# CEILING DIAPHRAGM ACTIONS IN COLD FORMED STEEL-FRAMED DOMESTIC STRUCTURES

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**ABSTRACT**

*In light framed structures, ceiling and roof diaphragms play a vital role in transmitting the lateral load (e.g. wind and earthquake) to bracing walls. The distribution of such loads from the diaphragms to the walls is dependent on their relative in-plane stiffness to the stiffness of the bracing walls. In some international codes of practice, designers may classify diaphragms as flexible or rigid in order to distribute the lateral loads to the bracing walls. However, in Australian design standards, there is no specific reference to the rigidity of the ceiling or roof diaphragms. The main focus of this paper is the determination of the strength and stiffness of a typical ceiling diaphragm in Australian houses. This paper describes some experimental results from a typical ceiling system used in cold formed steel-framed domestic structures. The tested specimens were made up of a plasterboard lining screwed to cold-formed steel battens that were, in turn, screwed to bottom chords.*

**KEYWORDS:** Light-framed structures, ceiling diaphragm, testing, cold-formed steel, testing methods.

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## 1. INTRODUCTION:

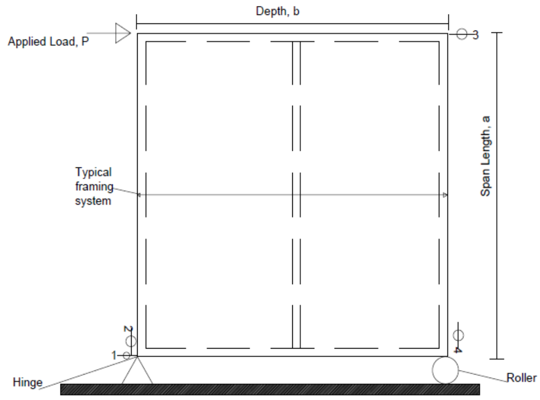
In Australia, domestic structures refer to one and two storey light-framed houses. In such structures, the lateral loads generated due to wind and earthquake at the roof level are transmitted to the foundation through the roof and/or ceiling diaphragms and bracing walls. A diaphragm can be defined as a structural system that acts to transmit lateral forces to the vertical lateral resisting system. Walker (1978) stated that the lateral loads are generally transferred through a complex interaction between the walls, roof structure and floor structure. While there was limited research undertaken on timber framed structures such as this by Walker and Gonano (1981 & 1983) and Walker et al. (1982), there is very little published research available on the capacity of ceiling and/roof structures of steel-framed Australian domestic structures.

Knowledge of ceiling and/roof diaphragm stiffness is important for proper distribution of the lateral load to the bracing walls. In Australian design standards, there is no reference to the rigidity of the ceiling or roof diaphragms. Common current practice is based on the provisions in the National Timber Framing Code AS1684 -2010 which places a maximum ceiling span between bracing walls for different geometric conditions and wind classifications. However, for any combination, the maximum span possible is 9m. While the limits set in AS1684 have been in used over a long time and often used for other forms of constructions there is little background on how these limits were established. Therefore, rational assessment of the stiffness and strength of horizontal diaphragms is essential for design of the lateral load resisting system.

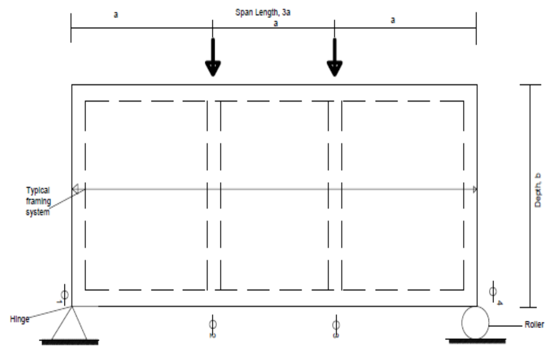
This paper is focussed on the behaviour of ceiling diaphragm in steel framed domestic structures. Specifically, the paper covers testing of typical ceilings made of plasterboard lining screwed to cold-formed steel battens which are in turn screwed to bottom chords of roof trusses. The main objectives of the tests are to investigate a suitable experimental setup and obtain typical strength and stiffness parameters for the tested ceilings.

