STRUCTURAL BEHAVIOUR OF CEILING DIAPHRAGMS IN STEEL-FRAMED RESIDENTIAL STRUCTURES

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ABSTRACT: *In residential structures, the ceiling structure is utilised as a structural diaphragm to transfer the lateral loads acting on the roof to the bracing walls. In steel-framed houses, the ceiling diaphragm is typically made of plasterboard lining screwed into steel ceiling battens which in turn are attached to the bottom chords of roof trusses. While the ceiling diaphragm is relied upon to perform an important structural function, there is very limited guidance available on the structural behaviour of such diaphragms. This paper presents results from experimental and analytical models which provide strength and stiffness data for typical diaphragms. These data can be used to carry out rational design for such diaphragms.*

KEYWORDS: Ceiling diaphragm, houses, plasterboard, lateral loading

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1 INTRODUCTION

The overall behaviour of a domestic structure under lateral loading from wind and earthquakes is influenced by both structural and non-structural components [1,2]. The ceiling is normally considered as a horizontal diaphragm which distributes such lateral loads to the bracing walls. In Australia, the ceiling diaphragm, in single and two storey cold-formed steel domestic structures, is typically made of plasterboard lining which is attached to ceiling battens which in turn are connected to the bottom chord of the roof trusses.

While the ceiling diaphragms need to be sufficiently strong to safely transfer the lateral loads to the bracing walls, knowledge of the stiffness of the diaphragms is required to correctly distribute the loads to the walls. For example, the International Building Code (IBC) [3] provides classification of diaphragms as being either flexible or rigid diaphragm relative to the stiffness of the bracing walls. However, in Australian design standards, there is no reference to the rigidity of the ceiling or roof diaphragms for either timber or steel framed houses. Reardon [1] conducted testing on a full scale steel-framed house and concluded that the ceiling diaphragm may be considered as rigid, while Breyer et al. [4] mentioned that ceiling/roof diaphragms can be considered as flexible. Phillips et al. [5] found that the design procedures for light-framed housing normally adopt the horizontal roof and ceiling diaphragms as flexible. Indeed, there is very limited data available on the strength and stiffness of ceiling diaphragms for Australian houses. The main source of information available is that contained in AS1684-2010 [6,7], which specifies the maximum distance between bracing walls which can be spanned by the roof system. This span is limited to a maximum of 9 m, regardless of the loading, roof geometries or material properties.

Therefore, it is necessary to evaluate the rational assessment of the strength and stiffness of horizontal diaphragms (i.e. ceiling diaphragms) to correctly design the lateral load-resisting system. The development of a rational design method would allow Australian designers and manufacturers to develop optimised systems rather than relying on extrapolation of historical empirical data. This would foster innovation in the important sector of industry in both Australia and internationally.

This paper investigates the lateral performance of typical ceiling diaphragms in cold-formed steel framed domestic structures in Australia. Particularly, the paper provides experimental testing of typical ceiling diaphragms in Australian domestic structures that are made of plasterboard lining screwed to cold-formed steel battens which are in turn screwed to bottom chords of steel roof trusses. The main objective of the test is to determine the strength and stiffness of a typical ceilings diaphragm. A finite element model is also developed and described in this paper and validated against the experimental results. This model is used to undertake parametric studies covering key factors which affect the strength and stiffness of ceiling diaphragms.

2 EXPERIMENTAL SETUP

Testing of full-scale ceiling diaphragm segments in the laboratory is the most common method for the determination of in-plane strength and stiffness of diaphragms. Diaphragms can be tested in two different configurations, namely cantilever or beam [9]. In the cantilever configuration, the diaphragm is essentially tested in racking as a shear wall, while in the beam configuration the diaphragm is assumed to act as a simply-supported deep beam spanning between bracing walls as shown in Figure 1. In this system, load is applied at one-third distance of the diaphragm to simulate the monotonic loading as presented in Figure 1. The advantage of cantilever setup is that it simpler to test. However, the beam test configuration is closer to the actual action of a ceiling but it is more demanding in terms of setup and testing. For this paper, the ceiling was tested in the beam configuration.

