CYCLONE TESTING STATION

INVESTIGATION OF DIAPHRAGM ACTION OF CEILINGS

PROGRESS REPORT 3

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PREFACE

It should be noted that this progress report is a summary of interim test results obtained as part of 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.

SYNOPSIS

The Department of Civil and Systems Engineering at James Cook University of North Queensland and the James Cook Cyclone Structural Testing Station are currently engaged in a major joint program of research related to the transmission of wind forces in domestic housing.

One of the major projects within this program is a study of the capacity of the ceiling structure to transmit horizontal forces from the external walls to the bracing walls by diaphragm action. This project, which is being undertaken within the Department of Civil and Systems Engineering, with assistance from the Cyclone Testing Station, is being supported by the Australian Housing Research Council.

This report describes the third and final phase of tests on ceiling panel assemblies undertaken as part of this project. Ten tests are described, five on plasterboard ('Gyprock') ceiling systems, one on a fibre cement ('Villaboard') system, three on asbestos cement ('Versilux') systems and one on a hardboard ('Readifix') system. Unlike the earlier tests, in which the systems were tested in the same manner as shear walls, in this phase the ceilings were tested as simply supported deep beams which may be considered more representative of actual ceiling behaviour.

The tests indicated that there are significant differences in behaviour between clad panels acting as shear walls and as deep beams. In general higher ultimate loads were obtained than had been predicted from the previous tests.

The tests showed that the behaviour of ceilings acting as deep beams is more complex than that of shear walls in simple racking. Factors such as aspect ratio and, in some cases, the configuration of the individual sheets of cladding appear to have a significant influence on the strength making general design recommendations more difficult.

The tests highlight the need for an analytical structural model on which to base design procedures if the limitations associated with the use of tests results in conjunction with simple criteria are to be avoided.

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1. INTRODUCTION

This is the third interim report on a research project funded by the Australian Housing Research Council which is focused on the action of ceilings in distributing lateral loads on dwellings to the shear walls.

The overall project involved three main aspects:

- experimental investigation of the behaviour of typical ceiling assemblies;
- correlation of results of tests on ceiling assemblies with predictions based on structural engineering theory and associated computer models;
- formulation of recommendations on the utilisation of ceilings for the transfer of horizontal loads based on these studies.

This report, as was also the first two progress reports, is concerned solely with the first aspect - i.e. the tests conducted on ceiling panels. These tests were undertaken in three phases:

- a preliminary set of three tests representative of the range of common ceiling systems;
- a set of twelve tests examining in more detail the effects of differences in construction of common ceiling systems;
- a set of ten tests using a different testing arrangement to

examine the influence of testing procedure.

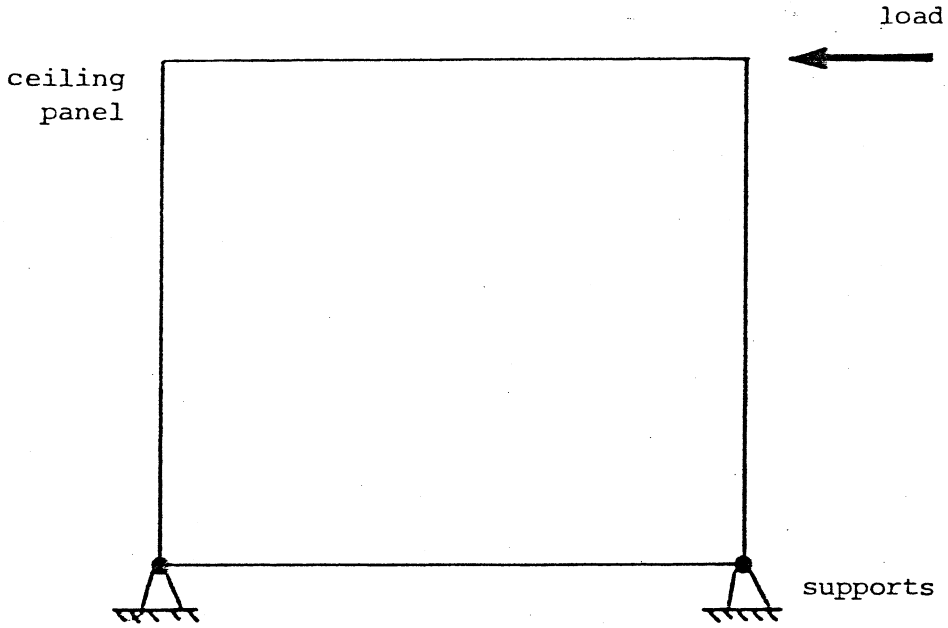
The first and second progress reports [1,2] described the results of the first two phases. This report describes the results of the ten tests conducted in the third phase. Of the ten tests, five were conducted on plasterboard ('Gyprock') systems, three on asbestos cement ('Versilux') systems, one on a fibre cement ('Villaboard') system, and one on a hardboard ('Readifix') system.

2. EXPERIMENTAL PROCEDURE

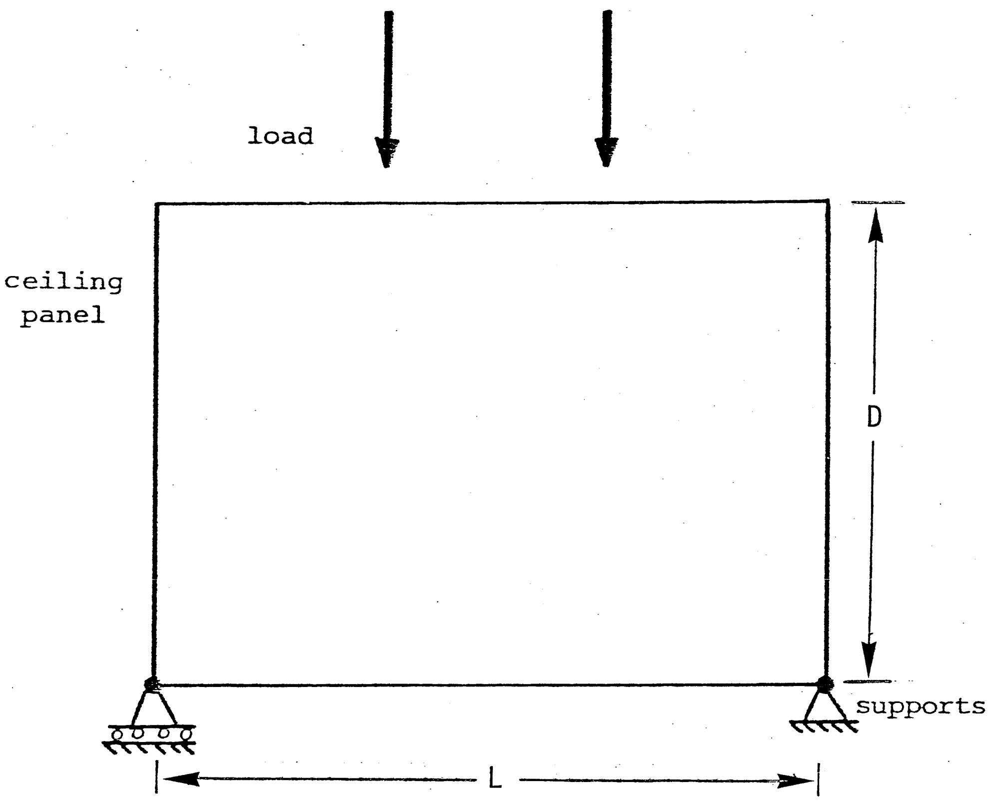
In the tests described in the previous interim reports [1,2], the panels were tested in racking as shear walls using established procedures [3]. However, although similar in assembly to shear walls, ceilings tend to act as deep beams spanning between shear walls, rather than deep beams cantilevered from the floor structure as is the case with shear walls. Design based on the racking tests was assumed to be conservative - i.e. safe - but it was considered important to undertake some tests in which the panels were tested as beams to see whether significant differences in behaviour did occur, and if design based on shear wall type tests is reliable. It was therefore decided that a series of tests be undertaken with the test panels acting as simply supported deep beams. The difference between the two systems of testing is shown diagrammatically in Figure 1.

Figure 2 presents a diagrammatic view of the testing arrangement for the beam type test panels. Each panel was nominally 4800 mm long by 2700 mm wide. The framework consisted of two 70 x 70 mm top plates running lengthwise along the sides of the panels which were connected by 70 x 45 mm ceiling joists. Both the top plates and ceiling joists were of spotted gum. Ceiling battens of 42 x 35 mm radiata pine and furring channels, when used, were attached to the ceiling joists. The top plate members were connected to the ceiling joist members by bolted angle brackets. In all but the first two tests the top plate was spliced at the centre with three 65 x 2.8 mm plain nails as shown in Figure 3.

The panels were tested in the vertical plane as beams spanning over their length as shown in Figure 2. Loads were applied as two equal loads at the third points in all but two tests when they were applied as a single load at midspan. The loads were applied to the top plate member. The