## 2. EXPERIMENTAL SETUPS:

The most common method for determining the in-plane strength and stiffness of ceiling diaphragm is laboratory testing of the full scale diaphragm segments. Construction and testing procedures for such assemblies are available in ASTM E455-04 'Standard Test Method for Static Load Testing of Framed Floor or Roof Diaphragm Constructions for Buildings'. There are two different configurations for testing the diaphragm assembly, namely: cantilever setup; and simple beam setup as shown in Figure 1. In the cantilever setup, the diaphragm is essentially tested in racking as a shear wall, while the in the beam setup the diaphragm is tested as a deep beam in bending. Both setups were employed in this research and the results from related two specimens are reported herein.




(a)




*(b)*

***Figure 1:*** *Schematic test setups for diaphragms: (a) cantilever setup; (b) beam setup.*

## 3. CANTILEVER TEST:

### 3.1 TEST SETUP:

In a cantilever test setup, the two end vertical members experience tension and compression (push-pull) forces generated by the horizontal racking force. The tension member would need to be restrained from unrealistic uplift otherwise premature failure may occur. Such restraints would be totally artificial and hard to practically achieve for a ceiling system unlike shear or bracing walls. Given that the purpose of this test was to obtain the shear resistance of a ceiling panel, a loading frame (parallelogram) was developed to apply the racking load which would also resist the tension and compression forces negating the need to provide supplementary restraints the ceiling members.

The loading frame, shown in Figure 2, was made of hot rolled steel channel sections with two horizontal members (top and bottom) and three vertical members. All members were connected to each other with a single bolt to allow free rotation (i.e., all members are pin connected). The bottom of the frame was anchored

to the floor of the Lab; and the top was restrained in the out of plane direction for stability.

The load was applied at the top of the loading frame via a hydraulic actuator. The racking load was measured by a load cell mounted at the loading point and deflections were measured by LDTs.

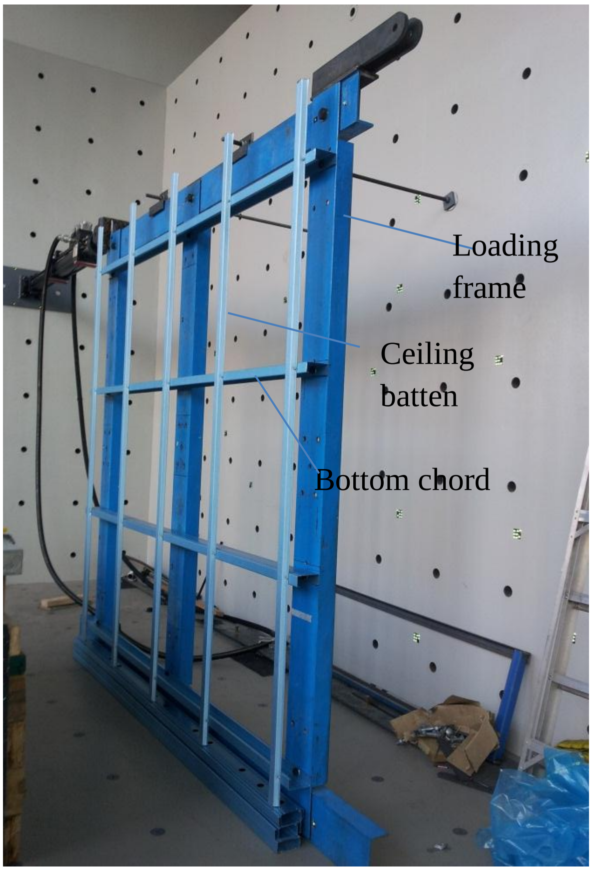



***Figure 2:*** *Photograph of loading frame with ceiling bottom chords and ceiling battens mounted on it.*

### 3.2 TEST SPECIMEN:

The test specimen simulated a section of a typical plasterboard ceiling whereby the plasterboard is attached to batten which in turn are fixed to the bottom chords of roof trusses.