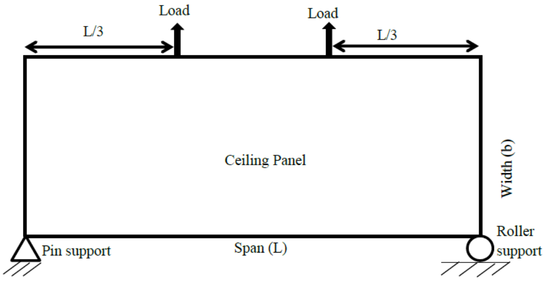

Figure 1: *Testing of diaphragm as deep beam*

3 TEST SPECIMEN

The size of the tested specimen was 5400 mm long and 2400 mm wide (Figure 2). The ceiling battens were top-hat 22 sections, while the bottom chord members were 90 x 40 x 0.75 mm lipped channel sections. The ceiling battens and bottom chord members were made of G550 cold-formed steel sections manufactured by BlueScope Steel. The spacing of the bottom chord members was 900 mm, while the spacing of the ceiling battens was 600 mm. The ceiling battens were attached to the bottom chord members using two Buildex 10G x 20 mm hex head self-drilling tek screws at each joint. Figure 3 shows the bottom chords and ceiling battens on the test jig before placement of the plasterboard.

The lining consisted of four 2400 x 1350 x 10 mm Gypsum plasterboard sheets manufactured by Boral which were screwed to the ceiling battens. The plasterboard sheets were attached to the ceiling battens using Buildex 6G-8 x 25 mm bugle-head needle-point screws at 270 mm spacing along each ceiling batten. The recessed joints between the plasterboard sheets were butt-jointed using the procedure recommended by the manufacturer. Figure 4 shows the completed test specimen prior to testing.

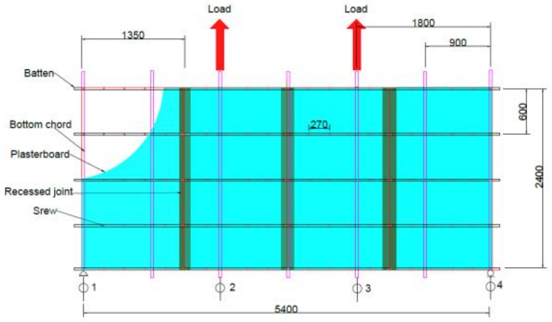

Figure 2: *Layout of test specimen*

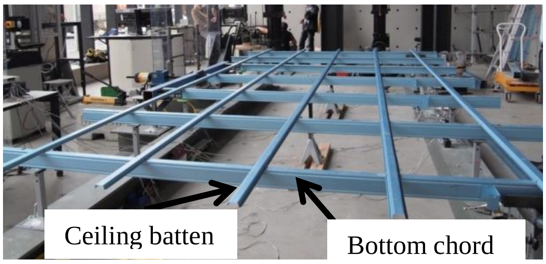

Figure 3: *Bottom chords and ceiling battens on the test jig before placement of plasterboard*

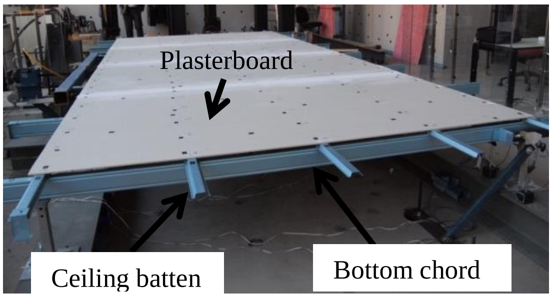

Figure 4: *Completed test specimen*

It should be noted that the distance between the end plasterboard screws and the plasterboard edges is typically between 15mm and 22mm. Therefore for this test specimen the plasterboard screws were provided at a typical edge distance of 20 mm along the perimeter of the diaphragm. In this research, adhesive was not used to connect the plasterboard sheathing with the battens.