(a) Racking



(b) Beam-Type

Figure 1. Ceiling Panel Testing Systems

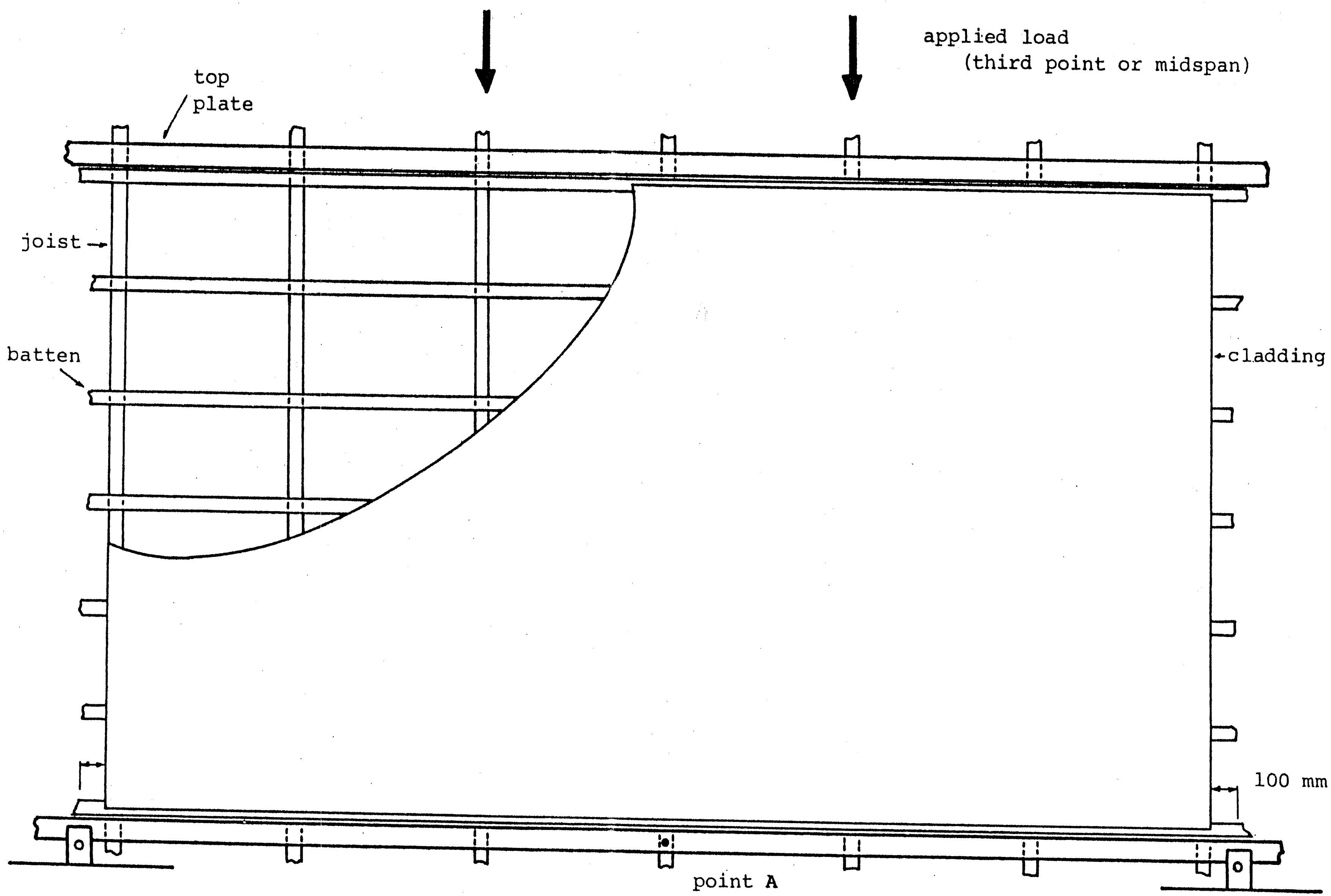


Figure 2. Beam Test Panel - General Structural Arrangement

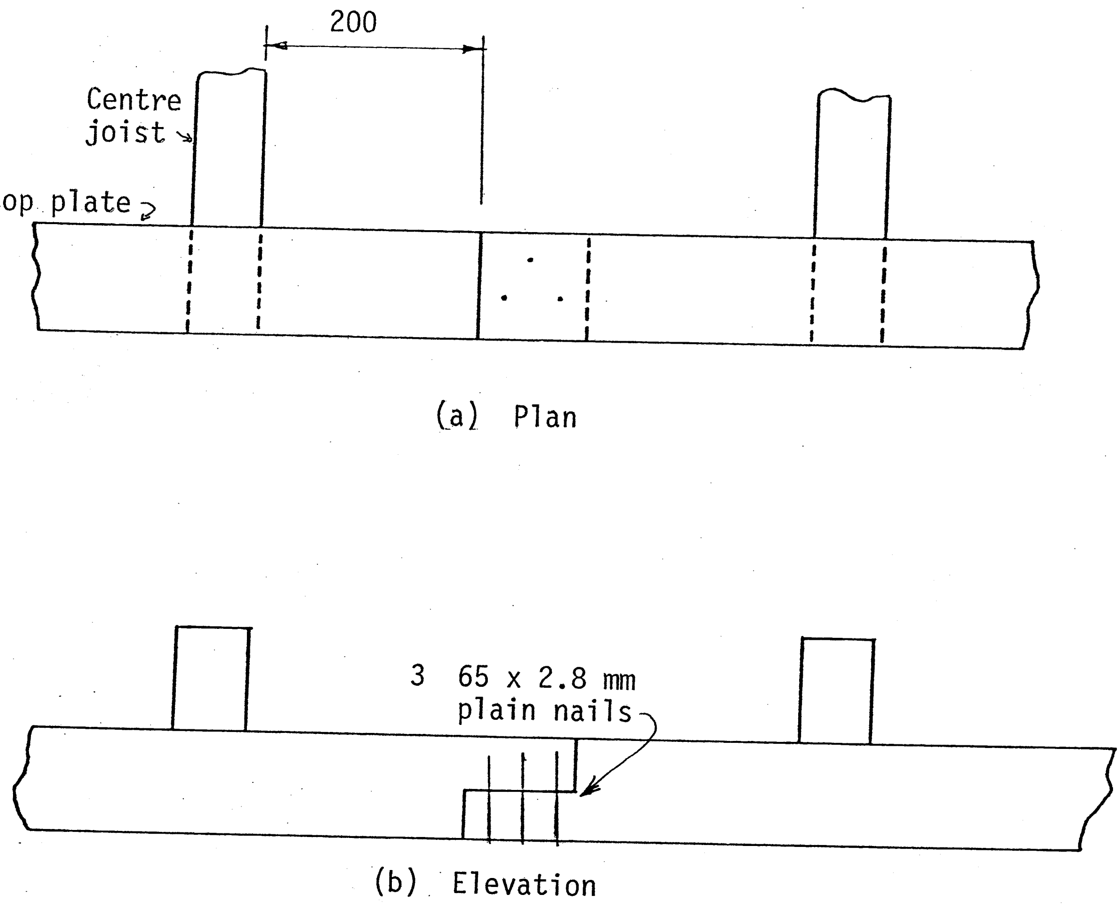


Figure 3. Details of Top Plate Splice

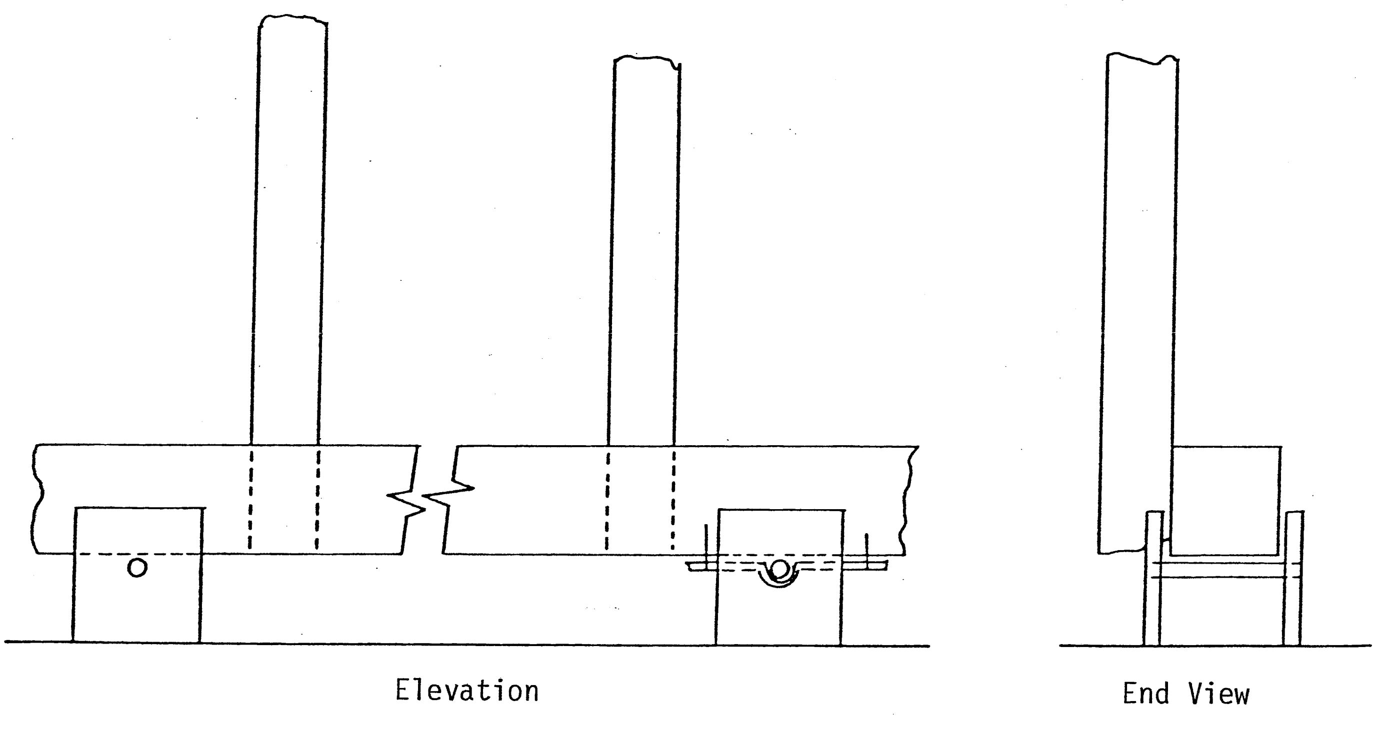


Figure 4. Details of Supports

panels were tied down to the laboratory floor by a pinned arrangement at one end of the bottom top plate and a roller arrangement at the other end as depicted in Figure 4. The load applied to the top of the panel was measured by a load cell and the deflections of the panel measured by mechanical dial gauges. A correction was made to the measured loads to take account of the self weight of the panel. A general view of a panel under test is shown in Figure 5.

Loads were increased in increments up to approximately thirty percent of the anticipated ultimate load, removed, and reapplied in increments up to failure.

3. DESCRIPTION OF TESTS

Full details of each test are given in the Appendix.

A summary of the tests is given in Table 1.

The load-deflection behaviour showed similar general characteristics to those obtained in the racking tests - i.e. non-linear, softening, inelastic characteristics such as shown in Figure 6.

In Table 1 the measured ultimate load is the peak load resisted by each panel during each test. The predicted ultimate load is based on the measured ultimate load of the equivalent racking test assuming the latter is a measure of the maximum shear force at ultimate load in the panels. The latter assumption was used in the derivation of the interim design charts presented in the second interim report [2].

Also presented in Table 1 are the equivalent design shear strength and corresponding stiffness for each panel. These correspond to similar quantities evaluated for the racking tests and presented in the second interim report [2]. They correspond to the equivalent design load which is defined as the ultimate load divided by 2.6 (which is the load factor for single tests on structural assemblies recommended in EBS Technical Record 440 [4]). The equivalent design strength is the maximum shear force per unit width under the equivalent design load, and the stiffness is the equivalent design load divided by the central deflection at this

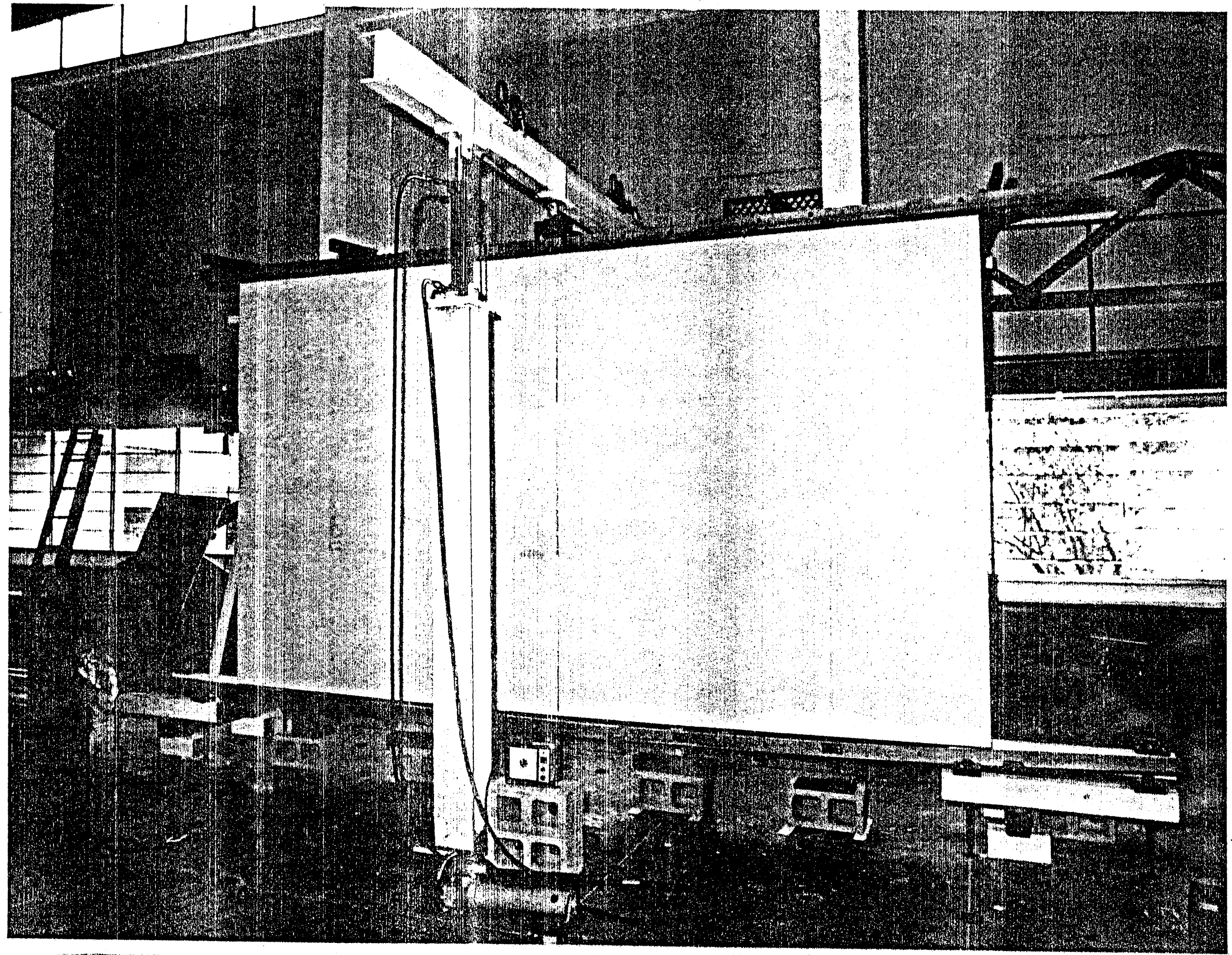


Figure 5. General View of Beam Test

TABLE 1

TEST NO	CLADDING		FASTENERS		BATTENS		JOIST SPACING mm	REMARKS	ULTIMATE LOAD(kN)			EQUIV. DESIGN SHEAR STRENGTH kN/m	STIFFNESS (kN/mm)
	Material	Size mm x mm	Type	Spacing mm	Materials	Spacing mm			Measured	Predicted	Measured / Predicted		
B1	Gyprock 10 mm	4 x 2400 x 1350	8.18 x 25 Hi-Lo Type S Screws	270	-	-	400	No splice in top plates	14.0	10.4	1.35	1.00	1.49
B2	Gyprock 10 mm	4 x 2400 x 1350	8.18 x 25 Hi-Lo Type S Screws	270	-	-	400	No splice in top plates	14.9	10.4	1.43	1.06	1.34
B3	Gyprock 10 mm	4 x 2400 x 1350	8.18 x 25 Hi-Lo Type S Screws	270	-	-	400		15.1	10.4	1.45	1.08	1.09
B4	Gyprock 10 mm	4 x 2700 x 1200	6 x 25 Bugle Head Tek Screws	300	CSR Furring Channel	450	800		16.3	2.2	7.4	1.16	0.19
B5	Versilux 4.5 mm	4 x 2700 x 1200	25 x 1.8 Flex Sheet Nails	150 per 200 ctr	Pine	450	800		13.5	11.2	1.21	0.96	1.50
B6	Versilux 4.5 mm	6 x 2400 x 900	25 x 1.8 Flex Sheet Nails	150 per 225 ctr	-	-	400		18.0	12.0	1.50	1.28	0.71
B7	Gyprock 1C mm	4 x 2400 x 1350	8.18 x 25 Hi-Lo Type S Screws	270	-	-	400	Mid span loading	12.1	10.4	1.16	0.86	0.69
B8	Readifix 5.5 mm	6 x 2400 x 900	25 x 1.8 Flex Sheet Nails	100 per 300 ctr	Pine	300	800	Nogging between battens	40.7	-	-	2.90	1.87
B9	Villaboard 6 mm	4 x 2400 x 1350	30 x 2.8 Lattice Head Nails	150 per 225 ctr	-	-	400		23.4	-	-	1.67	0.51
B10	Versilux 4.5 mm	6 x 2400 x 900	25 x 1.8 Flex Sheet Nails	150 per 225 ctr	-	-	400	Mid span loading	13.5	12.0	1.13	0.96	0.62

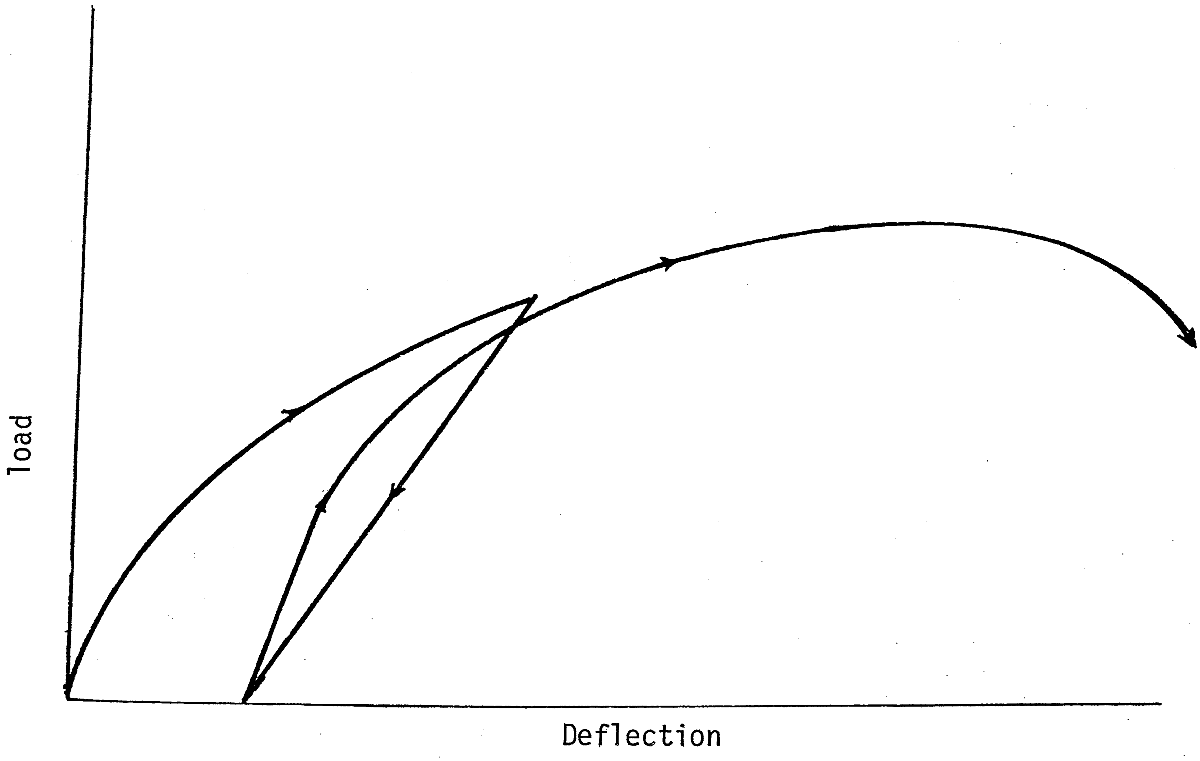


Figure 6. General Form of Load-Deflection Curve

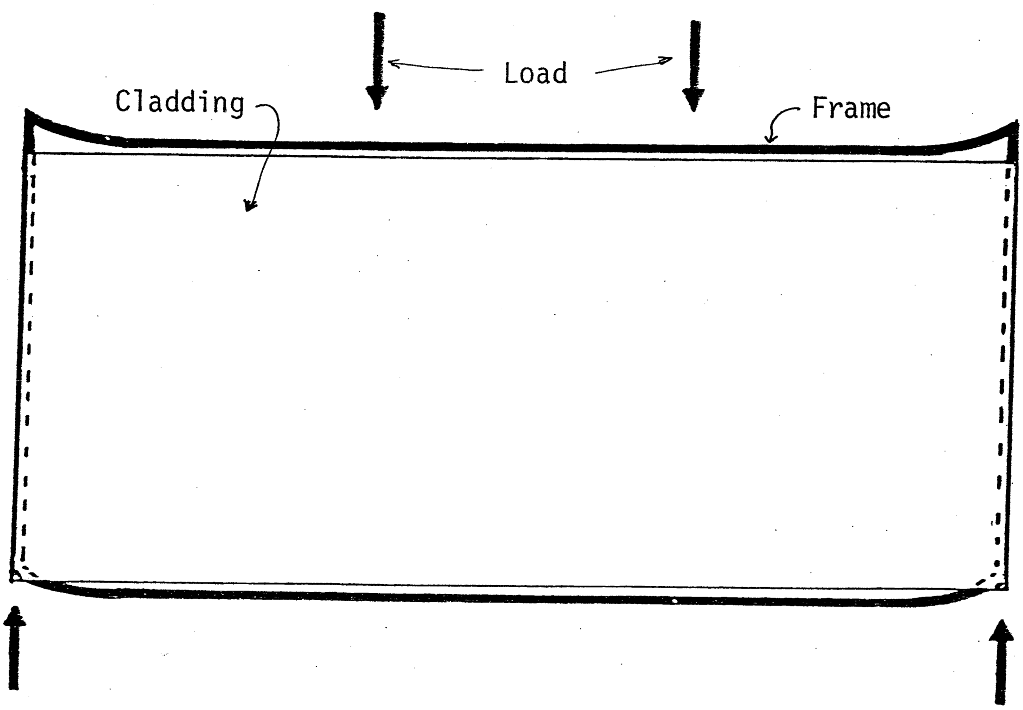


Figure 7. Deformation of Plasterboard Panels

load.