Hence, the first step in making the specimen was to attach the bottom chords (G550 90 x 38 x 0.75 mm lipped sections) to the loading frame by using M16 bolts. The bottom chords were placed 750 mm centres. The ends of the bottom chords were blocked to prevent unrealistic section twisting. The ceiling battens (G550 standard Top-hat 22 sections) were attached to the bottom chords at 600 mm spacing using double Buildex 10 gauge self-drilling screws at each joint. The plasterboard sheets (one 2400 x 1200 x 10 mm and another 2400 x 1350 x 10 mm) manufactured by Boral Plasterboard Pty. Ltd. were fixed to the battens using Buildex 6G-18 x 25 mm bugle head needle point screws at 300 mm centres along each batten. The plasterboard sheets were butt jointed using typical construction details. The overall dimensions of the test specimen were 2250mm high x 2400mm in length. The tested ceiling diaphragm assembly is shown in Figure 3.

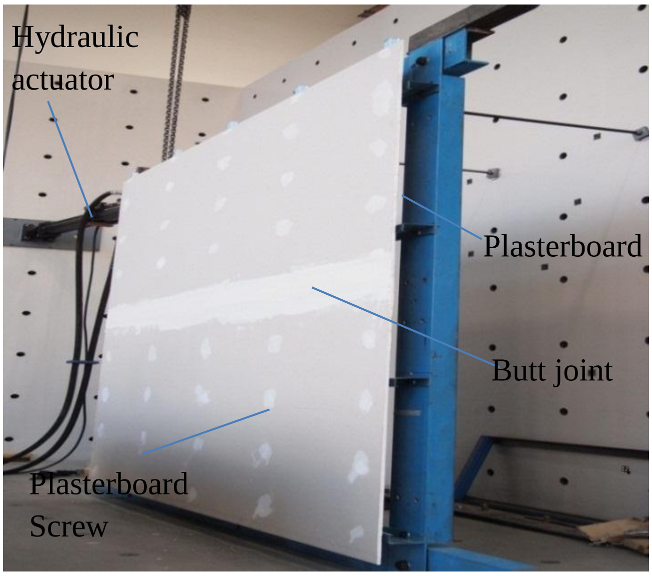



***Figure 3:*** *Tested ceiling diaphragm assembly*

### 3.3 LOADING FRAME FRICTION:

While the loading frame was assumed to be a mechanism without a lateral strength, an initial racking test was performed on the loading frame only (ie., without the ceiling) to ensure that it has very little in-plane stiffness. The resulting load vs. deflection curve of the loading frame is shown in Figure 4. As it can be seen, the maximum load capacity of the frame due to friction was approximately 0.2 kN. This value was deducted from subsequent ceiling results.

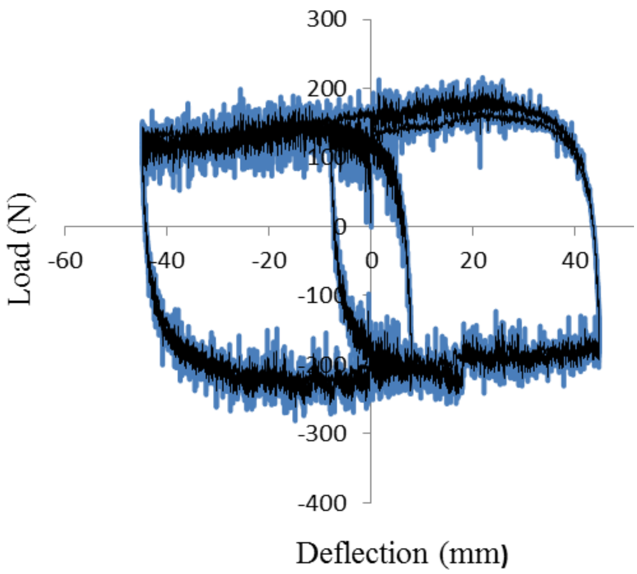



***Figure 4:*** *Load vs. deflection curve of loading frame only*

### 3.4 CANTILEVER TEST RESULTS

The cantilever test specimen was loaded in displacement control at the rate of 2 mm/min until failure. The resulting load versus net deflection is shown in Figure 5. Specific numbering of members and plasterboard screws is also shown in Figure 6 to aid the explanation of the failure mode.

