# The influence of plasterboard clad walls on the structural behaviour of low rise residential buildings

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## ABSTRACT

*While the design and technology of conventional low rise light framed residential structures are relatively simple, their response to lateral loading is quite complex. This is due to the high degree of redundancy, the irregular geometry and interaction between the structural and non-structural components. In addition, the designated lateral bracing elements within one structure may exhibit significantly different behaviour due to the different bracing actions and different materials. This paper focuses on the bracing capacity of plasterboard clad walls which could be considered either structural or non-structural. While such walls may be installed purely as partition walls, they may provide lateral strength and stiffness due to the complex load paths. The paper presents in detail the possible load transfer mechanisms to a variety of typical walls. It also highlights the difficulty with performing racking tests on isolated walls due to the complex boundary conditions surrounding walls in real structures. In addition, the paper reports racking test results that demonstrate the effects of different boundary conditions on the load carrying capacity and the failure modes.*

**KEYWORDS**
*Residential, lateral bracing, load sharing, plasterboard, light framed walls.*

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## 1. Introduction

In recent years, building regulations in Australia have steered away from being prescriptive in nature to reliance on performance-based standards. This change in emphasis has fostered creativity from industry to develop integrated systems for the likes of residential frames and walls, with individual companies striving for a market edge through creative development of products. Compliance of these new systems is normally confirmed by laboratory based testing of the individual subassemblies or components. However, based on testing of full scale houses it has been established that the overall lateral behaviour inherently incorporates contributions from the main structural elements and from the so called non-structural components, particularly plasterboard lining (Reardon [1] and Gad et al. [2]).

This paper reports the findings of a detailed investigation into the actual loading mechanism of plasterboard clad frames and the influence of the actual load paths on the design assumptions for such structures. The overall aim of the investigation is to increase the understanding of the system behaviour of residential buildings to ensure appropriate assumptions are used in combination with testing to prevent inappropriate reliance on secondary mechanisms for the integrity of such residential buildings.

Specifically, the paper presents the current level of understanding of the actual contribution plasterboard makes to the lateral capacity of light framed structures in Australia and details the load sharing and load transfer mechanisms of such structures. It also presents details of the properties of plasterboard that are routinely controlled as part of the manufacturing process for plasterboard and those properties that can be relied upon when considering the performance of an integrated wall system for compliance.

A series of results from static racking tests on clad walls that demonstrate the effect of boundary conditions on wall performance and failure modes are also presented.

## 2. Lateral bracing of residential structures

The most common form of domestic structures in Australia is brick-veneer construction; this is a form of light framed structure. In brick veneer structures the brick walls form the exterior cladding and plasterboard is generally used as interior lining. The brick-veneer walls and the plasterboard lining are considered as non-structural components. Lateral bracing of the frames is often provided by a combination of steel cross bracing (which also brace the frame during erection), sheet cladding (eg. plywood) and diagonal K bracing (Fig. 1).