4. DISCUSSION OF RESULTS

4.1 'Gyprock' Plasterboard on Timber Joists

The plasterboard tests B1, B2 and B3, with the plasterboard attached directly to the ceiling joists, were all directly comparable with Test 4 in the racking tests [2]. Tests B1 and B2 were identical and the differences between them reflect experimental variability only. Comparison of the results of these tests with those from Racking Test 4 indicates ultimate shear strengths of the order of forty percent greater and stiffnesses of the order of seventy percent greater for the beam tests. The difference appears to be due to changes in the structural behaviour arising from the additional continuity incorporated in the panel when used as a beam spanning between supports. As in the racking tests the plasterboard acts as a single cladding unit, but because it is continuous over the span and the loading is symmetrical there is no tendency to rotate so that the only movement relative to the frame is in the direction of the loading. Also because the plasterboard acting as a single element is much more rigid under the applied loads than the top plates, which are the only other members acting across the span, the latter are constrained to remain relatively straight over most of their length with most of the overall deflection of the panel being associated with a sharp curvature of the top plates at the ends of the span giving a deflected shape as shown in Figure 7. As a consequence most of the force transfer between cladding and frame occurs as a direct transfer of load from the frame to the cladding across most of the span, and direct transfer of the shear forces back to the frame in the end regions, with the cladding acting as a deep rigid beam in between. Failure occurred as a result of failure of cladding fasteners on the end joists where most of the transfer of shear forces appeared to take place. One consequence of this is that the performance is directional and hence the application of these results should be restricted to situations where the loading is in the same direction as the ceiling joists as in these tests.

The mode of failure observed in these tests is consistent with a maximum shear force model of failure,suggesting that application of the results of these tests using this model would be appropriate. However some caution would need to be exercised to ensure that in applying the results no increase in bending stresses in the cladding was implied which could lead to a tension failure in the plasterboard or the plastered joints between sheets of cladding, or buckling of the cladding between joists in the compression region. Such failures would not necessarily lead to overall failure but would result in a different structural behaviour, with the bending forces being transferred to the top plates and the cladding acting as two separate elements, one in each half, rather than one single element over the whole span. As this would be more like the racking test behaviour the racking test results should still be applicable. Without further investigation it would be necessary to base design data on the racking test results for this situation which would have to be assumed could occur for any aspect ratio (L/D as shown in Figure 1) greater than two, the ratio used in the tests. However inspection of the interim design charts in the second interim report [2] indicates that for the design wind loads used in the cyclone areas aspect ratios are unlikely to exceed two for this system so this may not be of practical importance.

In Tests B1 and B2 the top plates were continuous. Because it is not uncommon to have joints in the top plates Test B3 was undertaken with the only difference being that the top plates were spliced at mid span as previously described - see Figure 3. This joint would provide some resistance to axial forces in the top plates but little resistance to bending of the top plate. The results show that the splice had no effect on the strength of the panel although a reduction of 20 - 30 percent in the stiffness was observed suggesting that some redistribution of forces within the panel did occur. This should probably be no surprise in view of the observed behaviour of these panels with the top plates appearing to play little part in transmission of the loads except near the ends. Nevertheless it was decided that these midspan splices in the top plates would be incorporated in all future tests. In retrospect it may have been more critical if the splices had been placed near the ends of the panel in the region of large curvature of the top plates. For this reason it is suggested that in these types of ceiling systems splices be avoided in top plates adjacent to shear walls.

Tests B1, B2 and B3 were all conducted with third point loading. This is more representative of the distributed loading which occurs in practice than applying a single load at midspan, but the latter is more equivalent to the type of loading used in racking tests. If the maximum shear force criterion of failure holds however, as assumed in the application to design, there should be no difference in the strength obtained by using the two different loading configurations. Test B7 was undertaken to test the validity of this assumption. The only difference between this test and Test B3 was that the load was applied as a single load at the centre. The observed reduction in strength of the order of 15 - 20 percent suggests that the distribution of loads does affect the ultimate load and that this effect may account for approximately half the difference between the measured ultimate strengths in Tests B1, B2 and B3 and those predicted from Racking Test 4. An approximate halving of the stiffness suggests significant changes in the distribution of forces and stresses within the panel. The results suggest that there is some influence of moments on the ultimate strength with a reduction in strength occurring as the ratio of maximum moment to maximum shear force increases - i.e. as loading is concentrated more towards the centre. As even third point loading is more severe than distributed loading in this respect it is concluded that design for wind loads based on the third point loading tests will be conservative.

Treating Tests B1, B2 and B3 as replicates a load factor of 2.2 on the lowest measured ultimate load can be used for determining the design strength [3,4]. This gives a design value of maximum shear force of 1.18 kN/m width. For W42 construction this would imply a maximum aspect ratio of 1.3, for W51 construction a maximum aspect ratio of 0.9, for W60 construction a maximum aspect ratio of 0.65, and for W65 construction a maximum aspect ratio of 0.55. These should only be used for loading parallel to the ceiling joists. For loading at right angles to the ceiling joists no recommendations can be made on the basis of these tests.

4.2 'Gyprock' Plasterboard on Furring Channels

The remaining plasterboard test, Test B4, was conducted on a ceiling panel incorporating furring channels. This may be compared with Racking Test 3. A large increase in ultimate load will be observed. The primary reason for this appeared to be that with the furring channels normal to the direction of the loading, there was no tendency for the channels to slide as they did in the racking test. However they did produce a relatively flexible connection between the cladding and the timber frame, due to twisting of the channels under the eccentric transverse loads acting on them,which resulted in large deflections of the cladding relative to the frame as well as relative large overall deflections. As a consequence bearing of the plasterboard directly on the lower top plate occurred at a load of approximately 8 kN which limited further loading of the end cladding fasteners and thus inhibited their failure. Failure of the panel occurred as a result of buckling of cladding adjacent to one of the corners where the cladding was bearing against the top plate. This buckling would have been caused by the combination of high bearing stresses and shear stresses induced in the cladding in this region as a result of the behaviour described above. It may be felt that this made the system more like that of Racking Test 9 [2] where bearing was ensured by plastering the clearance gap between the cladding and the top plate. However, even in comparison with this test there was a doubling in strength so the racking tests were a very poor guide.

However because of the bearing, extrapolation is difficult as the bearing stresses are a function of the total load only. Where bearing is involved no increase in these above those used in the tests can be assumed. This means that design based solely on this test would have to be limited to spans of less than 3.5 m in W42 construction, 2.4 m in W51 construction, and less for higher design wind speeds, with the same limits on aspect ratios as suggested for plasterboard directly attached to the ceiling joists. Additional consideration would need to be given to serviceability design in view of the relatively large deflections measured at low loads.

Again, because of the directional nature of the behaviour, no recommendations can be made regarding the performance with the loads parallel to the furring channels. Bearing in mind the ease with which the furring channels slipped under axial loads in Racking Test 3 [1] it is anticipated that performance would not be as good as when loading is at right angles to the furring channels.

4.3 'Versilux' Asbestos Cement Panels

Three panels utilising 'Versilux' asbestos cement cladding elements were tested.

In the first of these - Test B5 - the cladding was fastened to pine battens in a similar manner to the panel used in Racking Test 6. Although failure occurred at a maximum shear force approximately twenty percent higher, and the stiffness was much greater, than obtained in the corresponding racking test, the structural behaviour was very similar. As in the racking test each individual sheet tended to rotate independently relative to the other sheets. The major difference was that since the directions of rotation were opposite each other at either end, they therefore tended to bear against each other in the compression region while moving apart in the tension region, thus providing some bending restraint, as shown in Figure 8. In comparing the results of Test B5 with Racking Test 6 it should also be noted that slightly smaller nails were used in fastening the cladding in Racking Test 6 - 25 x 1.5 as opposed to 25 x 1.8 in Test B5 - so this could account for some of the difference.

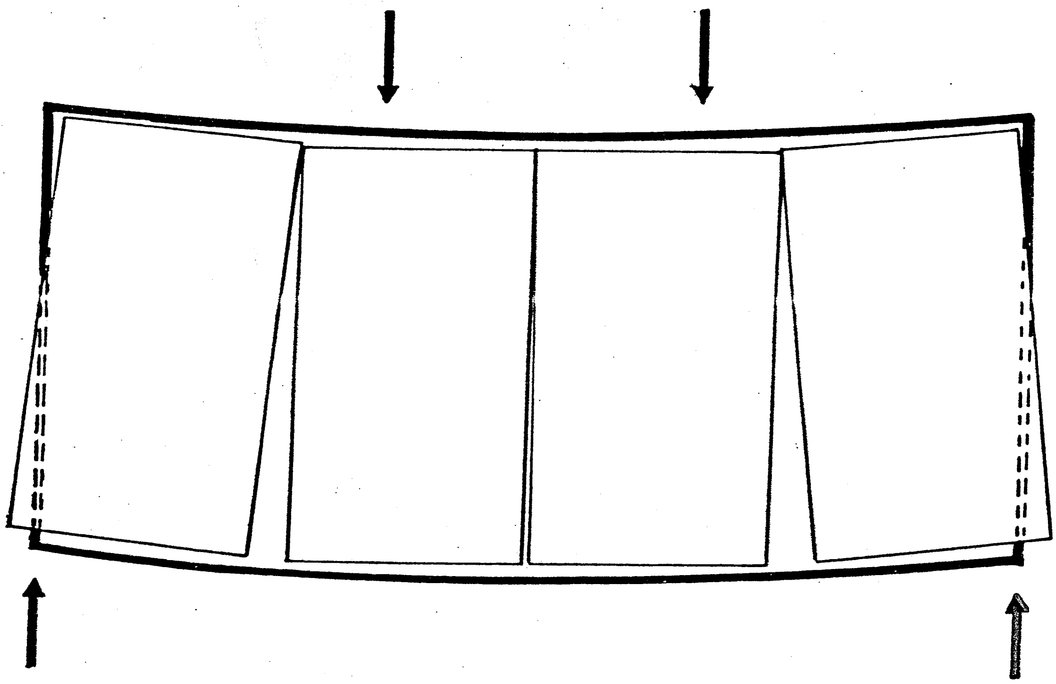


Figure 8. Deformation of 'Versilux on Battens' Panel

In the other two tests - B6 and B10 - the 'Versilux' sheets were fastened directly to ceiling joists in a similar manner to that used in Racking Test 5. This meant that the sheets were laid so that lengthwise they were at right angles to the direction of loading, unlike Test B5 where lengthwise the sheets were parallel to the direction of loading. The only difference between Tests B6 and B10 was in the loading, the load being applied at the third points in B6 and at midspan in B10. The general behaviour under load is shown in Figure 9.

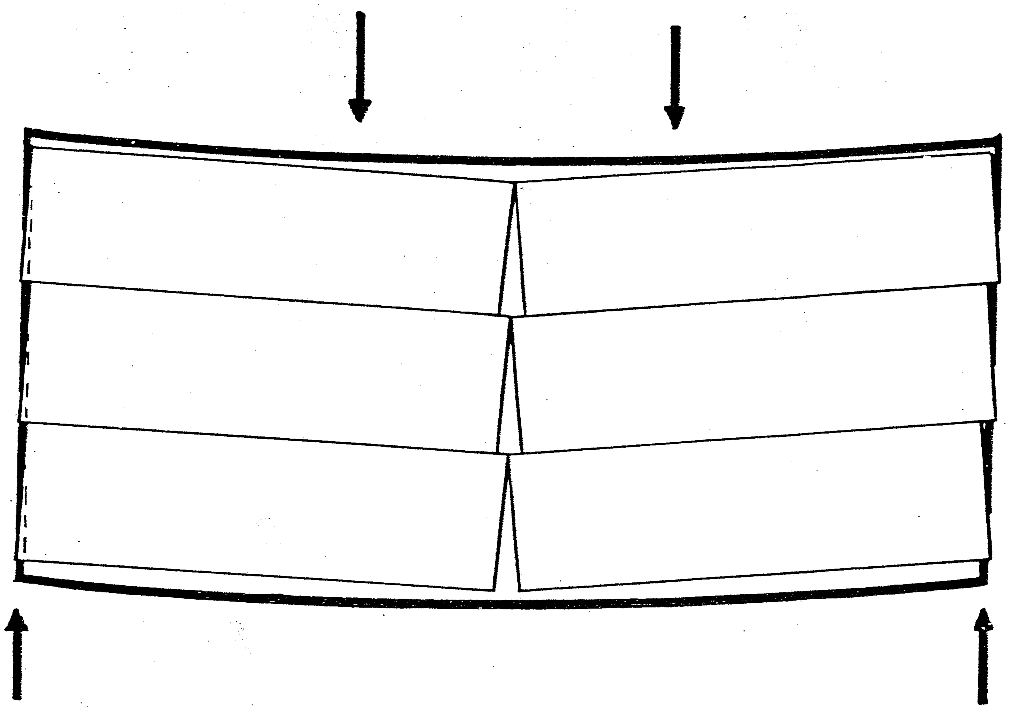


Figure 9. Deformation of 'Versilux on Joists' Panel

With the midspan loading - i.e. Test B10 - the same ultimate load was obtained as in Test B5. This confirmed the impression gained from the racking tests and analytical studies [5] that orientation and the use or not of battens makes little difference to the shear resistance of systems such as this where the individual sheets of cladding act independently. The small increase in ultimate load over that obtained in the racking tests can be attributed to the slight increase in restraints imposed by the continuity of the frame members over the span and interference between cladding sheets due to differing directions and amounts of rotation. The results of Tests B5 and B10 support the assumption of a limiting maximum shear force for design purposes for these systems with an increase of 10 - 15 percent in ultimate strength being justified when used in a beam situation as opposed to a cantilever situation as in the racking tests.