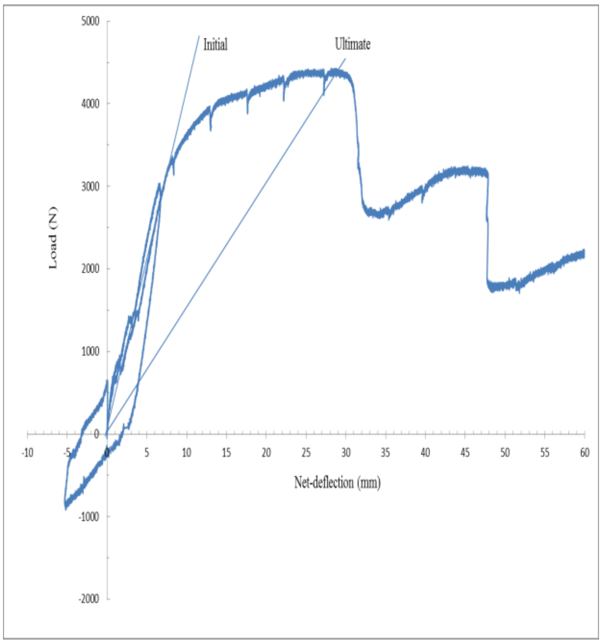



***Figure 5:** Load vs. net-deflection curve of the tested specimen*

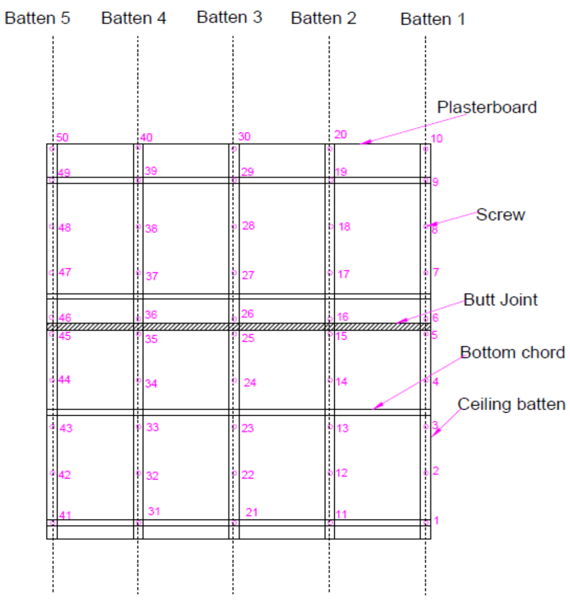
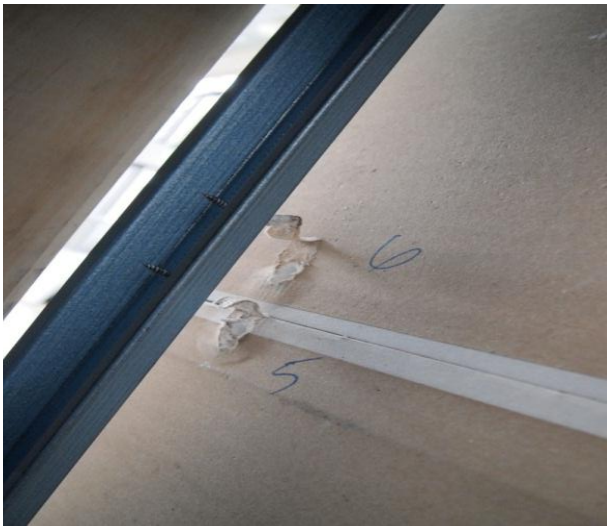



***Figure 6:** Tested ceiling diaphragm assembly (showing numbering for explanations)*

The maximum load that could be supported by the specimen was 4.5 kN. The specimen lost load capacity suddenly past this load due to failure of plasterboard screw connections along batten 1 (refer Figure 6). The failure of screw connections was in the form of tearing of plasterboard around the screw heads and pull through of the plasterboard as shown in Figure 7.

(a)

(b)



(c)

***Figure 7:** Failure mode of cantilever specimen: (a) tearing of plasterboard around screws along batten 1; (b) pulling through of plasterboard; (c) view of plasterboard from the back side.*

Upon failure of the plasterboard screws along batten 1, the majority of the remaining racking capacity was resisted by screws along batten 2 which eventually failed in the same manner as for batten 1. Similarly, following the failure of the screw connections along batten 2, the screw connections along batten 3 failed. This unzipping effect along the three battens (1, 2 and 3) is manifested in the three discrete steps in the load-deflection curve shown in Figure 5.