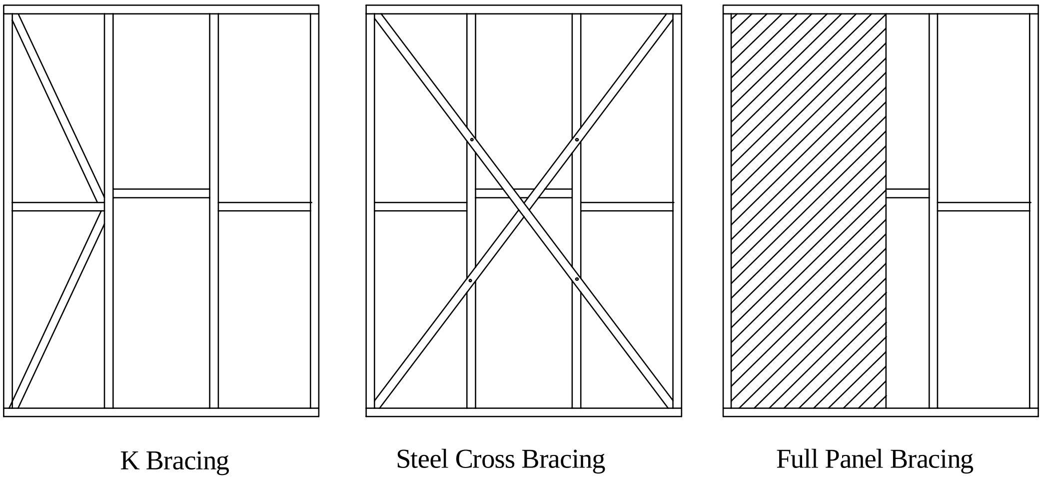


**Fig. 1** Bracing types used in light framed residential structures.

The lateral capacity of the bracing walls is quite complex and depends on factors such as material properties, configuration of the frame and the connectivity of all components. Factors that may influence the lateral capacity of wall panels are summarised in Fig. 2. Some of these factors have been investigated by various researchers such as Reardon [1], Barton et al. [3] and Gad et al. [4] in Australia; Wolfe [5], Tarpy [6], and McCutcheon [7] in the United States. A major finding from these investigations was that plasterboard lined walls, a non-structural component, contribute significantly to the lateral strength and stiffness of these light framed structures. The magnitude of this contribution was quantified by testing full-scale houses and assemblies by Reardon [8] and Gad et al. [9]. Gad et al. [9] found that plasterboard, combined with ceiling cornices, skirting board and set corner joints resisted 60% to 70% of the lateral load compared to a contribution of only 30% to 40% by strap braces.

Plasterboard has not only been used as a non-structural lining material, but also used for bracing purposes. Its bracing capacity is presented in several codes and standards around the world including the Uniform Building Code [10] in the United States and in New Zealand [11]. In Australia, walls with nominally fixed plasterboard (non-bracing walls) were also indirectly used for lateral bracing. In the recently superseded timber framing code (AS1684:1992) [12] it was assumed that such plasterboard lined walls provide 40% and 20% of the lateral bracing required for single and double story houses, respectively. However, in 1999, this code was revised (AS1684:1999) [13] and it now explicitly defines the contribution of nominally fixed plasterboard clad walls as 0.45kN/m for plasterboard cladding on one side and 0.75kN/m for cladding on two sides. These values are in line with the provisions of the Australian plasterboard manufacturers. However, the housing construction industry at large considers the plasterboard in houses as a non-structural component.