Test B6 was similar in all respects to Test B10 except that the loading was applied at the third points instead of the centre. The results will seem very suprising, with a 33 percent increase in ultimate strength being obtained relative to that measured in Tests B5 and B10. This is strongly in conflict with the assumption of a limiting value of maximum shear force at failure. The reason appears to be that this assumption only holds if the critical cladding sheets are located in a region of constant shear force, a condition which was present in the other two beam tests and the racking tests on 'Versilux' panels. Where loading is applied within the length of a cladding sheet the maximum shear force at failure will be greater. In the case of Test B10 with third point loading and each sheet extending from the end to mid span the loading is actually applied two thirds of the way along the sheet. In practice with distributed loading this effect will always be present to some degree. In the case of sheets extending half the span, as in Test B10, the effect is likely to be even greater than obtained with third point loading so that it should be conservative to use the latter for design purposes. As the number of sheets along the length of the span increases the effect will become less marked. Until further studies are undertaken of this effect it is suggested that it only be taken into account when one sheet only or two sheets of equal length meeting at midspan are used to span the distance between shear walls. The maximum shear force at ultimate load when using one sheet only is expected to be greater than when using two sheets but further testing would be required before a separate design recommendation could be made.

On the basis of these tests it is suggested that the same limits on aspect ratio as were suggested for the 'Gyprock' plasterboard system would be satisfactory for either of the 'Versilux' system tests in general. In the particular case where one sheet or two sheets of equal length are used across the span these limits can be increased by thirty percent providing the aspect ratio does not exceed two. The latter is necessary to protect against possible bending modes of failure undetected by the tests.

With the phasing out of asbestos cement as a construction material the design values for this material are becoming of academic interest. They should not be used for fibre cement which is replacing it as it generally has a lower strength. However, the results are of importance in demonstrating the way in which ceiling systems behave when clad in such a way that the individual sheets of cladding act independently.

4.3 'Villaboard' Fibre Cement Panel

Test B9 was similar to Test B3 except that 'Villaboard' with cemented joints was used instead of 'Gyprock' as the cladding material. Prior to failure, the panel behaved in a similar manner to the 'Gyprock' panels. It failed differently, with the ultimate load corresponding to tensile failure of the central joint between cladding sheets under bending forces, following bearing of the cladding at the ends against the top plate. The failure load is therefore not an indication of the shear strength of the panel. It is probable that higher shear forces at failure would have been obtained for smaller aspect ratios. Further testing would be required to ascertain this. Because bearing was involved there are problems in extrapolating the test results. In the interim based on this test it would appear satisfactory for loading parallel to the ceiling joists to allow aspect ratios up to 40 percent greater than the limits indicated for the 'Gyprock' plasterboard on ceiling joists system, subject to a maximum span of 5.0 m for W42 construction. For W51 construction a span of 3.4 m is recommended, and correspondingly smaller spans should be used for higher design wind velocities. These recommendations assume the aspect ratio does not exceed two, and edge clearance are small enough to allow the cladding to bear against the top plates before cladding fastener failure occurs. No recommendation can be given for loading in the other direction.

4.4 'Readifix' Hardboard Panel

As a test on a panel with independently acting cladding sheets fastened to pine battens, Test B8 using 'Readifix' cladding had the most similarities with Test B5 using 'Versilux' cladding. However in addition to the cladding material there were other significant differences between these tests. The battens were closer together, the cladding sheets were placed in the other direction - i.e. parallel to the battens rather than across the battens - the ends of the sheets were nailed to noggings nailed between the battens, and the spacing of the fasteners was much less. The difference in direction of the cladding is important because it makes the test more comparable with Test B6 as the same mechanisms of behaviour will be involved. The large difference in the number of cladding fasteners due to the different structural arrangement probably accounts for most of the difference in strength between this test on "Readifix' and Test B6 on 'Versilux'. It can be inferred from these results that the 'Readifix' system used in Test B8 is over twice as strong as the 'Versilux' systems used in Tests B5, B6 and B10 and that therefore it would be satisfactory to use the system for aspect ratios up to twice those suggested for the 'Versilux' system subject to the aspect ratio not exceeding two. This could make this system useful in Category 1 and Category 2 locations in cyclone area.

5. DISCUSSION OF FAILURE MECHANISMS

In all the tests other than B4 ('Gyprock' on furring channels) and B9 ('Villaboard') failure occurred as a result of failure of the cladding fasteners pulling through the cladding. In the case of Test B4 failure occurred as a result of buckling of the cladding in the end region under bearing and shear. In Test B9 failure occurred as a result of tensile failure of the cemented joint between cladding sheets.

This again highlights the importance of the cladding fasteners in the strength of sheet clad systems under in-plane shear forces and suggests increasing the number of fasteners as the best approach to increasing panel strength should this be desired. In the case of the 'Gyprock' plasterboard on ceiling joist systems it is possible that only the number of fasteners on the end joists would need to be increased.

The exceptions occurring in tests B4 and B9 highlight the presence of other failure modes which may become critical if the geometry is changed or other systems used. For this reason come caution is needed in extrapolating the results of tests described in this report to other situations. It is believed that the restrictions placed on the application of the results in the previous section should provide sufficient protection against failure by other modes but this is not guaranteed.

In the plasterboard tests other than with the furring channels clearances were maintained between the plasterboard and top plates to ensure that the plasterboard did not bear against the top plate. If these clearances had been kept very small, or the gap filled with plaster as in Racking Tests 8 and 9, then failure of the cladding fasteners would have been inhibited and higher ultimate loads may have been recorded. In this case failure by tension in the joints or buckling of the sheets would be more likely modes of failure. In the case of the Tests B4 and B9 with the furring channels and 'Villaboard' respectively, this is what did happen, with the cladding bearing against the top plate preventing cladding fastener failures in both cases. However where bearing occurs extrapolation of results is difficult since bearing stresses are likely to be a function of the total load only.

In the case of the 'Versilux' and 'Readifix' tests the bending tends to be resisted by each sheet of cladding acting as a small deep beam together with direct tension and compression in the top plates, and battens where present. Transfer of the bending forces span wise from one sheet of cladding to the next occurs by bearing on the compression side and through the cladding connections via the common battens or ceiling joist on the tension side - see Figure 9. Because of the relative flexibility of the cladding sheets in this behaviour much of the bending is probably shed to the frame. The strength of splices in the top plates and battens on the tension side may therefore be critical. For this reason it would seem unwise to apply the results to situations which may produce greater bending forces relative to shear forces.

How important the bending forces are in practice is not clear. If the walls to which the top plates are connected are capable of acting as shear walls then they may be able to resist the bending forces at ceiling level, assuming the connections are sufficient to transfer the forces from the ceiling to the walls. Because of this the beam test itself is not necessarily completely representative of the real situation. However, because the real situation involves further restraints, the beam tests can be expected to give a conservative estimate of the real behaviour and hence be a safe guide for design purposes, provided bearing of the cladding against the frame does not occur.

What this does highlight is the essentially three dimensional nature of the structural response of ceilings to in-plane loading.

6. CONCLUSIONS

These tests have highlighted the complexity of the behaviour of ceilings under in-plane loads such as those induced by wind. Prediction of the ultimate strength of the panels, based on the shear strength derived from the equivalent racking test, underestimated the measured ultimate strength in every test. However the degree of underestimation varied widely, thus it cannot be assumed that the prediction would always be conservative.

The best correlation between racking tests and beam tests was obtained with the cladding systems in which each sheet of cladding was free to move and deform independent of the other sheets of cladding - i.e. as in the 'Versilux' tests. For these a small increase in shear strength was observed in the beam tests, which appeared independent of the orientation of the sheets or use or not of battens, but dependent on the critical sheets being in uniform shear. Where the latter did not hold a significant increase in shear strength was observed which has implications for relatively short spans using only one or two sheets to cross the span. It can therefore be concluded that for this type of system, represented in these tests by the 'Versilux' and 'Readifix' panels, design based on racking tests will be safe providing the top plates are capable of resisting the bending forces, either on their own or in combination with the supporting walls. For small spans the degree of safety will tend to increase. Thus beam tests would not be necessary for safe design but could be expected in general to result in higher design strengths being recommended than would be evaluated from racking tests.

For systems where the cladding acts as a single unit as a result of plastering or cementing of the joints between cladding elements, tests showed that racking tests may be a poor indicator of the actual strength of ceiling systems, due to a different mode of behaviour occurring when the panels are used to span between supports. In this case the main load transfer mechanism appears to be the cladding itself acting as a stiffened deep beam over most of the span with the load being transferred to the supporting shear walls via the ceiling frame by the end cladding fasteners or direct bearing of the cladding at each end of the span on the top plates. This mechanism is not simulated by racking tests and hence results obtained from the latter could be quite misleading. Because the behaviour of the panels was very directional, different configurations of construction relative to the applied load need to be tested separately. In general two beam tests would be required for each type of panel for which design information is required. If failure occurs as a result of cladding fastener failure at the ends without bearing of the cladding against the top plate occurring then the use of the results for design purposes appear safe, but not unduly so, providing they are not used for aspect ratios greater than that used in the tests. If failure is the result of bending stresses in the cladding then it is still safe to apply the results with the same provisos, but it may be unduly safe for aspect ratios much less than that used in the tests. Where bearing occurs extrapolation of results for design purposes is difficult as failure in bearing tends to be a function of total load only. In this case the use of test results in conjunction with the maximum shear force criterion of failure may be unsafe unless limits are set on the span.

The overall conclusion is that the beam test is better than the racking test but it has limitations,especially when systems in which the cladding acts as a single unit are being used and bearing of the cladding against the top plate is being relied upon for local transfer from the cladding to the frame. In respect of the latter,while it obviously makes a significant contribution to the strength of small panels such as those used in tests, its relative contribution may be much less in large panels. It now appears that the performance of these may not be as good as suggested in the second interim report [2] on the basis of the racking tests and recommendations made therein in this regard should be disregarded.

The influence of so many variables on the ceiling behaviour and the problems this creates for extrapolation of test results highlights the need for the development of more reliable analytical models of the structural behaviour for design purposes than the simple shear model currently being used.

7. ACKNOWLEDGMENTS

The work described in this report was undertaken as part of a research project on the behaviour of houses subject to wind forces which was funded by the Australian Housing Research Council. The contributions of James Hardie & Coy. Pty. Ltd, CSR Limited, and Hardboards Australia Limited who supplied the cladding materials were also much appreciated.

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APPENDIX

A.1 TEST B1

A.1.1 Test Panel

The panel geometry for this test was as follows:

- distance between top plates 2815 mm
- spacing of ceiling joists 400 mm

The cladding which consisted of four 2400 x 1350 x 10 mm recessed edge 'Gyprock' sheets was screwed directly onto the ceiling joists. The sheets were fixed perpendicular to the ceiling joists and were fastened by 'Gypsum 8.18 x 25 mm Hi-Lo Type S' power driven screws at 270 mm spacing along each joist (see Figure A.1). The recessed joints between the sheets and the screw head depressions were cemented using the 'Gyprock GB100 System' with GBRM and perforated paper tape as suggested by the manufacturer.

A.1.2 Loading Pattern

The panel was loaded in increments of approximately 0.6 kN up to a load of 9.4 kN, unloaded, and then reloaded to failure in slightly larger increments. The panel was tested under the third point loading system.

A.1.3 Test Results

The observed load-deflection behaviour of the panel is shown in Figure A.2.

The deflection refers to the displacement measured at the centre of the panel from the lower top plate. (See point A on Figure A.1).

The load refers to the total load being applied and not the load at each point.