There was no relative movement observed between the individual plasterboard sheets. The entire plasterboard lining rotated as a single unit. Further, no relative displacement was observed between the ceiling battens and the bottom chords. No damage was observed for the bottom chords or battens.

Based on the presented results, the strength of the tested diaphragm is calculated to be 1.87 kN/m and is expressed as force per meter depth (i.e., 4.5kN/2.4m).

While the failure mode was as expected, the specimen seemed to have lower stiffness. This was the case for both the initial and ultimate stiffness values as shown in Figure 5. Therefore, to ensure that the performance of the ceiling specimen is not highly influenced by the test setup, the alternative beam setup was considered as discussed below.

## 4. BEAM TEST:

In this setup, the ceiling is assumed to act as a simply supported deep beam spanning between bracing walls. This setup is closer to the real action of a ceiling, however it is more demanding in terms of testing due to the required larger space and more complex loading and measurement system as described below.

### 4.1 TEST SETUP:

Figure 8 shows a diagrammatic view of the testing arrangement for the beam test setup. The size of the test specimen was 5400 mm long and 2400 mm wide. The spacing of bottom chord members was 900 mm (compared to 750 mm for the cantilever specimen) and spacing ceiling battens was 600 mm (same as cantilver specimen).

All the materials used for this test are identical to those used for the cantilver test (ie., same bottom chord section, battens, plasterboard and screws). The construction details were also identical.

The different stages of the preparation of the tested specimen are shown in Figures 9 and 10.

It should be noted that the test specimen was supported vertically only at a number of locations (marked by squares in Figure 8), but the in-plane suports were only placed at two corners with one being a pin and the other being a roller support.

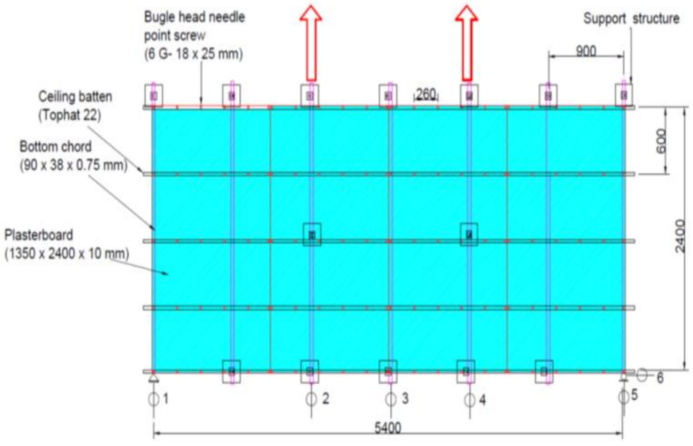



***Figure 8:*** *Layout of beam test speimen*

***Figure 9:*** *Bottom chords and ceiling battens on the test jig before placement of plasterboard*

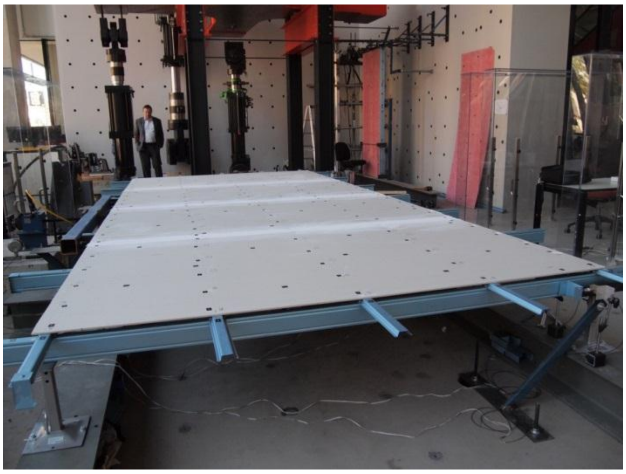


***Figure 10:*** *Complete beam test specimen. The dark spots on the plasterboard are reflective photogrammetry target.*

In this setup, the load was applied at two bottom chords as shown in Figure 8 using a hydraulic jack. The deflections of the panel were measured by LVDTs and a photogrammetry system.