4 TEST RESULTS

The test panel was loaded in increments up to failure, and the load-deflection behaviour of the tested ceiling diaphragm is shown in Figure 5. Failure occurred at the load of 7.5 kN as result of failure of plasterboard connections to the battens along edges and tear-out of plasterboard at the screw connections at corners of the diaphragm, as shown in Figure 6.

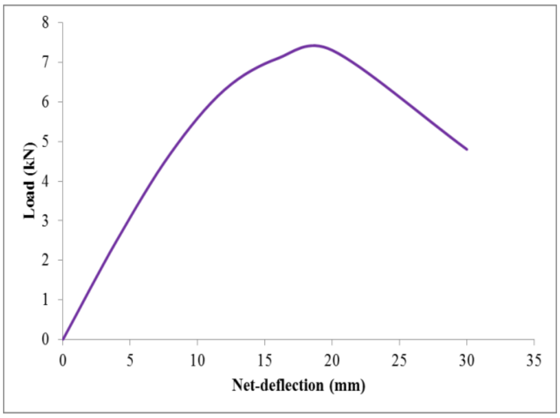

Figure 5: *Experimental load vs. net-deflection*

Figure 6: *Tear-out of plasterboard at the screw connections located at the corners of the diaphragm*

There was no relative movement between the individual plasterboard sheets. The whole lining system translated as a single unit. Further, there no relative displacement was observed between the ceiling battens and the bottom chords. However, considerable bending of the ceiling battens was observed as illustrated in Figure 7. No damage was observed to the bottom chords. Only minor local buckling of the bottom chord members was observed during the test but it was recoverable after unloading.

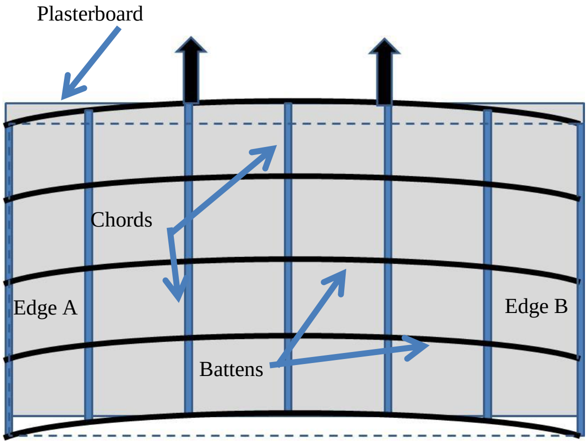

Figure 7: *Deformed shape of the test specimen showing bending of battens and translation of the plasterboard as a rigid body. The plasterboard screw connections failed mostly along edges A and B.*

Based on the results from this test specimen the ultimate load capacity is found to be 1.6kN per meter depth of diaphragm (2.4m for this specimen). The initial stiffness is 0.28kN/mm/m which is applicable to a load level up about 80% of the ultimate load.

The ultimate load and stiffness value deducted from this test represent low bound values. This is due to the fact that this test specimen did not include additional resistance provided by out-of-plane walls on which the chord members would be supported. Such walls would contribute in terms of: (i) their own flexural strength; (ii) the top plate of the walls providing a bearing surface for the translating plasterboard (Figure 7) which changes the failure mode from the plasterboard connections to plasterboard crushing along its bearing edge; and (iii) contribution from ceiling cornices which connect the ceiling plasterboard to wall plasterboard.

A large number of other ceiling diaphragms were tested covering a range of parameters such aspect ratio of diaphragms and spacing of battens.

5 FINITE ELEMENT MODELLING

Modelling is important for achieving in depth understanding of behaviour and for extending the benefits of experimental results. In this research, finite element models are developed and used to fully understand the influence of different parameters in order to develop a generalised design guides.