Failure occurred at a load of 14.0 kN as a result of the fasteners

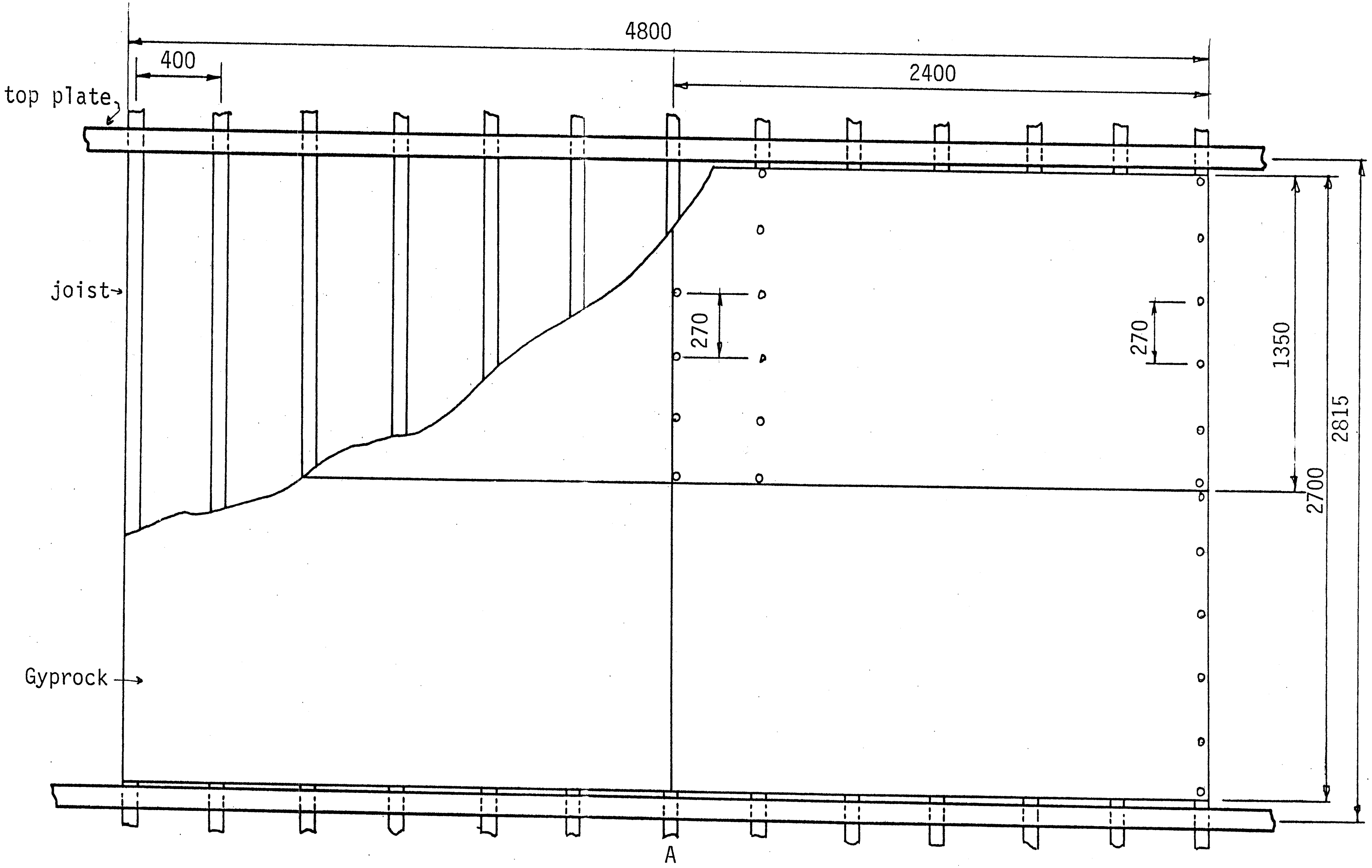


Figure A.1 Test Panels B1, B2, B3 and B7

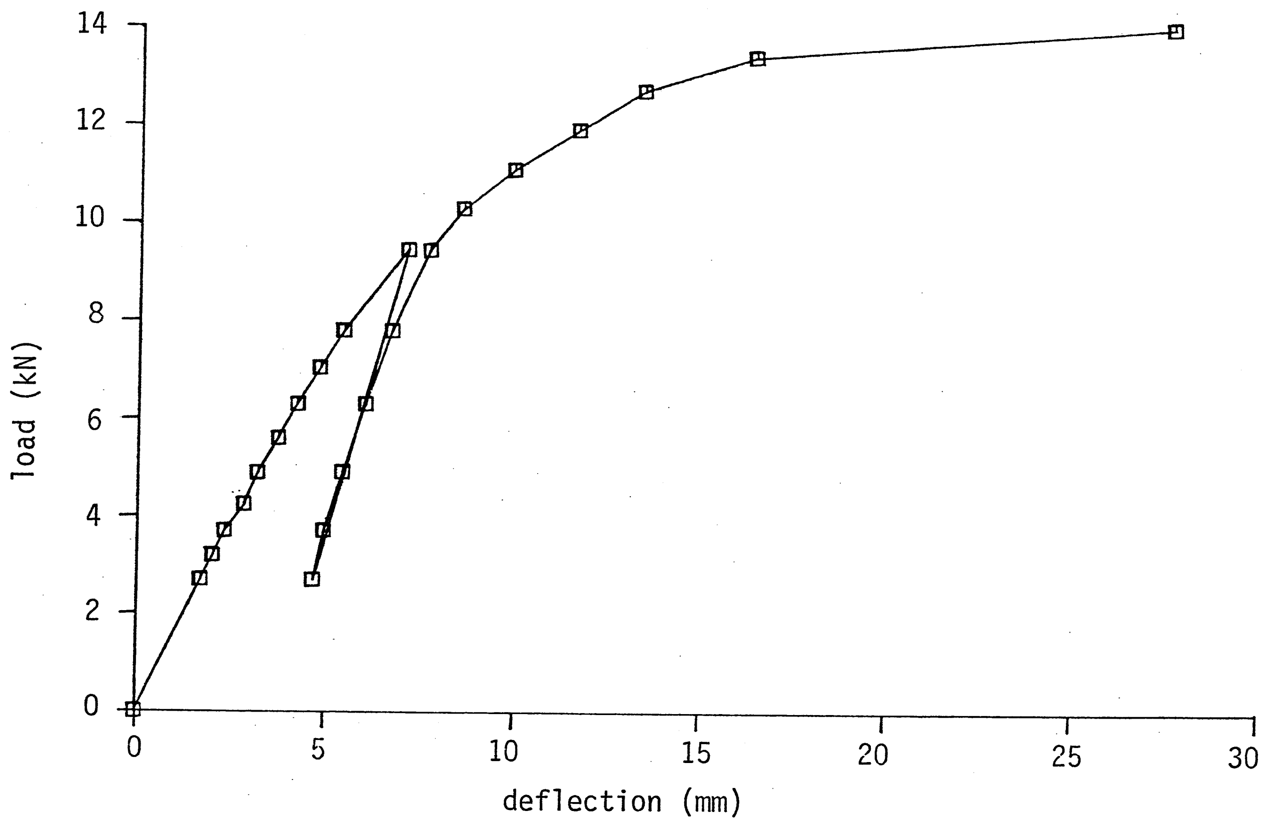


Figure A.2 Load-Deflection Curve: Test B1

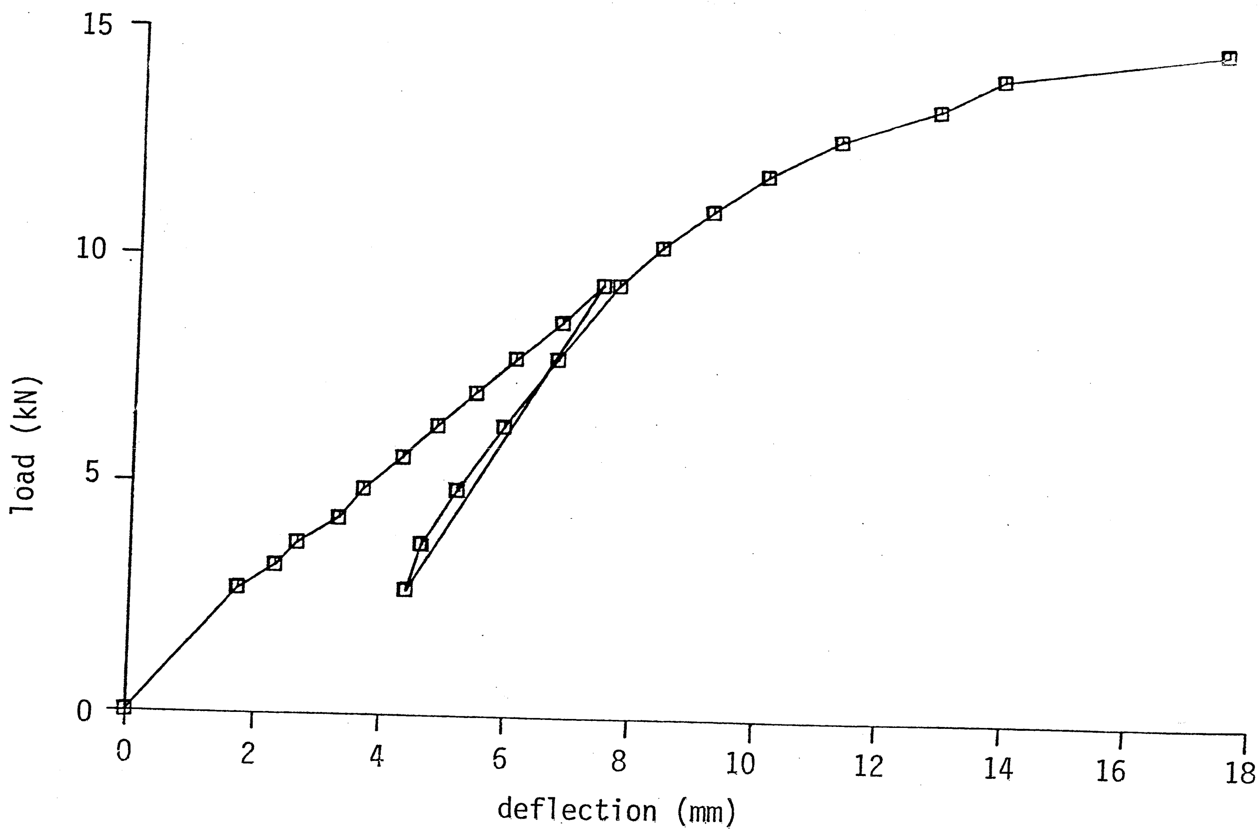


Figure A.3 Load-Deflection Curve: Test B2

pulling through the cladding. No relative movement occurred between individual sheets and hence the entire cladding moved as a single unit. (Figure 7).

A.2 TEST B2

A.2.1 Test Panel

Test panel 2 was identical to the panel used in Test B1 (Figure A.1).

A.2.2 Loading Pattern

The panel was loaded in increments of approximately 0.6 kN up to a load of 9.4 kN, unloaded, and then reloaded to failure in slightly larger increments. The third point loading system was employed in this test.

A.2.3. Test Results

The observed load-deflection behaviour of the panel is shown in Figure A.3. Failure occurred at a load of 14.9 kN as a result of the fasteners pulling through the cladding. No relative movement occurred between the sheets.

A.3 TEST B3

A.3.1 Test Panel

In this panel the two top plates were made discontinuous by the introduction of a splice. (See Figure 3). The joint was situated midway along the top plate and was held together by three 65 x 2.8 mm plain nails.

In all other respects, panel 3 was identical to the panels in Tests B1 and B2.

A.3.2. Loading Pattern

The panel was loaded in increments of approximately 0.6 kN up to a load of 9.4 kN, unloaded, and then reloaded to failure in slightly larger increments. The panel was tested under the third point loading system.

A.3.3 Test Results

Failure occurred at a load of 15.1 kN as a result of the fasteners pulling through the cladding. The observed load-deflection behaviour of the panel is shown in Figure A.4. No relative movement occurred between the sheets. The joint in the top plates did not appear to contribute to the failure of the panel.

A.4 TEST B4

A.4.1 Test Panel

The panel geometry for this test was as follows:

- distance between top plates 2815 mm
- spacing of ceiling joists 800 mm
- spacing of CSR furring channels 450 mm

The furring channels were fixed to the ceiling joists with direct fixing clips according to the manufacturers instructions. The cladding consisted of four 2700 x 1200 x 10 mm recessed edge 'Gyprock' sheets. The sheets were fastened perpendicular to the channels using 'Gypsum 6.2 x 25 mm Bugle Head Tek' power driven screws at 300 mm spacing. The joints and the screw depressions were cemented using the previously detailed method (see Figure A.6). As in Test B3, a splice was made in each top plate.

A.4.2 Loading Pattern

The panel was loaded in increments of approximately 0.6 kN up to a load of 5.3 kN, unloaded, then loaded to failure in slightly larger increments. The panel was tested under the third point loading system.