**4.2 TEST RESULTS:**

The test panel was loaded in increments up to the failure. The obtained load-deflection behaviour of the tested ceiling diaphragm is shown in Figure 11. The load-net deflection behaviour showed similar characteristics to that obtained in the cantilever test, i.e. being highlu non-linear.

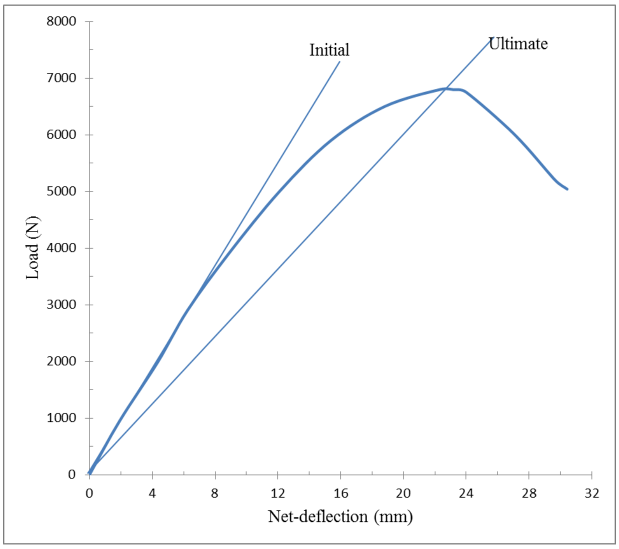



***Figure 11:*** *Load vs. net-deflection curve of the specimen*

Failure occurred at a load of 6.8 kN (or 2.83kN/m) as a result of failure of the plasterboard connections at the corners of the specimen. Ultimately, similar to the cantilever specimen the plasterboard pulled through the screws as shown in Figures 12 and 13.

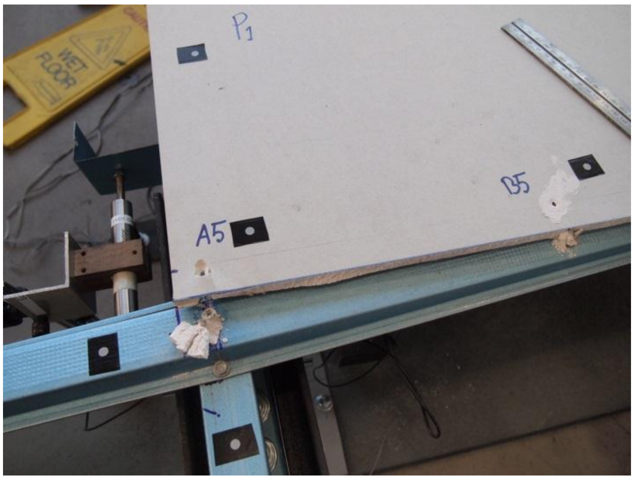


***Figure 12:*** *Tear out of plasterboard at the left corner of diaphragm*

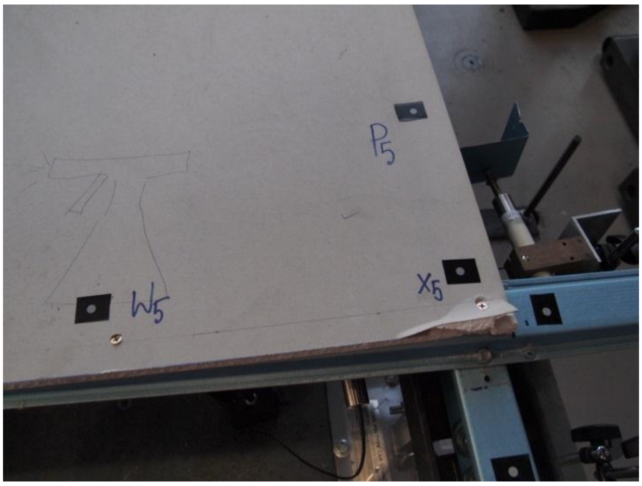


***Figure 13:*** *Tear out of plasterboard at right corner of diaphragm*

The overall deformed shape of the specimen is illustarted in Figure 14 which shows bending of the battens and translation of the plasterboard as a rigid body. There was no observed relative movement between individual plasterboard sheets nor between the battens and chords.