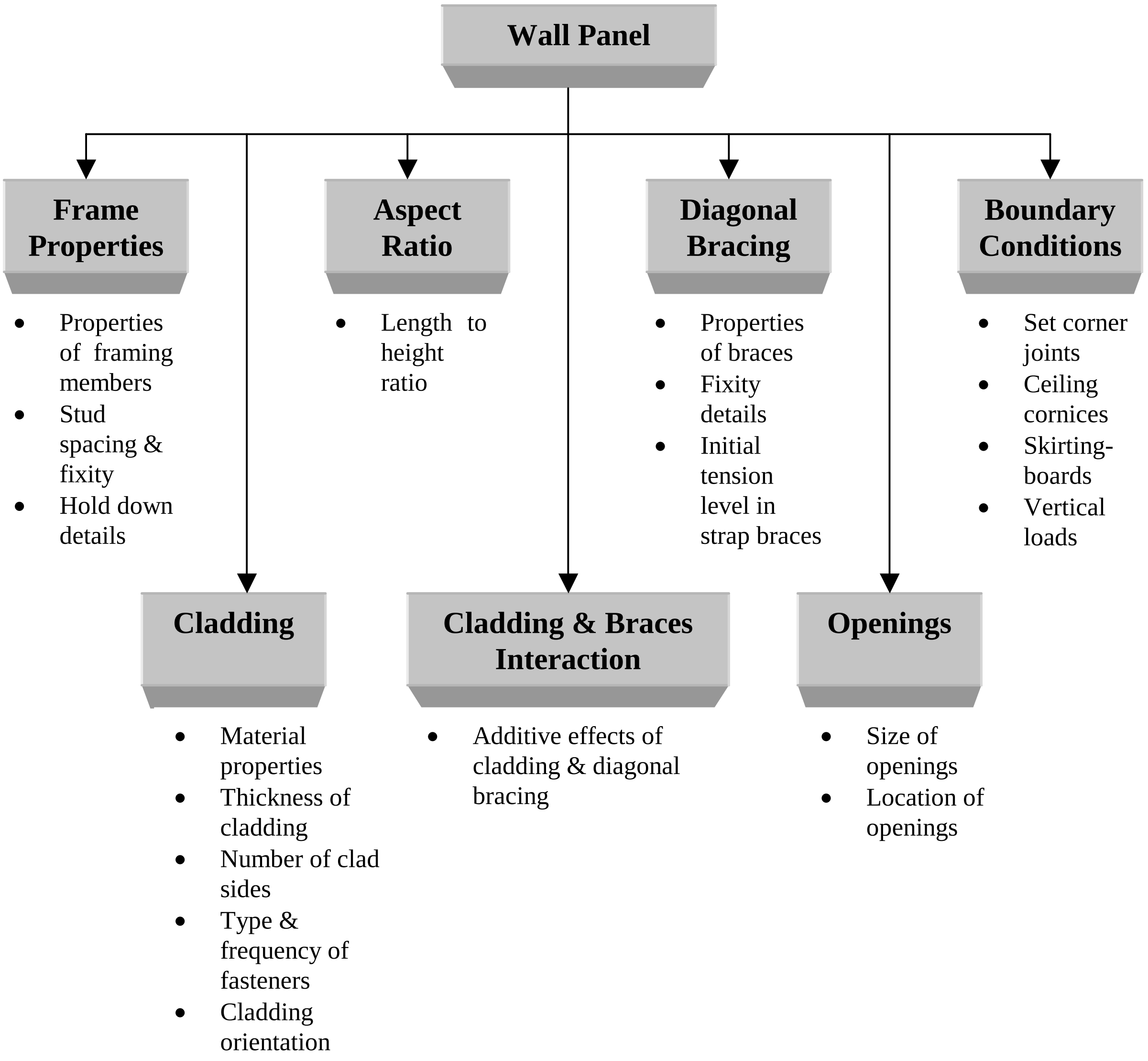


**Fig. 2** Factors affecting wall panel behaviour under lateral loading. (Gad et al. [9]).

## 3. Plasterboard specifics

Prior to the development of plasterboard or gypsum wallboard, the interior walls of many finer homes in the United States and Europe were mostly made of a system of laths and wet plaster. The function of the lath is to provide a surface for the plasterer to apply coats of wet plaster. At the conclusion of World War II, plasterboard was developed. Plasterboard is a composite panel that has a gypsum core sandwiched between two sheets of paper linerboards. The development of plasterboard allows the plasterer to screw or nail the board directly to the studs with relative ease thus saving significant cost on labour.

In Australia, the most common type of plasterboard used in residential construction has two important physical features, commonly known as recessed edges and centre portion or field. (Refer to Fig. 3).

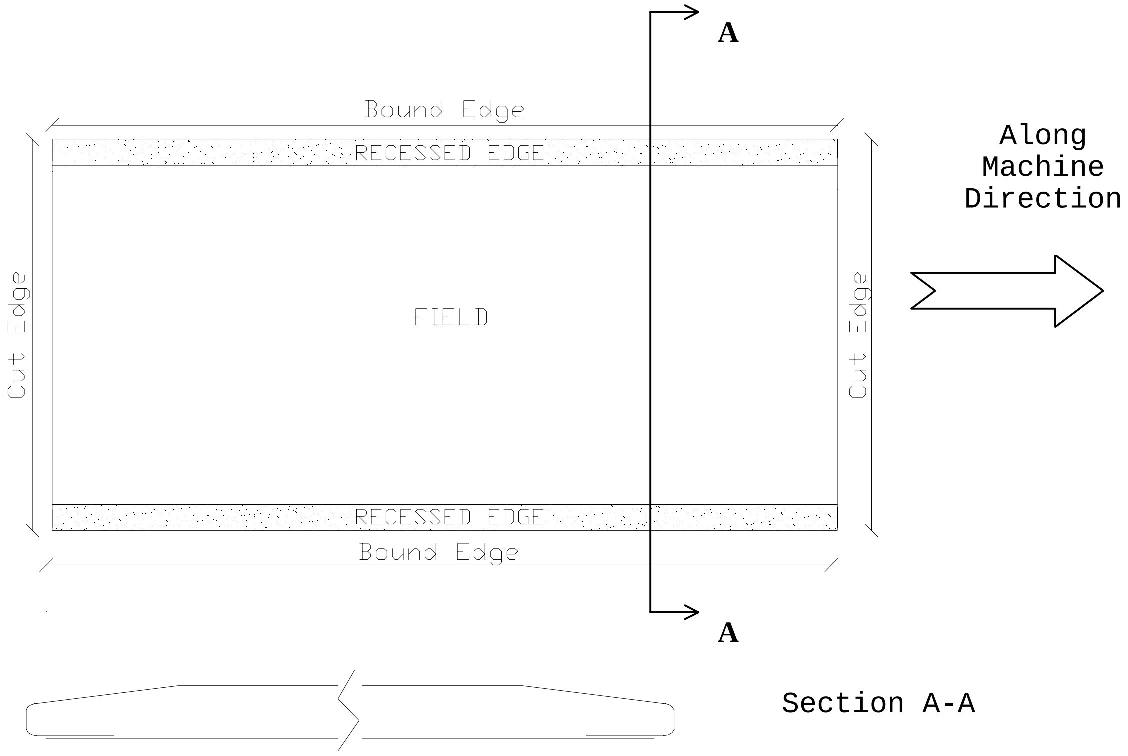


**Fig. 1** Typical plasterboard with recessed Edges used in Residential Construction in Australia.

The recessed edges, sometimes called the bounded or tapered edges, are found along the longer length of the board (along the machine direction) and their purpose is to accommodate butt joint reinforcement. The definition for machine direction is the direction along which continuous sheet of plasterboard undergoes various fabrication stages, such as rolling, before it is cut into sheets of specific length and proceed to the drier.

