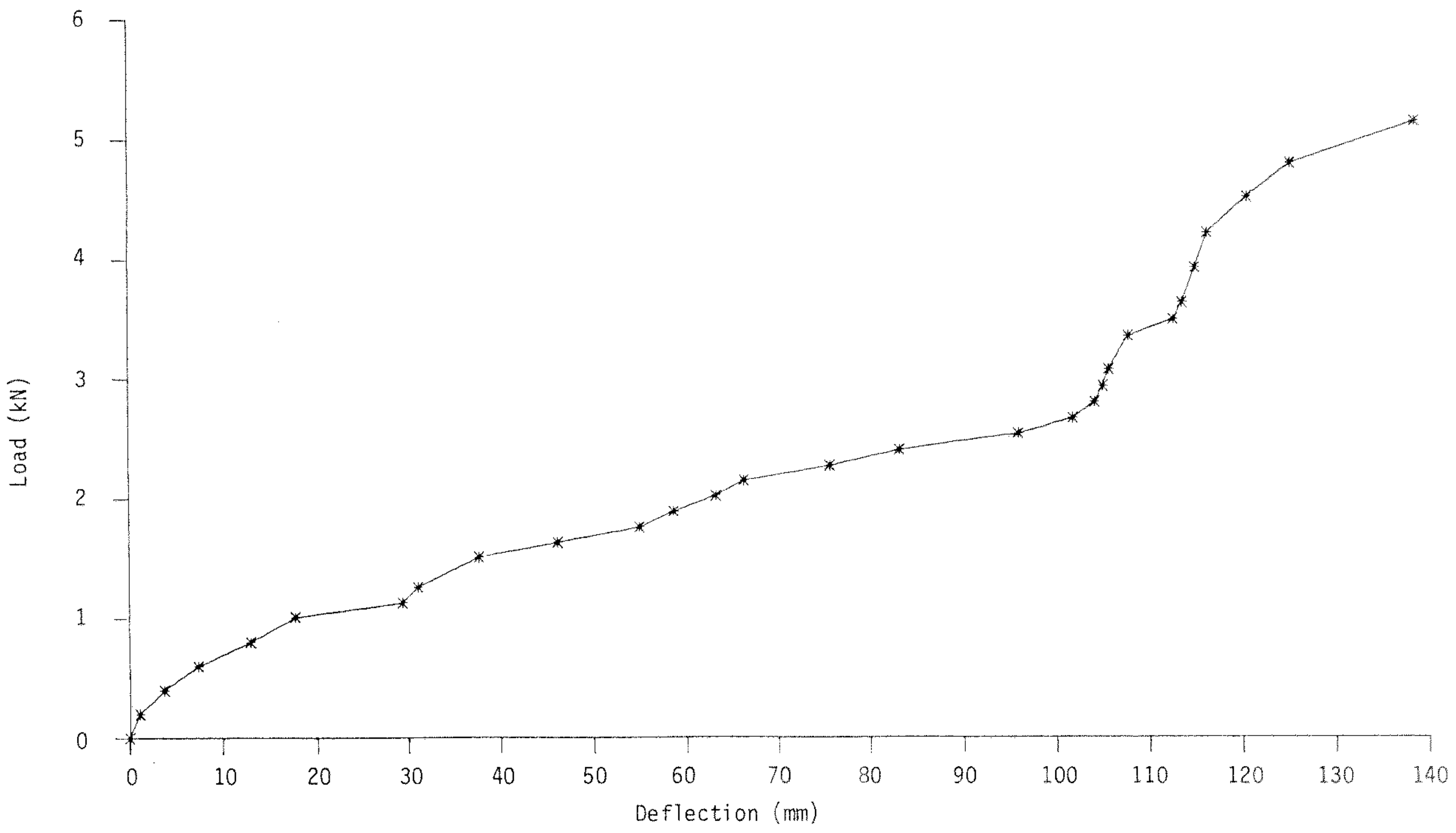

Figure 10 Load-Deflection Curve - Test 3

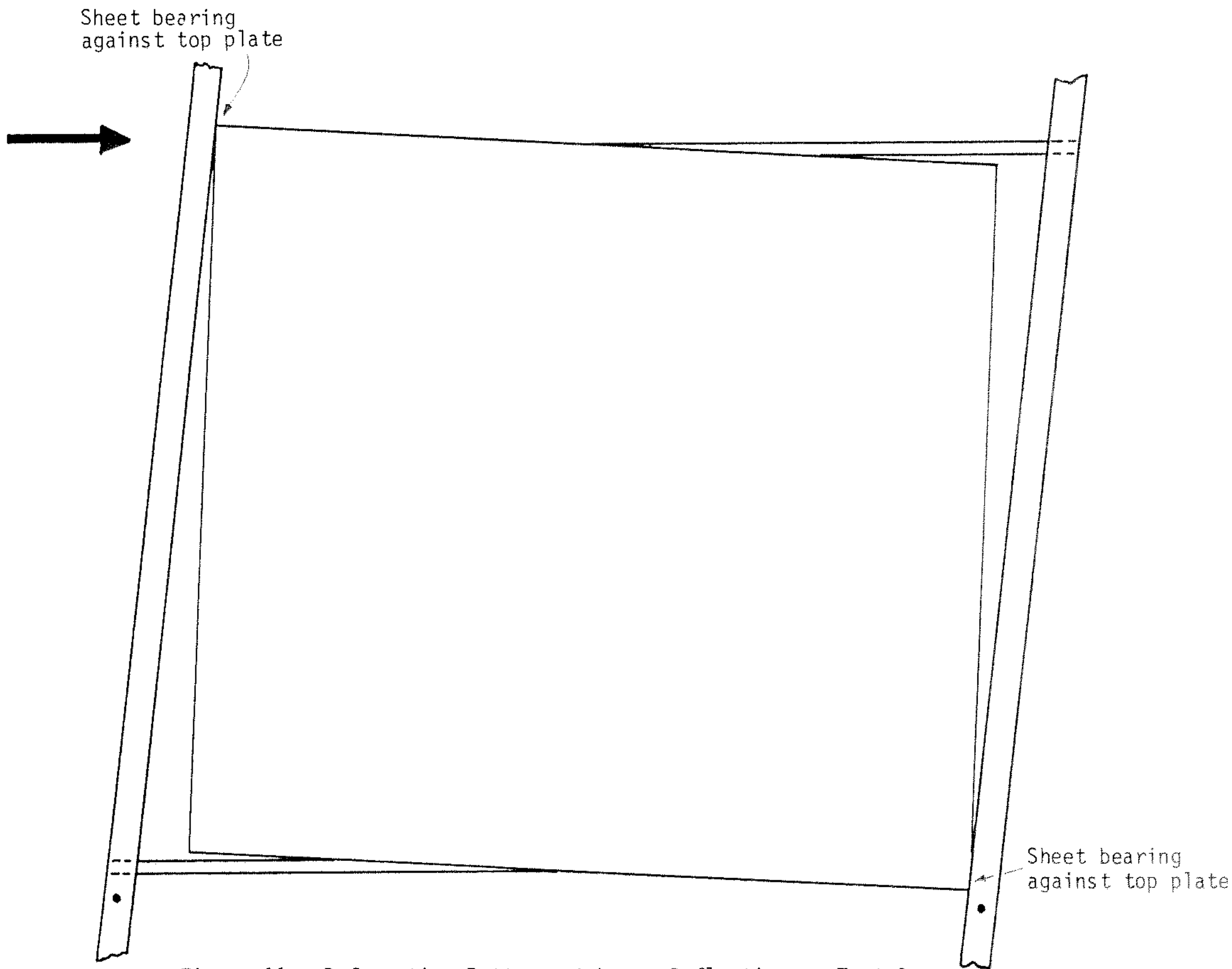

Figure 11. Deformation Pattern at Large Deflections - Test 3

As in the previous plaster board test the entire cladding rotated as a complete unit with the cemented joint between the sheets retaining its integrity.

3.3.4 Comments

The test demonstrated the poor ability of the clipped furring channel system to transmit the shear forces from the cladding to the ceiling joist members. A more positive connection of the furring channels to the ceiling joist members would be necessary if they are to be used in this manner.

The additional load attained following the contact between the plaster board and the top plate members suggests that a significant improvement could be achieved by ensuring contact from the beginning. Clearance is necessary for erection purposes but if the gap could be subsequently fill-ed with cement it seems that the shear forces could be directly transferr-ed from the top plate to the cladding without having to utilise the furring channels. It may also considerably increase the resistance of plaster board on timber batten systems.

4. CONCLUSIONS

Each of these tests can be treated as a prototype of the system tested and a design strength evaluated according to the principles established in EBS Technical Record 440 'Guidelines for the Testing and Evaluation of Products for Cyclone-Prone Areas' (EBS, 1977) and further amplified in Technical Report No. 5 of the James Cook Cyclone Structural Testing Station (Reardon, 1980). In accordance with these principles the design strength can be obtained from the observed strength by dividing the failure load by 2.6 when only one test has been performed.