ANSYS software was used to construct Finite Element (FE) model. ANSYS covers various types of non-linearity, such as material non-linearity, geometric non-linearity, element non-linearity. In the development of the FE model of the ceiling diaphragm, different types of elements were used to simulate all relevant components. All elements used in the model are listed below:

- Bottom chords and ceiling battens were modelled as two-node beam elements. The connections between the bottom chord and ceiling battens members were modelled as pinned connections using coupling system.
- The plasterboard was modelled by eight node plane stress plate elements with a thickness of 10 mm.
- The plasterboard screws were modelled as non-linear spring elements. Each screw was modelled by three springs, with two springs acting in two orthogonal directions within the plane of the plasterboard and the third acting in the out of plane direction. These spring elements had different load-slip characteristics, depending on the location of the screw (field screws away from edge and edge screws close to plasterboard edge).
- The values used to define the load-slip curves of the non-linear springs were obtained from the shear connection tests [8] which were performed to cover both edge screws and field screws (connections not influenced by edge effects).

The results from FE model were compared with the experimental results and were found to be good agreement. The comparisons of the experimental and analytical load-deflection curves are presented in Figure 8. The failure mode and overall deformed shape from FE model were also in agreement with the experimental results.

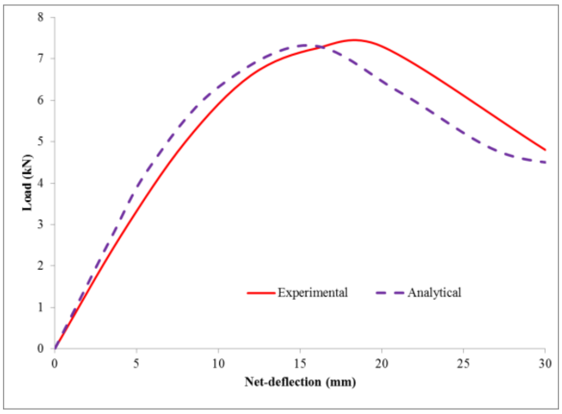

Figure 8: *Comparison between experimental and FE results for the test specimen*

6 PARAMETRIC STUDY

The results presented earlier are for loading on the diaphragm in the direction perpendicular to the ceiling battens (parallel to the chords). This represents the more flexible and weaker direction as opposed to loading perpendicular to the chords. To demonstrate this difference two FE models were created based on the validated model presented in

Section 5. One model represented loading perpendicular to the battens and another for loading perpendicular to the chords (parallel to the battens). Both models had the same materials, size and spacing of members and connection details.

Both models measured 5.4 m long and 5.4m wide. The spacing of the ceiling battens was kept at 450 mm, while the bottom chord spacing was 900 mm. The plasterboard screws were fixed at 270 mm spacing along all ceiling battens.

The resulting load-deflection curves for both loading directions are depicted in Figure 9.

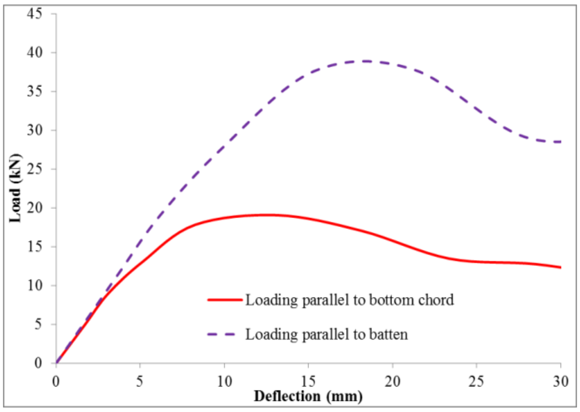

Figure 9: *Comparison of load-deflection behaviour between loading directions perpendicular to batten and parallel to bottom chords*

From Figure 9, the ultimate capacity of the ceiling diaphragm in loading parallel to the ceiling battens is 3.6kN/m while that for loading applied perpendicular to the battens is only 1.8kN/m.