The field is the middle section of the plasterboard. According to Australian Standard AS/NZS 2588:1998 [14] the section that is 100mm away from all edges can be considered as field section. Usually the field sections have fewer connections to the supporting frame in house construction compared to the edges.

The front and back faces of plasterboards are known as “face” and “back”, respectively. The face linerboard may be slightly heavier than the back due to the finishing requirements. Standard plasterboard dimensions are 1200mm ´ 2400mm with 10mm thickness, special longer, wider and thicker boards are also produced.

There are two Australian/New Zealand Standards that consider the specification and general application of plasterboard. First, AS/NZS 2589:1997 [15] provides manufacturers and users of gypsum lining with specifications covering the application and finishing of such linings for use in residential and light commercial applications. Second, AS/NZS 2588:1998 [14] is based on ISO 6308 [16] and ASTM C473 [17]. This standard provides manufacturers of gypsum plasterboard with specifications covering the manufacturing and performance of such plasterboard for use in domestic, commercial and industrial application.

The current standards and codes for manufacturing gypsum plasterboard do not have relevant tests to ensure the quality of plasterboard for bracing purposes. According to ASTM C473 [17], the tests presented in the code do not have proven correlations with the actual service performance of plasterboard. Indeed, tests such as bending strength and edge hardness outlined in the codes are mainly for maintaining performance of plasterboard during transportation and installation. Furthermore, these standards do not specify the minimum density for plasterboard or the minimum weight of the linerboard.

While the timber framing code (AS1684:1999) is capitalising on the inherent bracing strength of the plasterboard by explicitly defines the contribution of nominally fixed plasterboard clad walls as 0.45kN/m for plasterboard cladding on one side and 0.75kN/m for cladding on two sides, the plasterboard manufacturers continue to modify the properties of the plasterboard to be more cost competitive. This is done through changes to the linerboards and the plaster mix. Such changes may indeed alter the bracing performance of plasterboard. In fact, there is very limited data on the relationship between the plasterboard properties and its bracing performance.

Thus, it is essential that the minimum requirements set in the timber framing code are clearly met by the plasterboard manufactures and the industry is aware of the role played by the plasterboard in providing lateral bracing. In other words, the plasterboard needs to meet certain quality control measures to ensure that the lateral bracing of houses is not compromised. This is an extra responsibility placed on the plasterboard manufacturers, which this research is addressing through the development of a new test procedure for bracing properties. This new test is essentially replicating how the loads are resisted by the plasterboard through shearing action at the fasteners connecting the plasterboard to the frame. The test setup is currently being simplified and verified for possible application on the production line. The possible load transfer mechanisms to plasterboard clad walls in a house are discussed in detail below.

## 4. Load sharing and transfer mechanism

Typically in residential structures, a wall frame consists of top and bottom plates, studs and noggings. The frame has little or no in-plane stiffness. For a clad wall, the in-plane lateral resistance is almost entirely provided by the sheeting material that transforms the frame into a shear wall.

In Australia, for non-bracing walls, plasterboard is fixed to the frame by either screws or nails at the perimeter of the frame and glue at intermediate studs. On the other hand, when walls are designed as bracing panels, sheeting is attached to the studs and top and bottom plates using nails or screws only. The reason for not using glue in the bracing panels is that the glue tends to make the failure mode more brittle [18]. Furthermore, the durability of the glue over the design life of the structure may be questionable.

In a single storey house, the lateral loads are generally transferred from the roof to the walls (internal and/or external) and then to the floor with the walls acting as the lateral load resisting elements. The actual load transfer mechanism to a specific wall is dependent on how the wall is connected to the rest of the structure (i.e. the connections to the ceiling, adjacent walls and floor).

It has been found from tests on a full scale house that the plasterboard roof and ceiling system acts as a rigid diaphragm (relative to the walls) [8]. In typical (Australian) house construction, ceiling cornices are glued to both the ceiling and wall plasterboard. This in effect establishes a positive connection between the ceiling diaphragm and all the walls. Thus, internal non-bracing partition walls, which do not normally have a solid connection to the roof framing, become engaged in resisting lateral loads applied to the house.