A.4.3 Test Results

The observed load-deflection behaviour is shown in Figure A.5. Failure

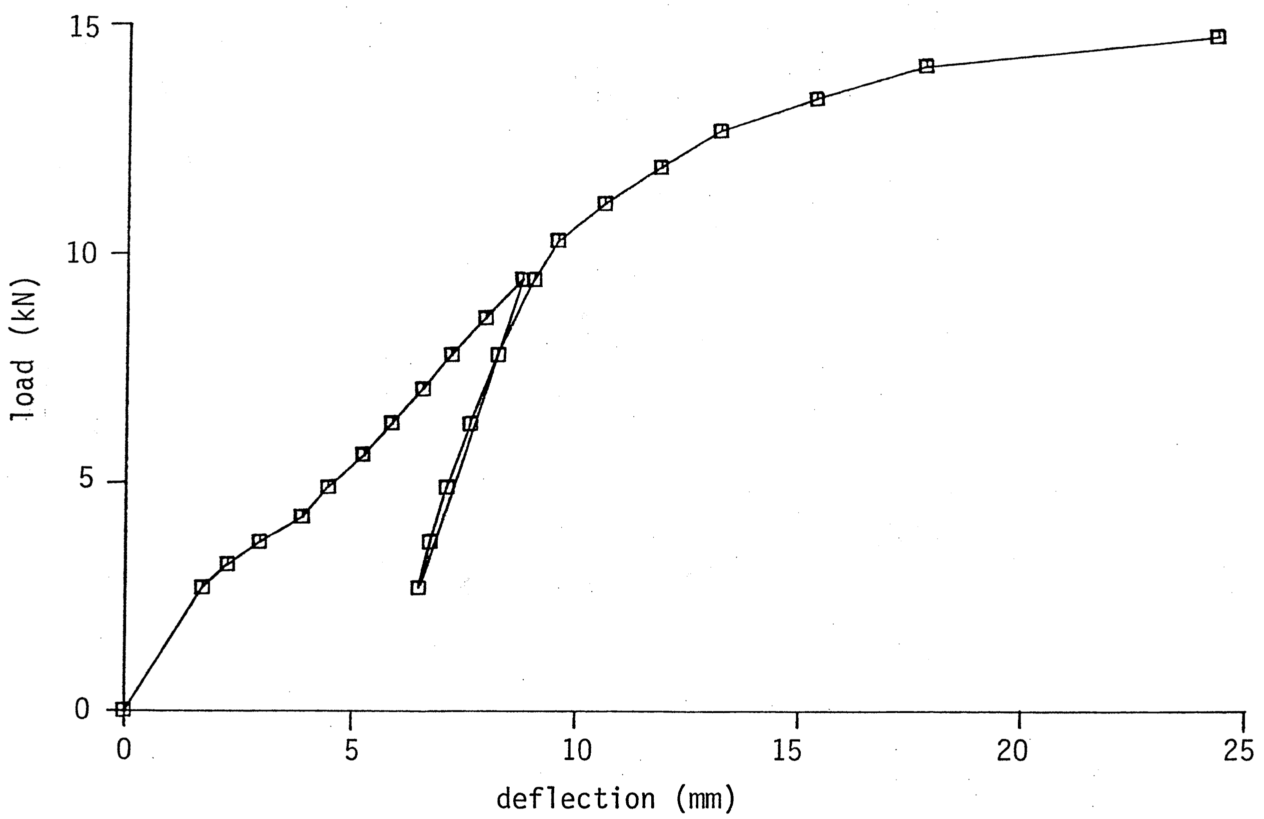


Figure A.4 Load-Deflection Curve: Test B3

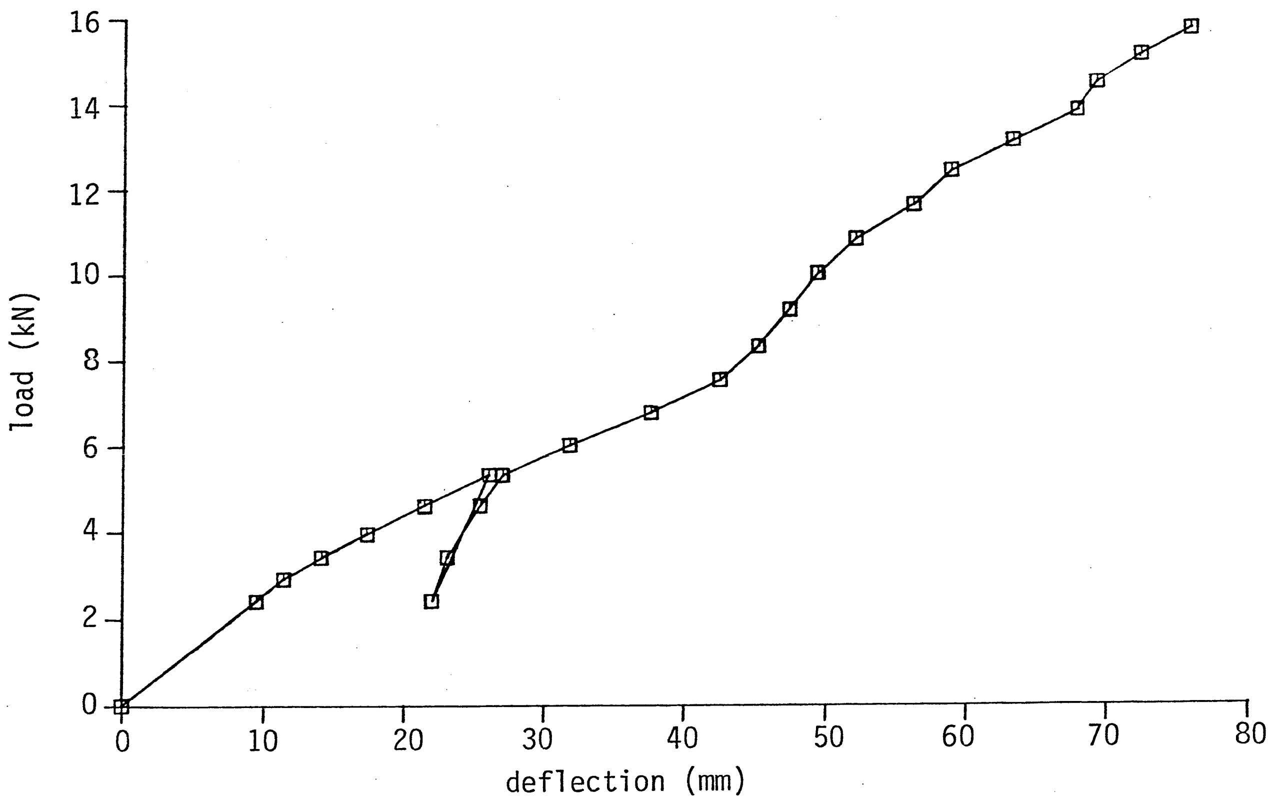


Figure A.5 Load-Deflection Curve: Test B4

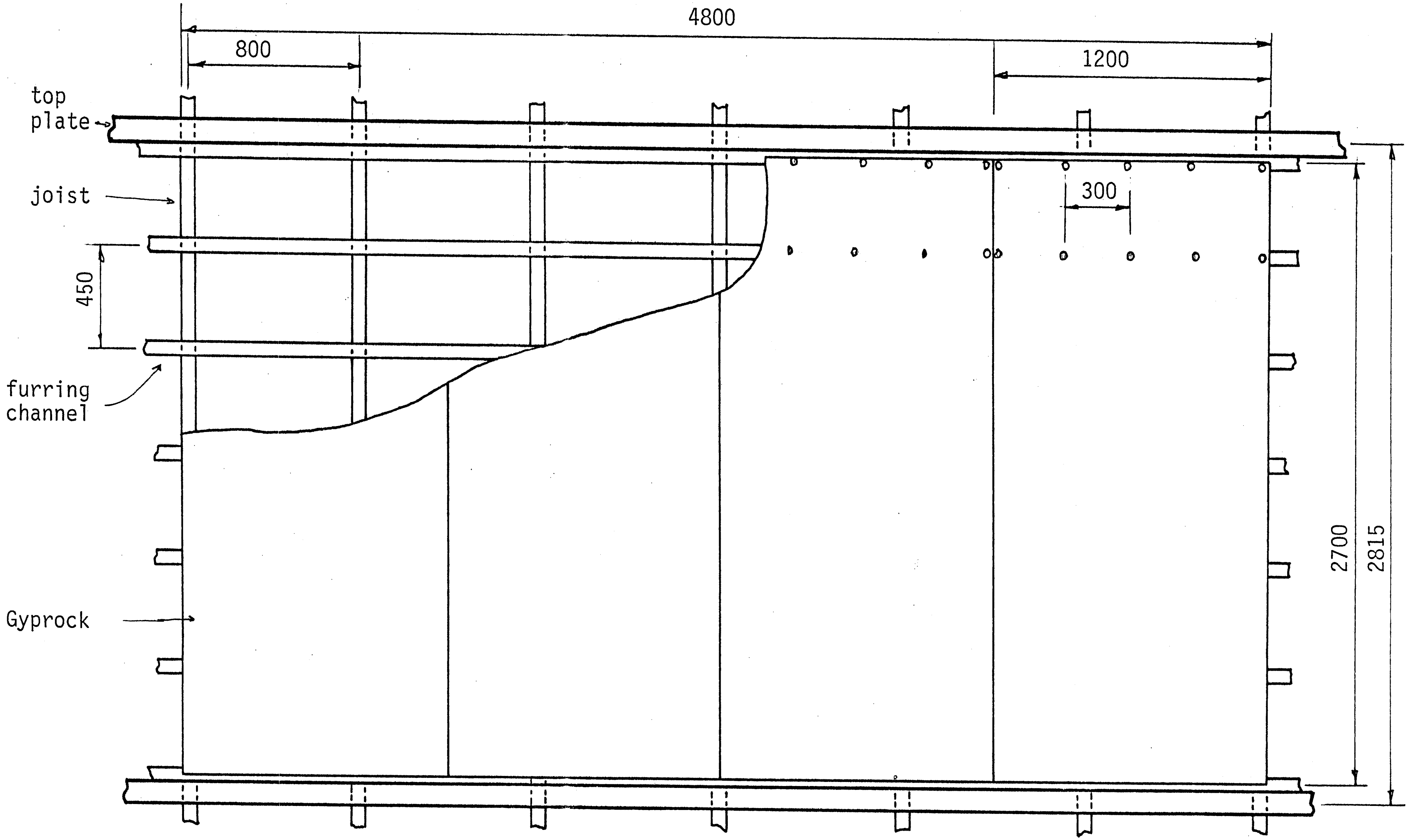


Figure A.6 Test Panel B4

occurred at a load of 16.3 kN as a result of the sheet buckling in a bottom corner. The furring channels moved considerably. This movement allowed the cladding to bear against the top plates before the cladding fasteners had failed. The buckling occurred adjacent to one of the locations where bearing was occurring.

A.5 TEST B5

A.5.1. Test Panel

The panel geometry for this test was identical to Test B4. However, 42 x 35 mm radiata pine timber battens were used instead of furring channels. The timber battens were nailed to the ceiling joists by one 75 x 3.75 mm plain nail. The cladding consisted of four 2700 x 1200 x 4.5 mm 'Versilux' asbestos cement sheets. The sheets were fastened perpendicular to the battens using 25 x 1.8 mm Flex Sheet nails at 150 mm spacing around the perimeter of each sheet and 200 mm spacing in the centre of each sheet. (See Figure A.7). As in Test B3 a splice was made in each top plate.

A.5.2 Loading Pattern

The panel was loaded in increments of approximately 0.6 kN up to a load of 7.5 kN, unloaded, then reloaded to failure in slightly larger increments. The panel was tested under a third point loading system.

A.5.3. Test Results

Failure occurred at a load of 13.5 kN as a result of the fasteners pulling through the cladding. The observed load-deflection behaviour of the panel is shown in Figure A.8.

Rotation of the two end sheets did occur, but the two middle sheets showed almost no relative displacement (see Figure 8).

A.6 TEST B6

A.6.1. Test Pannel

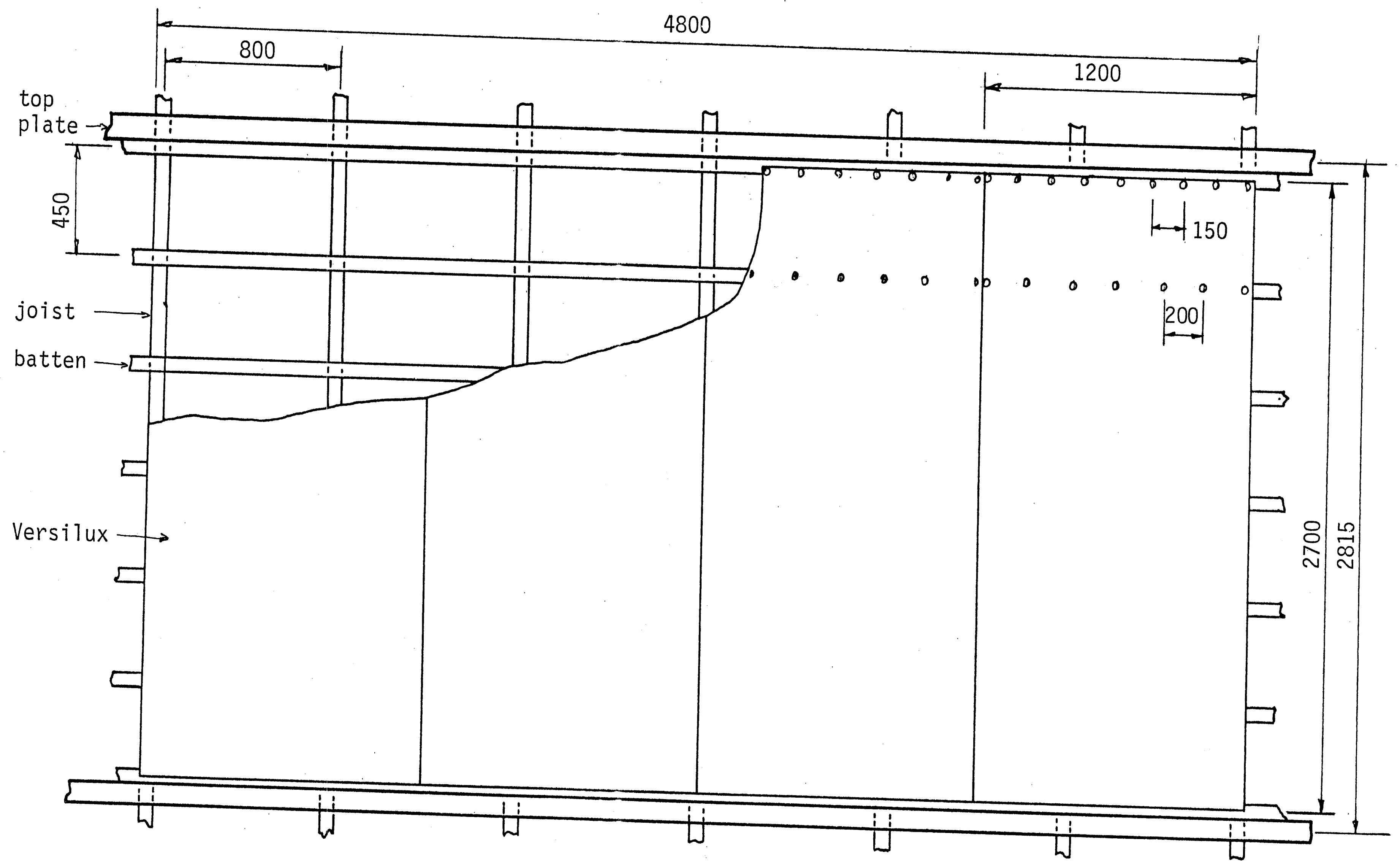


Figure A.7 Test Panel B5

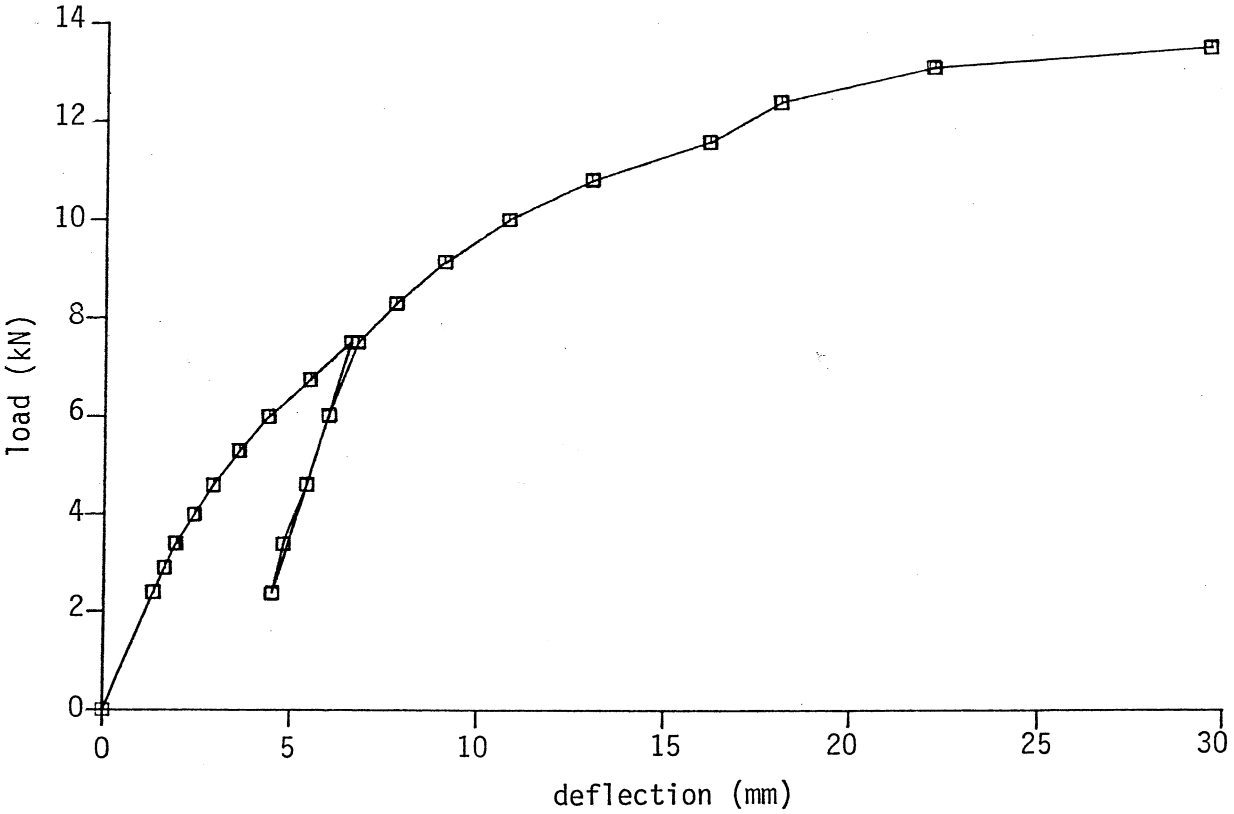


Figure A.8 Load-Deflection Curve: Test B5

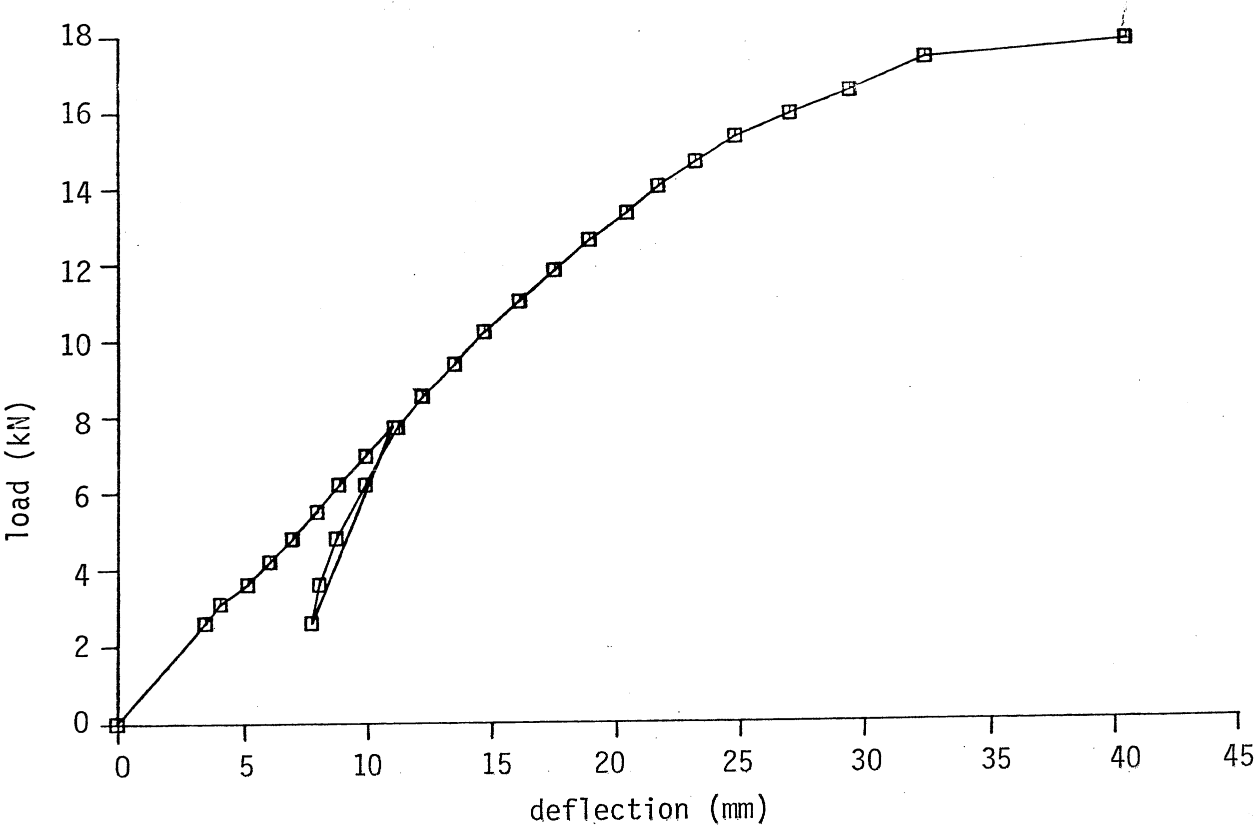


Figure A.9 Load-Deflection Curve: Test B6

The panel geometry for this test was as follows:

- distance between top plate 2815 mm
- spacing of ceiling joists 400 mm

The cladding which consisted of six 2400 x 900 x 4.5 mm 'Versilux' sheets, was nailed directly onto the ceiling joists. The sheets were fixed perpendicular to the ceiling joists and were fastened by 25 x 1.8 mm Flex Sheet nails at 150 mm spacing around the perimeter of each sheet and 225 mm spacing in the centre of each sheet (see Figure A.10). As in Test B3 a splice was made in each top plate.