This is attributed in part to the higher stiffness of the actual steel frame (battens and chords without the plasterboard). However, the main reason for this increase in strength is the fact that for loading perpendicular to the battens, there are fewer plasterboard screws along the diaphragm edges (edges A and B in Figure 7) compared to loading parallel to the battens. For loading parallel to the chords the spacing of the screws along the edges (A&B in Figure 7) is the same as the batten spacing which is 450mm. Increasing the number screws along these edges results in almost proportional increase in strength. This is simply because the ceiling diaphragm acts in a similar manner to a deep beam with its capacity governed by its shear resistance. In turn the shear resistance is governed by strength of the connections between the plasterboard and supporting battens.

It should be mentioned that the above strength and stiffness values do not include contributions from the full roof trusses, roof cladding and roof bracing. If contributions from the full roof are to be considered, the in-plane strength and stiffness values of the roof system would be greater.

7 CONCLUSIONS

Results from testing a ceiling diaphragm under in-plane loading were presented in this paper. Further, finite element model was developed and validated against the experimental results. Based on the results and analyses of the full-scale ceiling diaphragm presented in this paper, the following remarks can be observed:

- The strength and stiffness of ceiling diaphragms can be obtained by testing in a deep beam configuration.
- FE modelling can be used to represent the behaviour of such diaphragms, but experimental load-slip behaviour of the connections between the plasterboard and battens is required as part of the model input.
- Under in-plane loading, the behaviour of the ceiling diaphragm is analogues to a deep beam where the ultimate strength is related to its shear capacity. In turn, the shear capacity of a diaphragm is directly related to the capacity of the screw connections between the plasterboard and battens at the ends of the diaphragm.
- For typical steel framed ceiling with plasterboard lining, the lower bound for in-plane strength is around 1.8kN/m. This is for loading in a direction perpendicular to the ceiling battens. For loading parallel to the ceiling battens (i.e., perpendicular to the chords) the strength is about 3.6kN/m.
- The above strength values do not include contributions from the roof cladding and its bracing. Further, these do not include contributions from out-of-plane walls supporting the roof trusses and additional contributions which can be made by the ceiling cornices.

Further research is currently underway to utilise the experimental and FE results to produce a rational design guide for cold-formed plasterboard lined ceiling diaphragms.

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REFERENCES

[1] Reardon, G.F. (1990). 'Simulated cyclone wind loading of a Nu–steel house', *Technical*

Report No. 36, Cyclone Testing Station, James Cook University, Townsville.

[2] Liew, Y.L., Gad, E.F., and Duffield C.F., (2004). “Development of test method for determining plasterboard bracing performance”, Journal of Structural Engineering, ASCE, Vol. 130, No. 7, pp. 1108-1116.

[3] International Building Code (IBC) (2006). Final draft, International Code Council, Birmingham.

[4] Breyer, D. E., Kenneth J. F., Kelly E. C., David G. P. (2007). ‘*Design of Wood Structures-ASD/LRFD.*’, Sixth edition, McGraw-Hill.

[5] Phillips, T.L., Itani, R.Y. and McLean, D.I. (1993). ‘Lateral load sharing by diaphragms in wood-framed buildings’, *Journal of Structural Engineering,* Vol. 119, No. 5, pp. 1556–1571.

[6] Standards Australia (2010). ‘AS 1684.2: Residential timber-framed construction - Non-cyclonic areas’.

[7] Standards Australia (2010). ‘AS 1684.3: Residential timber-framed construction - cyclonic areas’,.

[8] Liew, Y.L., Gad, E.F., and Duffield, C.F., (2006) “Experimental and analytical validation of a fastener bearing test as a means of evaluating the bracing characteristics of plasterboard”, Journal of Advances in Structural Engineering, Vol.9 (3), pp. 421-432.

[9] ASTM E455-04 (2004). ‘Standard test method for static load testing of framed floor or roof diaphragm constructions for buildings’, *Annual Book of Standards,* West Conshohocken, PA