Typical lateral load transfer mechanisms are illustrated through two example walls detailed below. It may be assumed that these two walls are in a typical single storey, slab on ground, brick veneer house with trussed roof. The house is assumed to have standard wall and ceiling plasterboard lining and typical ceiling cornices.

The first example is a partition (non-bracing) wall that is only connected to the ceiling lining via the ceiling cornices. The second is an external wall that is located at the corner of a house and is connected to the bottom cord of the edge roof truss and to the ceiling lining via the cornices. In these two examples, the walls are assumed to be parallel to the applied load.

## 4.1 Partition walls

An example wall, shown in Fig. 4, illustrates the mobilisation of non-structural partition walls. It is assumed that this wall is not connected to any other adjacent walls. In this case the lateral loads (assuming wind load) would transfer from the roof (1), into the ceiling diaphragm (2), then to the ceiling cornices (3), into the wall plasterboard (4), then to the wall frame (5) (via the plasterboard fasteners) and finally to the floor (6). In this case the ultimate failure mode involves the tearing of the plasterboard around the nails or screws fixing it to the frame as shown in Fig. 5.

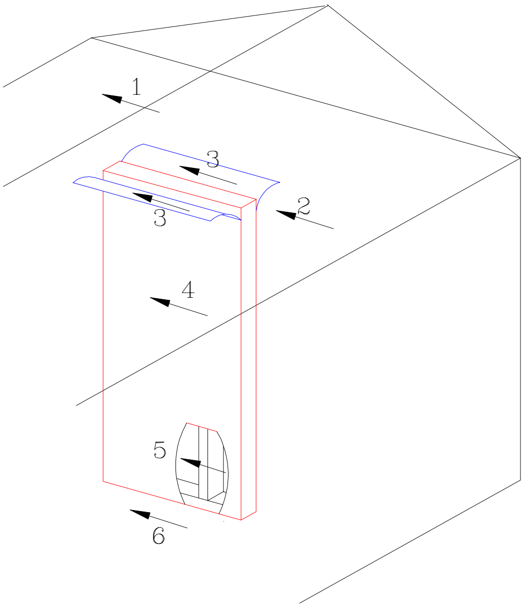


**Fig. 4** Schematic diagram showing the lateral load path in simple case of a partition wall with no adjacent walls. The arrows and adjacent numbers indicate the sequence of load transfer.

**Fig. 5** Typical failure mode of a nail connection between plasterboard and frame in shear. (Note: Tearing of plasterboard and embedment of the nail head within the thickness of the board).

It should be noted that correctly installed wall plasterboard is 10mm off the floor (to avoid damage of the plasterboard from water). If the plasterboard is in contact with or close to the floor, the above load transfer mechanism would be different and indeed the loads from the wall plasterboard (4) would be directly transferred to the floor by bearing action as the plasterboard rotates and comes in contact with the floor. One of the failure modes in this case would involve crushing of the plasterboard where bearing takes place.

## 4.2 External walls

The lateral load transfer to walls that are located along or attached to the house perimeter is more complex. This is illustrated by an example of an external wall that is assumed to be parallel to the applied load (assume wind loading) and is located on the corner of a house. For this case, up to four distinct load transfer mechanisms are possible as illustrated below.

Mechanism A: This mechanism, as shown in Fig. 6, involves the load being transferred from the roof (1) to the bottom chord of the truss (2). The load is then transferred to the top plate of the wall (3), hence the wall experiences a racking force. The load is then transferred to the plasterboard cladding (4) via the connecting fasteners. This is most common mechanism used in testing procedures where the racking load is applied directly to the top plate.