From the results of the tests the following design strengths are obtain-ed for each of the 3 systems expressed in terms of force per metre width.

1. For 2400 x 900 x 4.5 mm 'Versilux' asbestos cement cladding fixed along 42 x 35 mm radiata pine battens at 450 mm centres and trans-verse noggings as described in section 3.1.1 the estimated design strength is 1.7 kN/m.

2. For 2700 x 1200 x 10 mm recessed 'Gyprock' plasterboard sheets fixed across 42 x 35 mm radiata pine battens at 450 mm centres as described in section 3.2.1 the estimated design strength is 0.5 kN/m.

3. For 2700 x 1200 x 10 mm recessed 'Gyprock' plasterboard sheets fixed across Gyprock furring channels at 450 mm centres as described in section 3.3.1 the estimated design strength is 0.15 kN/m.

In comparing these figures it should be noted that the primary factor accounting for the differences in estimated design strengths is the method of fixing.

The first system using asbestos cement cladding may be considered representative of systems in which the ceilings are constructed along the same lines as bracing walls with the cladding being fastened at close centres around the *entire perimeter* of the cladding unit. This implies the necessity for nogging along the edges not supported by the battens.

The second system using plasterboard on timber battens may be considered representative of systems in which the cladding is laid across the battens or ceiling joists with a consequent significant reduction in the number of fasteners, especially around the perimeter where they are most effective.

The third system using plasterboard on furring channels may be considered representative of systems using clip fixed light gauge steel members in place of timber battens.

The design values of strength may be compared with the estimated horizontal design loads transmitted to the roof structure at ceiling level from the walls. For 2.4 m high walls which carry the loads by beam action between floor and ceiling, the estimated load at the ceiling level is 1.8 kN/m along the length of wall in a category 3 cyclone area and double this in a category 2 cyclone area. Assuming a 7 m wide house, a design shear strength of 1.7 kN/m across the width of the roof would support a 13 m length of dwelling between bracing walls in a category 3 cyclone situation and 6.5 m length in a category 2 cyclone situation; a design strength of 0.5 kN/m would support 4 m in a category 3 cyclone area and 2 m in a category 2 cyclone area; and a design strength of 0.15 kN/m would support 1.2 m in category 3 cyclone area and 0.6 m in category 2 cyclone area.

The degree to which the test procedure simulates the real behaviour of ceilings varies depending on the degree of continuity between shear walls. It is believed that the results obtained will tend to indicate a lower limit to the strength of ceilings of similar construction. The actual strength may be significantly greater where a high degree of continuity exists.

The results obtained suggest that if the ceiling alone is required to transmit the reaction forces from the wind loads on the walls, systems constructed similar to bracing walls with closely spaced perimeter fastening may be adequate for category 2 cyclone situations if bracing walls are to be at spacings of up to 6 m in houses not less than 7 m wide.

The results of the timber battened plasterboard tests indicate that it should be possible to utilise this cladding in category 3 cyclone locations. Although the tests indicated that the furring channel system is totally inadequate if used as tested, the system may prove suitable if continuity between bracing walls can be achieved or if the channel was pierce fixed rather than clipped.

It is important to realise that the problem is more acute the narrower a house. For instance, the second system tested would be adequate for bracing wall spacings up to 6 m if the house width exceeded 10.5 m.

The tests have demonstrated the wide range in shear strengths of commonly used ceiling systems. They have shown that it is possible to achieve the necessary strengths to satisfy current rules in respect of bracing wall spacing but indicated that in practice some of the systems being used may fail to achieve this, possibly by a large margin. If the low shear strength systems are preferred, they should be used in conjunction with a roof cladding system capable of providing bracing. Otherwise a special bracing system should be provided in the roof structure.

These preliminary tests have indicated that the shear strength of the roofing structure, including the ceilings and roof cladding, may well be a weakness of current house building practice. Further tests are now planned to obtain design strength information on a wider range of systems currently being used and to investigate ways in which they may be improved with a view to establishing a more rational approach to this aspect of housing construction.

The exercise of attempting to interpret the results has also indicated shortcomings in our current appreciation of the mechanics of the diaphragm behaviour of ceiling systems. Analytical studies will be undertaken with a view to solving this problem.

5. ACKNOWLEDGEMENTS

The work described in this report was undertaken as part of a research project on the behaviour of houses subject to wind being funded by The Australian Housing Research Council. The contributions of James Hardie Pty Ltd and CSR Pty Ltd who supplied the cladding materials is acknowledged. The authors are also grateful to their colleagues G.F. Reardon and G.N. Boughton of the Cyclone Testing Station, and G. Baxter, the technician assigned to the project, for their contribution.

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