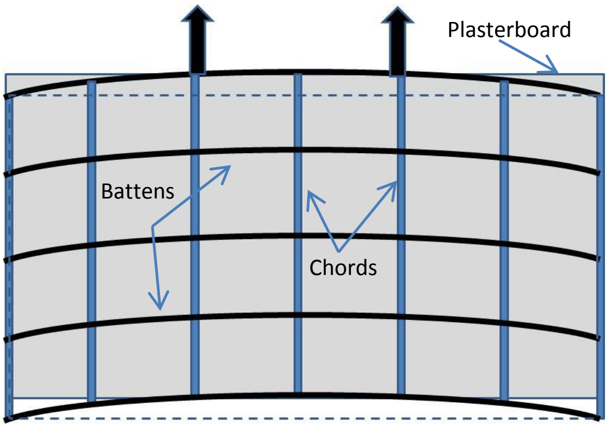



***Figure 14:*** *Deformed shape of the test specimen showing the bending of battens and translation of the plasterboard as a rigid body. The dashed lines indicate the original position of the plasterboard.*

The ultimate capacity of the beam specimen was approximately 50% greater for an almost identical layout. Further, the beam specimen was also stiffer in comparison. These results suggest that in developing design parameters for ceiling diaphragms the beam setup is likely to yield more realistic results compared to the simpler cantilever setup.

The beam setup could further be enhanced to consider the effects of top plates of walls supporting the roof trusses. These top plates would provide further bending resistance to the ceiling diaphragm and would also provide bearing area for the plasterboard ceiling as it

translates in the direction of an end wall. These effects are currently under study.

## 5. CONCLUDING REMARKS

Two different test setups for evaluating ceiling diaphragms were presented in this paper, namely, the cantilever setup and beam setup. While the cantilever setup is simpler from experimentation point of view, the beam analogy is more realistic of how a ceiling spans between bracing walls. Based on the results presented for two specimens, the following remarks can be made.

- For both specimens the ultimate failure mode was found to be the same. In both cases, the plasterboard connections failed at the locations where maximum relative movement between the plasterboard and battens occurred.
- In both cases, the plasterboard moved or rotated as a rigid body without relative movement between individual sheets connected to each other using standard butt joints.
- There was no observed relative movement between the ceiling battens and chords.
- The ultimate strength from the beam test was approximately 50% greater than the cantilever test (2.83kN/m compared to 1.87kN/m). Further, the beam specimen was also stiffer.
- The load capacity and stiffness of the beam test could be further increased by incorporating the effects of top plates of load bearing walls. These top plates would add to the bending resistance of frame and also provide a stop and bearing to the plasterboard as it translates towards an end wall.

Further studies are currently underway to produce rational design data for plasterboard ceilings in cold framed steel houses using additional experimental results, finite element analyses and numerical models.

## ACKNOWLEDGMENT

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## REFERENCES

[1] AS1684. National Timber Framing Code. Standards Association of Australia, 2010.

[2] ASTM E455-04 ‘Standard Test Method for Static Load Testing of Framed Floor or Roof Diaphragm Constructions for Buildings, *Annual Book of Standards*, ASTM, West Conshohocken, PA.

[3] Walker, G.R. & Gonano, D. Investigation of Diaphragm Action of Ceilings. Progress Report I, Technical Report No. 10, Department of Civil and Systems Engineering, James Cook University of North Queensland, Townsville, Australia, 1981.

[4] Walker, G.R. Boughton G.N, & Gonano, D. Investigation of Diaphragm Action of Ceilings. Progress Report II, Technical Report No. 15, Department of Civil and Systems Engineering, James Cook University of North Queensland, Townsville, Australia, 1982.

[5] Walker, G.R. & Gonano, D. Investigation of Diaphragm Action of Ceilings. Progress Report III, Technical Report No. 20, Department of Civil and Systems Engineering, James Cook University of North Queensland, Townsville, Australia, 1983.

[6] Walker, G.R. The design of Walls in Domestic Housing to Resist Wind. Design for tropical cyclones, Vol 2. James Cook University, 1978.