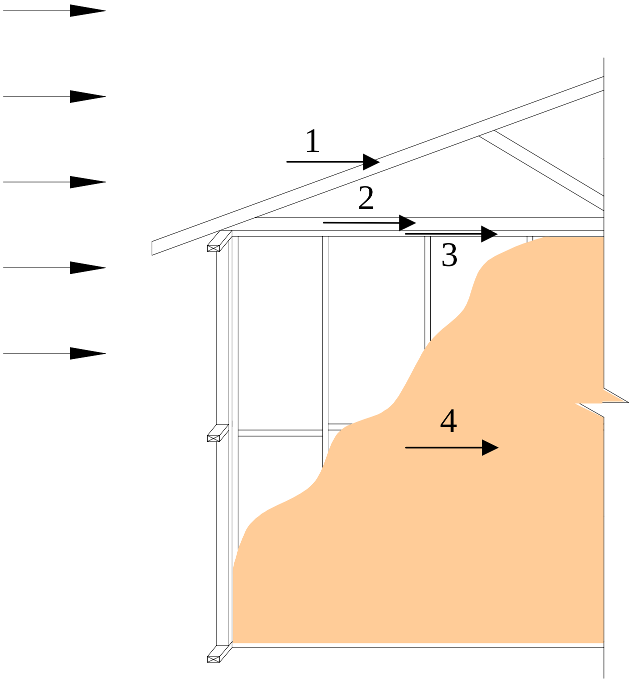


**Fig. 6** Mechanism A, loading through the top plate.

Mechanism B: This possible mechanism involves the load being transferred through the ceiling lining as shown in Fig. 7. In this mechanism the load is transferred from the roof (1) to the bottom chord (2) as in Mechanism A. From there the load is transferred to the ceiling lining (3) which is attached to the bottom chords of the roof trusses (mostly via ceiling battens which are not shown here for clarity). The load is then transferred to the ceiling cornices (4) and then directly to the wall plasterboard (5). From there the load travels in a similar manner as shown for the partition wall described in Section 4.1.

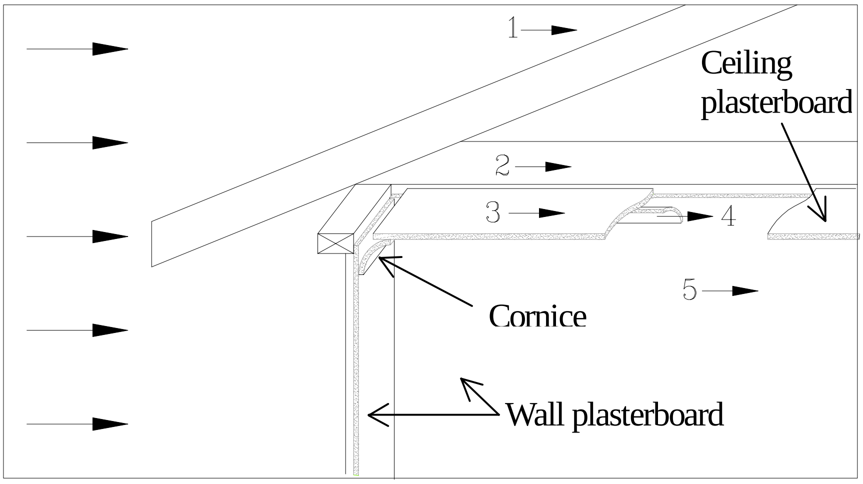


**Fig. 7** Mechanism B, loading through the ceiling cornice.

Mechanism C: This mechanism involves transferring the applied lateral load to the wall via the cluster of end studs as shown in Fig. 8. In plasterboard installation, it is common to have a small gap (in the order of 5mm) between the vertical edges of the plasterboard and the end studs of return (perpendicular) walls. As a result of the load transfer from either Mechanisms A or B described above, the frame distorts and the gap would close at two diagonal corners. As the gap closes the lateral load is transferred from the frame directly to the plasterboard by bearing rather than through the fasteners connecting the plasterboard to the frame. The ultimate failure mode in this case involves the crushing of the plasterboard edges where bearing takes place. Based on experimental and analytical investigations, this mechanism of load transfer was found to significantly increase the lateral load carrying capacity of plasterboard clad wall frames [9, 19, 20]. This is illustrated further in Section 6.

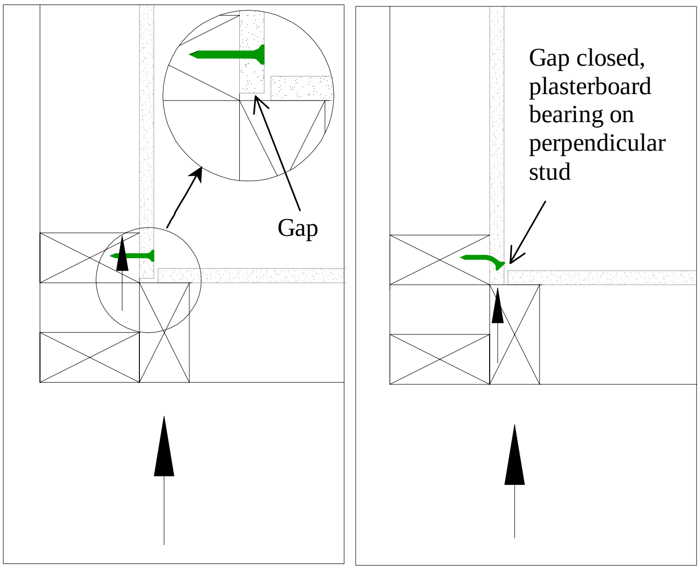


**Fig. 8** Mechanism C, loading through bearing on an end stud of a perpendicular wall.

Mechanism D: This is a load sharing mechanism that takes place at corners where the plasterboard of two intersecting walls is taped and joined. When one wall is resisting lateral loads, the plasterboard of the perpendicular wall may provide some resistance through the shear action developed through the taped joint as shown in Fig. 9. In other words, out-of-plane walls may contribute to the lateral resistance through this possible load sharing mechanism.