A.6.2 Loading Pattern

The panel was loaded in increments of approximately 0.6 kN up to a load of 7.7 kN, unloaded, then reloaded to failure in slightly larger increments. The panel was tested under the third point loading system.

A.6.3 Test Results

The observed load-deflection behaviour of the panel is shown in Figure A.9. Failure of the panel occurred at a load of 18.0 kN as a result of nails pulling through the cladding. Rotation of the individual cladding elements occurred as shown in Figure 9 with some local buckling occurring in the cladding sheets in the mid span region adjacent to where they were bearing against each other.

A.7 TEST B7

A.7.1 Test Panel

Test panel B7 was identical to the panel used in Test B3 (see Figure A.1).

A.7.2 Loading Pattern

The panel was loaded in increments of approximately 0.6 kN up to a load of 7.2 kN, unloaded, then reloaded to failure in slightly larger increments. The panel was tested under a centrally positioned point load.

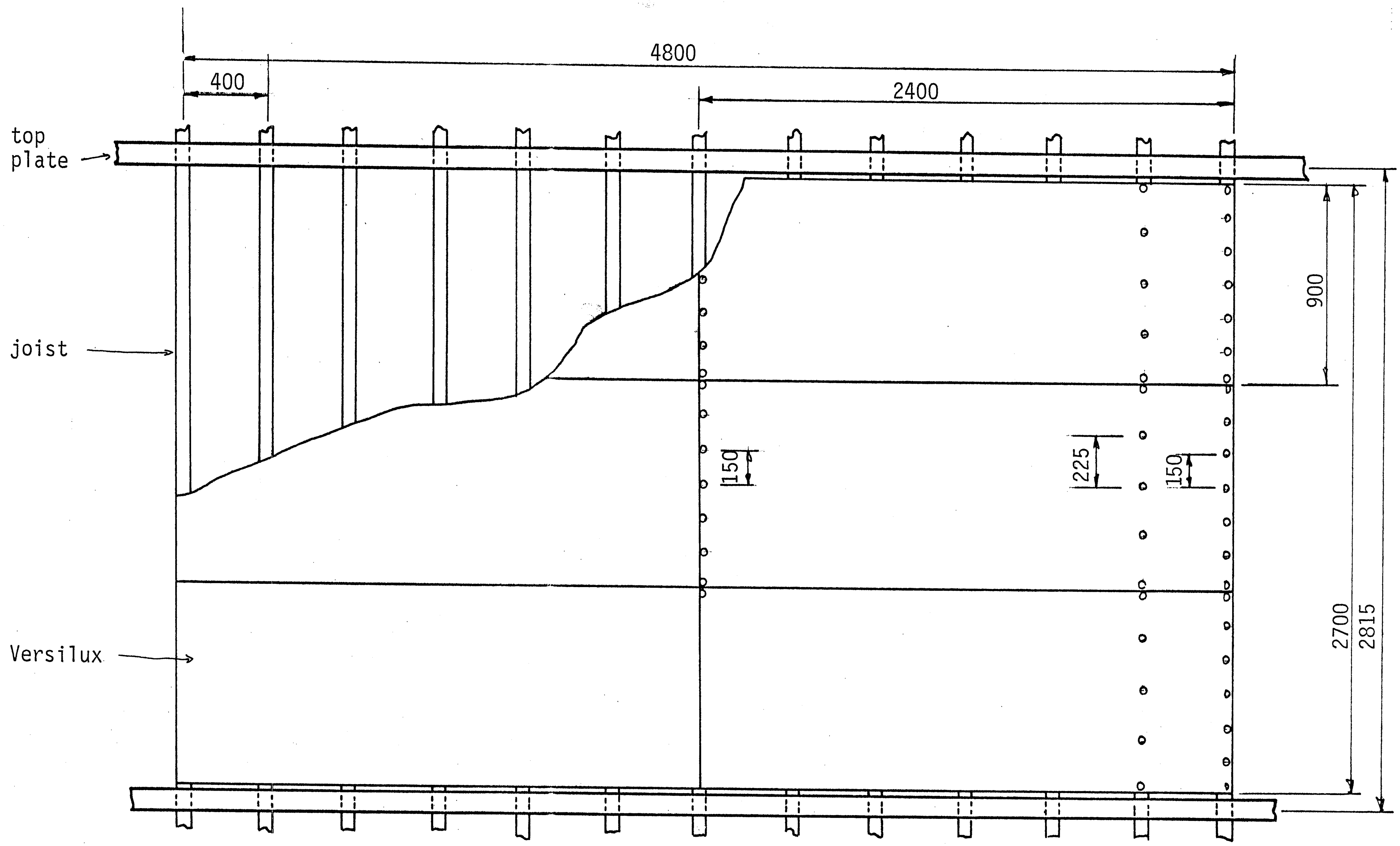


Figure A.10 Test Panels B6 and B10

A.7.3 Test Results

The observed load-deflection behaviour for the panel is shown in Figure A.12. Failure occurred at a load of 12.1 kN, as a result of the fasteners pulling through the cladding. The cemented joints showed no distress and the cladding moved as a single unit.

A.8 TEST B8

A.8.1 Test Panel

The panel geometry for this test was as follows:

- distance between top plates 2815 mm
- spacing of ceiling joists 800 mm
- spacing of ceiling battens 300 mm

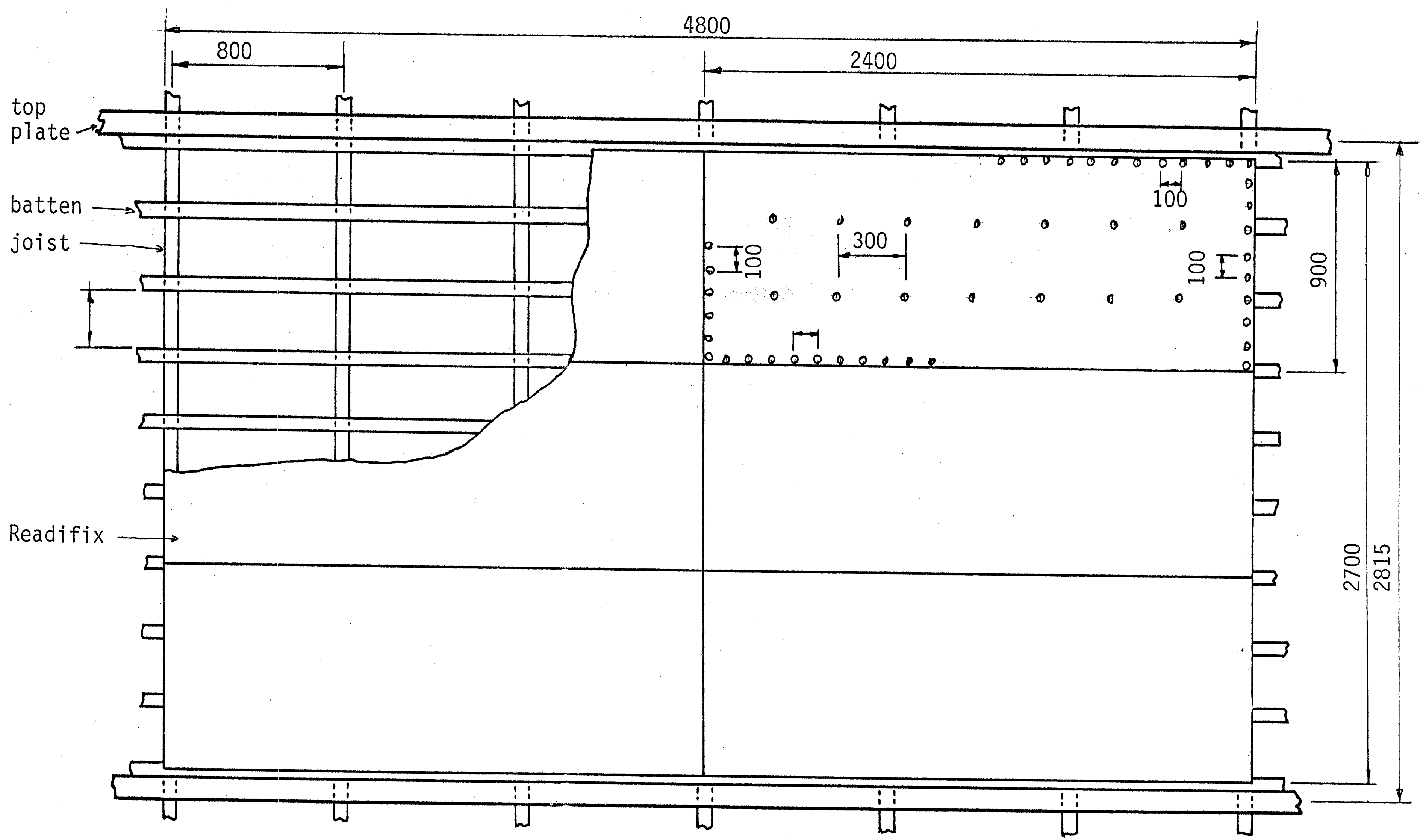
The 45 x 36 mm radiata pine timber battens were nailed to joist by one 75 x 3.75 mm plain nail. End nogging between the battens was used in the panel. The nogging was of the same material as the battens and was skew nailed with two 50 x 2.8 mm nails at each end. The cladding consisted of six 2400 x 900 x 5.5 mm 'Readifix' hardboard sheets. The sheets were nailed to the battens and nogging using 25 x 1.8 mm Flex Sheet nails at 100 mm spacing around the perimeter of each sheet and a spacing of 300 mm in the centre of each sheet (Figure A.11). As in Test B3, a splice was made in each top plate.

A.8.2. Loading Pattern

The panel was loaded in increments of approximately 0.6 kN up to a load of 9.25 kN, unloaded, then reloaded to failure in slightly larger increments. The panel was tested under a third point loading system.

A.8.3. Test Results

The observed load-deflection behaviour of the panel is shown in Figure A.13. Failure of the panel occurred at a load of 40.7 kN as a result of the fasteners pulling through the cladding. Little rotation of the