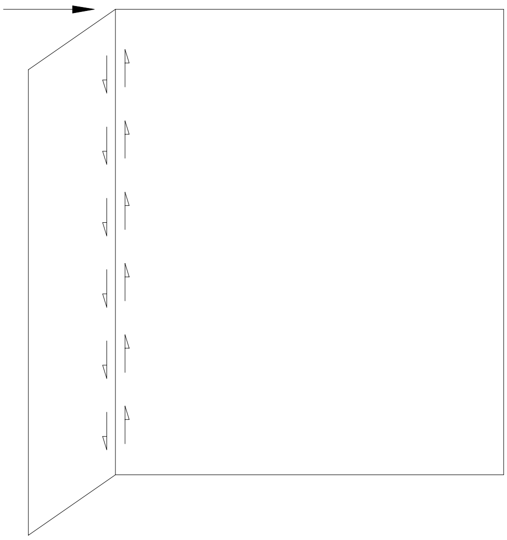


**Fig. 9** Mechanism D, load sharing through jointed plasterboard at corners.

## 5. Testing procedures for clad walls

To date, the most common method of evaluating the bracing capacity of clad walls is by conducting isolated wall tests. There are several codified testing procedures worldwide. In Australia, the main testing procedure is the TR440 [21] which considers both cyclone and wind loading. However, it has no provision for rating walls for earthquake loads. Other test methods such as the American ASTM E564 [22] and ASTM E72 [23] and Japanese JIS A 1414 [24] only consider monotonic loading representative of wind. The New Zealand P21 [25, 26] considers both wind and earthquake loads and hence the loading regime contains double amplitude cyclic loading. Some of these methods allow the incorporation of relevant wall boundary conditions to the isolated wall.

Although testing isolated walls is convenient and cost efficient to determine the racking capacity, it is often difficult to validate that a wall constructed and tested in isolation would exhibit the same behaviour and performance of that located in a house. The main difficulty is providing additional hold down restrains on the isolated wall to replicate realistic boundary conditions. The additional boundary restraints may be needed to simulate the wall continuity and connections to transverse walls, roof and ceiling. For example, if a plasterboard-clad wall is tested in isolation with the same hold down detail, as it would be installed in practice, stud uplift and/or bottom plate uplift will take place. These two premature failure modes are shown in Fig. 10 and Fig. 11.