N.B. Nogging between battens at ends of sheets

Figure A.11 Test Panel B8

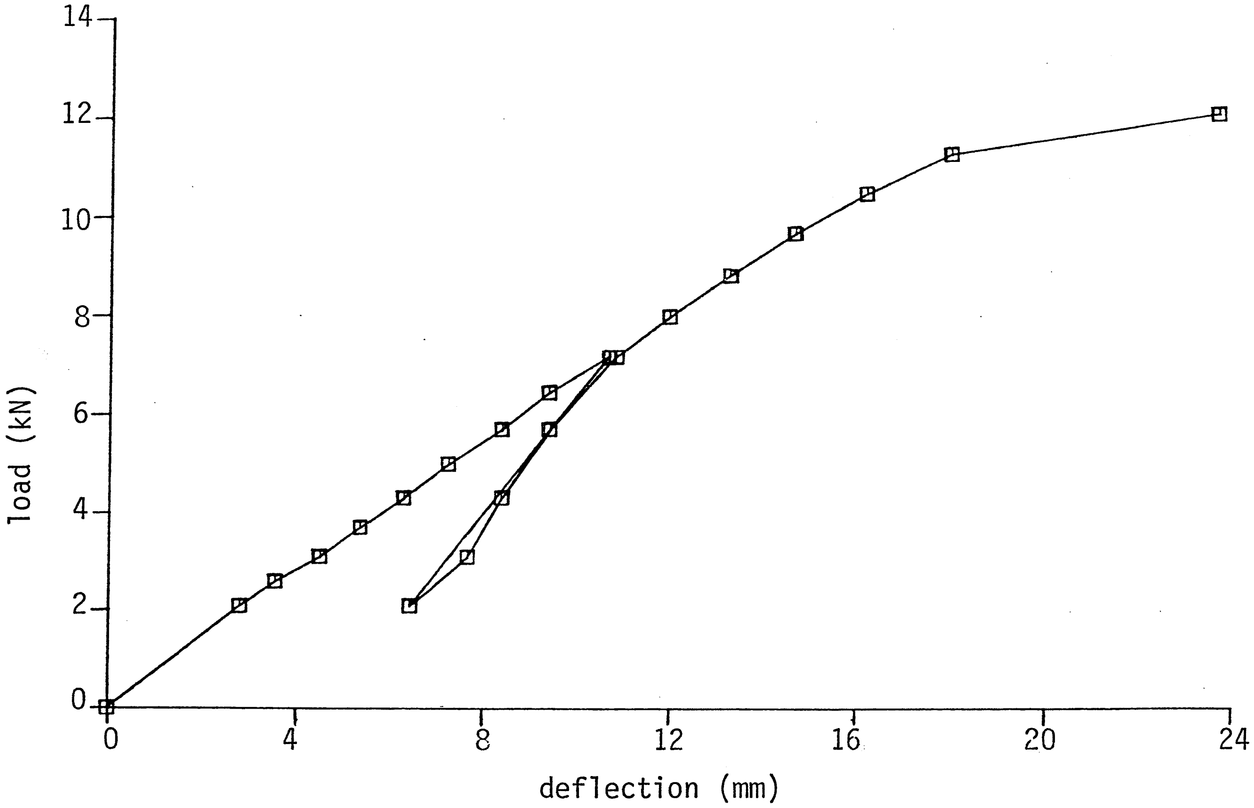


Figure A.12 Load-Deflection Curve: Test B7

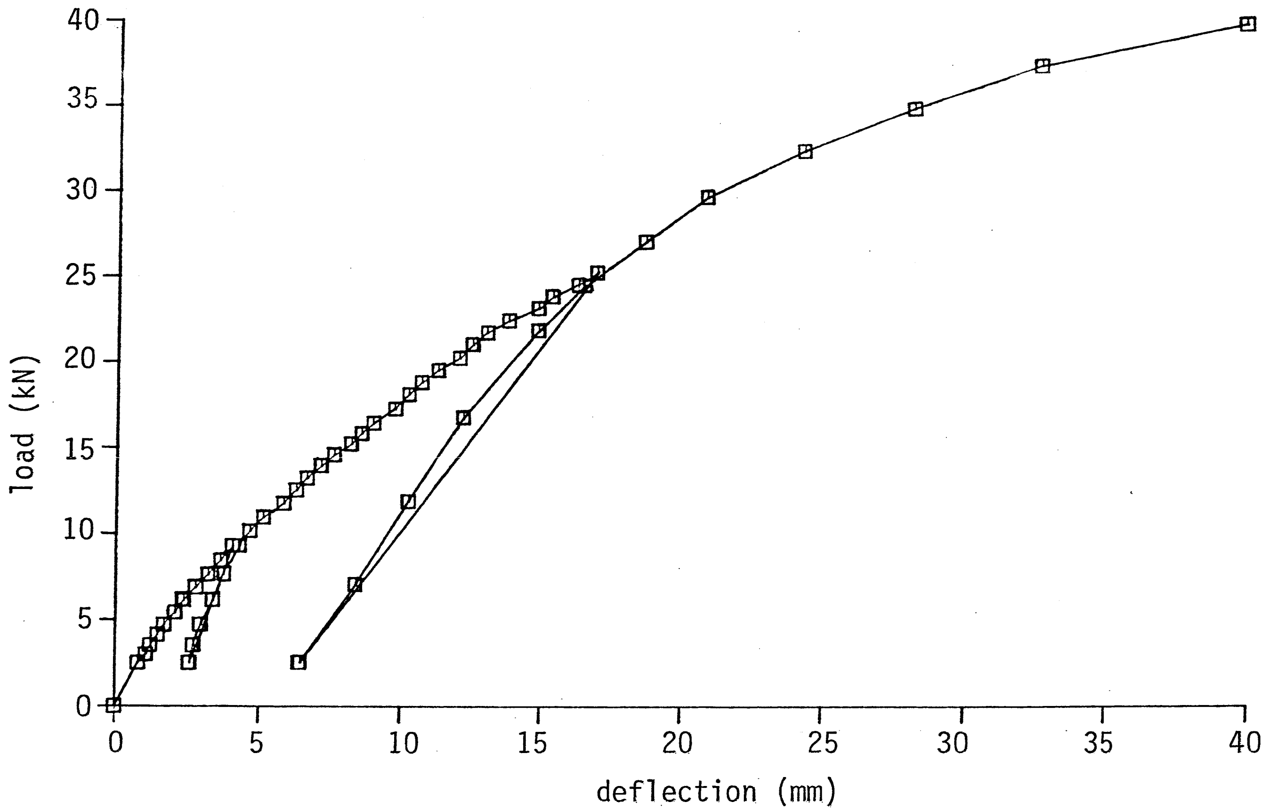


Figure A.13 Load-Deflection Curve: Test B8

individual cladding occurred due to the small displacement of the battens relative to the ceiling joists.

A.9 TEST B9

A.9.1 Test Panel

The panel geometry for this test was as follows:

- distance between top plates 2815 mm
- spacing of ceiling joists 400 mm

The cladding consisted of four 2400 x 1350 x 6 mm 'Villaboard' sheets. The sheets were fixed perpendicular to the ceiling joists and were fastened by 30 x 2.8 mm lattice nails at 150 mm spacing around the perimeter of the sheets and 270 mm spacing in the centre of the sheets. The joints and screw depressions were cemented using the previously detailed method. As in Test B3 a joint was made in each top plate (Figure A.14).

A.9.2 Loading Pattern

The panel was loaded in increments of approximately 0.6 kN up to a load of 7.9 kN, unloaded, then reloaded to failure in slightly larger increments. The panel was tested under the third point loading system.

A.9.3 Test Results

The observed load-deflection behaviour is shown in Figure A.15. Failure of the panel occurred at a load of 23.4 kN as a result of the failure of a plastered joint. The cladding came in contact with the top plates before failure of the fasteners had occurred.

A.10 TEST B10

A.10.1 Test Panel

Test panel B10 was identical to the panel used in Test B6 (Figure A.9).

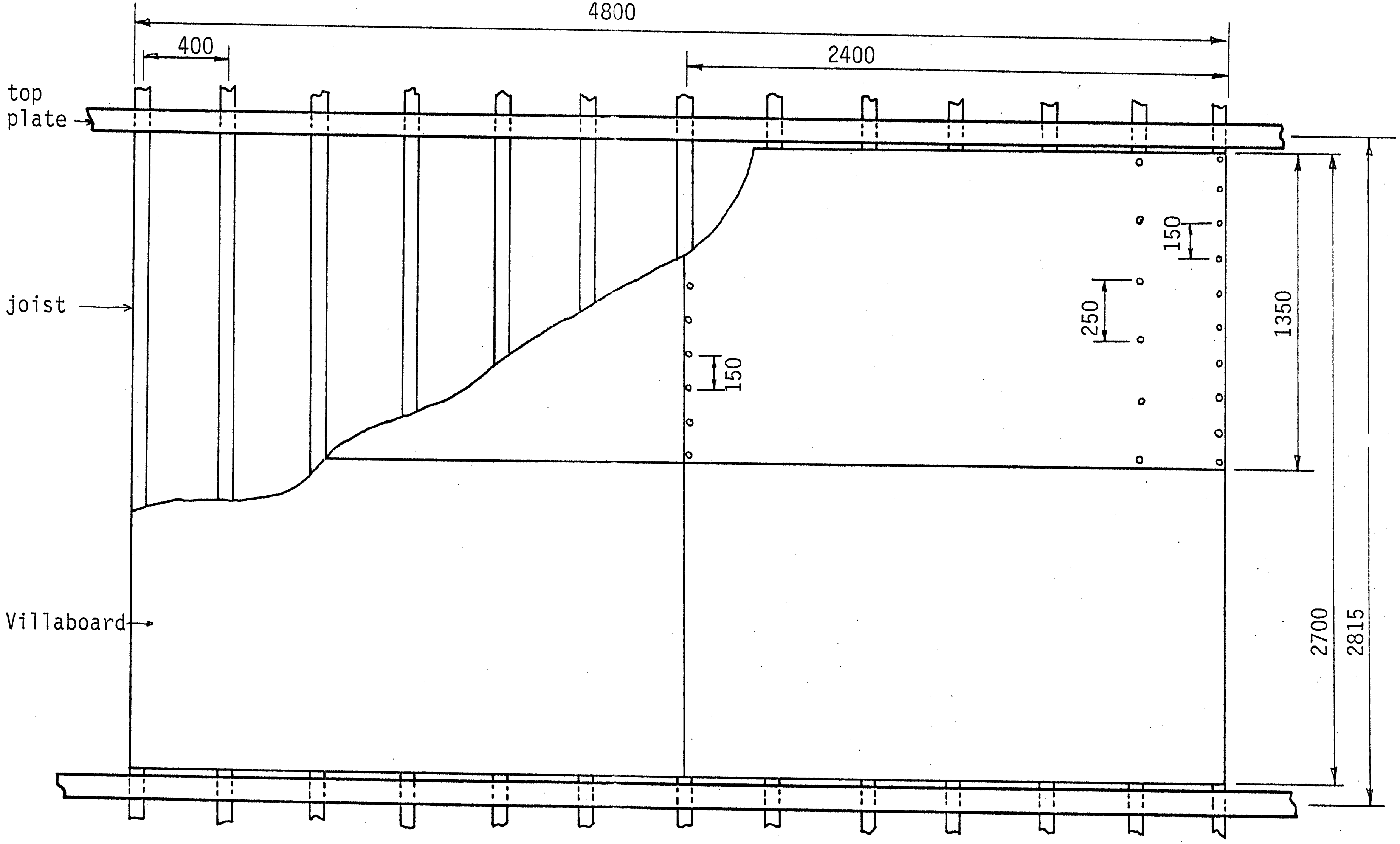


Figure A.14 Test Panel B9

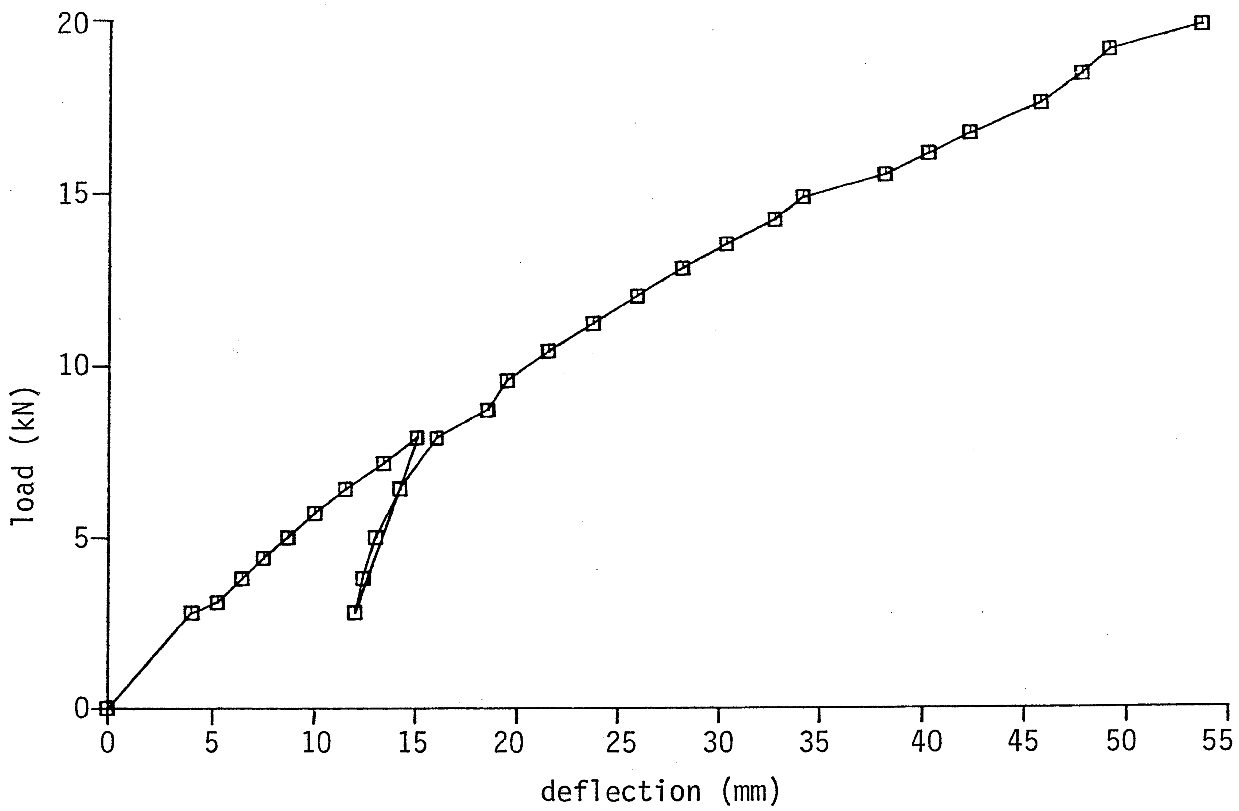


Figure A.15 Load-Deflection Curve: Test B9

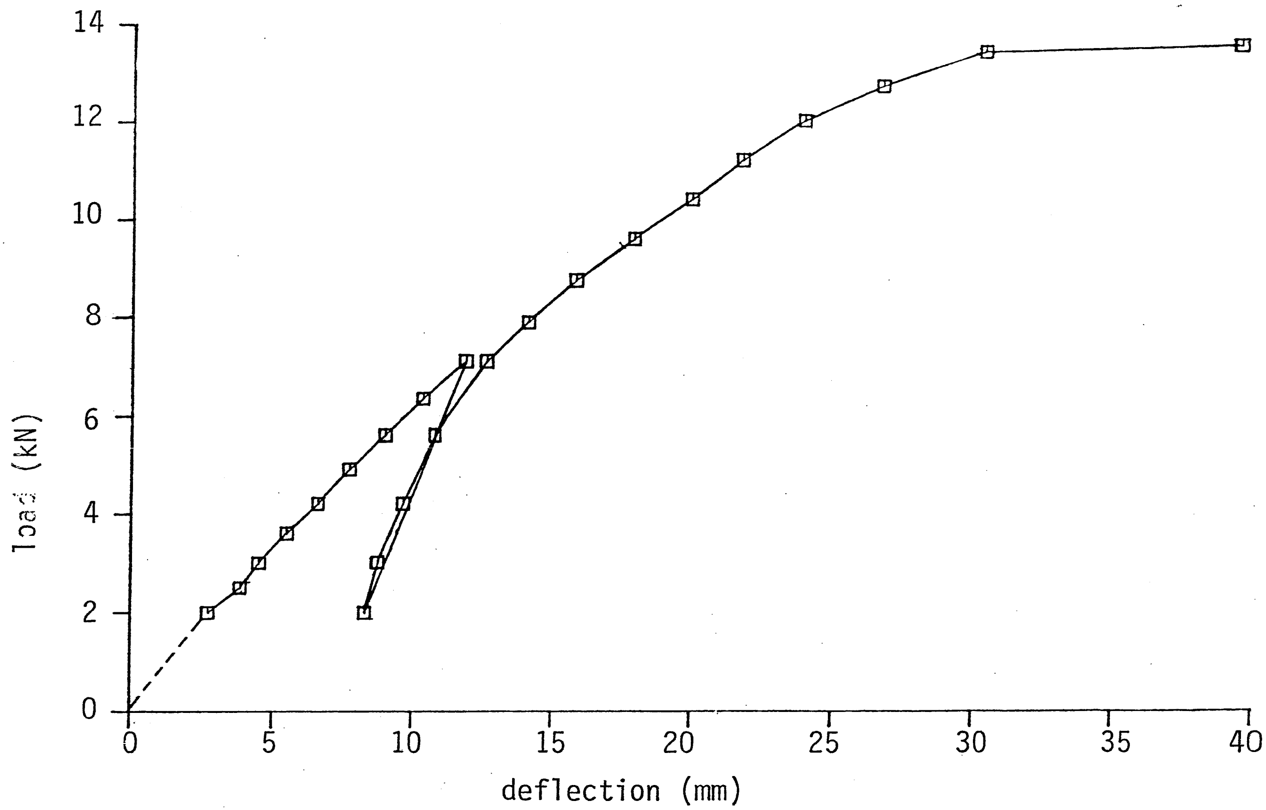


Figure A.16 Load-Deflection Curve: Test B10

A.10.2 Loading Pattern

The panel was loaded in increments of approximately 0.6 kN up to a load of 7.1 kN, unloaded, then reloaded to failure in slightly larger increments. The panel was tested under a centrally positioned point load.

A.10.3 Test Results

The load-deflection behaviour of the panel is shown in Figure A.16. Failure of the panel occurred at a load of 13.5 kN as a result of fasteners pulling through the cladding. Rotation of the individual cladding elements occurred with local buckling of the cladding occuring in the mid span area adjacent to the bearing between cladding sheets as in Test B6.