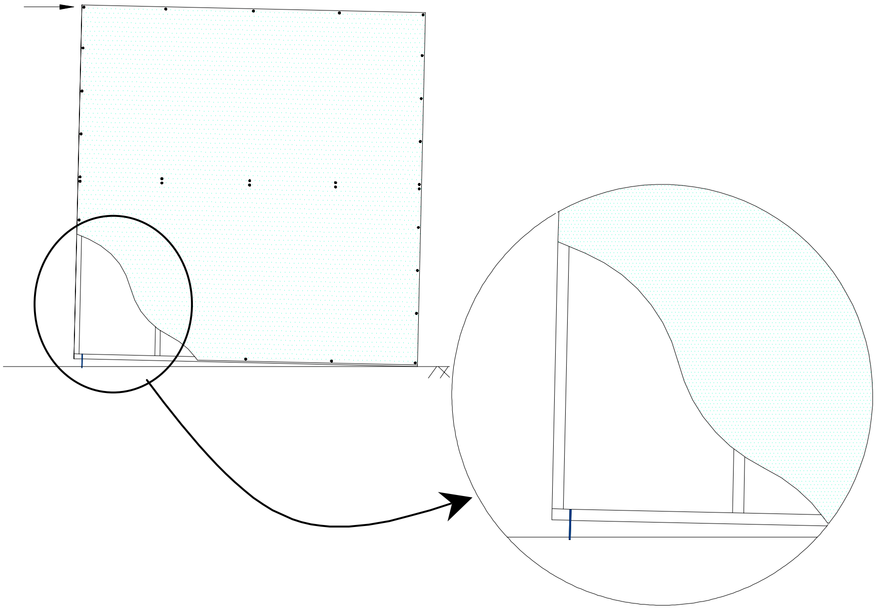


**Fig. 10** Diagram illustrating bottom plate uplift.

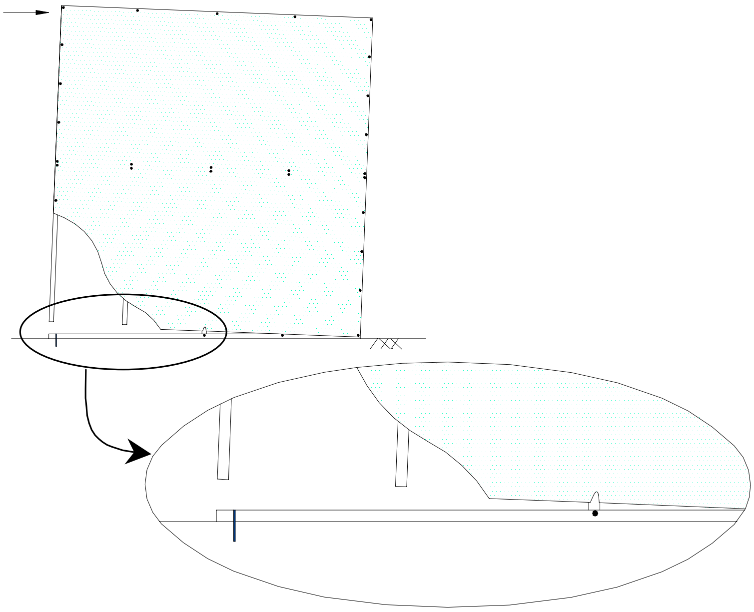


**Fig. 11** Diagram illustrating stud uplift.

The bottom plate uplift does not reduce the racking capacity of the wall but decreases the stiffness. On the other hand, when stud uplift takes place, the ultimate capacity is reduced due to the premature failure of the connections between the cladding and the frame along the bottom plate. This is demonstrated by the load-deflection curves shown in Fig. 12 for two plasterboard-clad timber-framed walls each measuring 2.4m ´ 2.4m. These curves are obtained from a detailed Finite Element model [19] based on screw connections between the plasterboard and the frame, which are located at 150mm centres along the perimeter and 300mm along the intermediate studs.

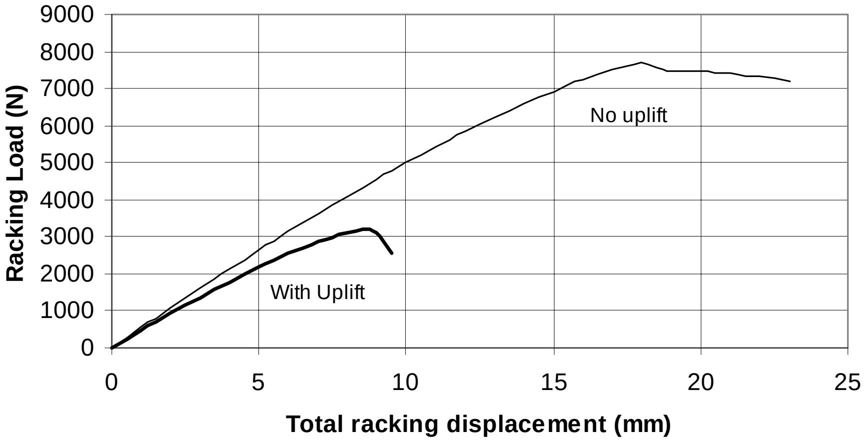


**Fig. 12** Load-deflection curves for two plasterboard-clad walls with and without stud uplift

Based on full-scale test on houses [8] and damage observations post large earthquake events [27] these two failure modes seem to be unrealistic, but this depends largely on the detailing of the hold-downs.

This highlights the importance of incorporating appropriate hold-down details. For testing purposes, it may not be sufficient just to reproduce which is being used in the field as hold-down connection. Extra restraints may be required as part of the test set-up to simulate other effects such as connections to adjacent walls, continuity of top plates and connection to ceiling diaphragm. The New Zealand P21 testing procedure addresses this issue by providing supplementary uplift restraints to the ends of the wall to reduce or eliminate stud uplift. The restraints simulate possible contributions from fixtures to adjacent walls, door or window lintels. The supplementary restraint at each end provides a vertical uplift resistant of 6kN.

It should be noted that there might be modes of failure other than those obtained from tests on isolated walls (even with appropriate supplementary restraints). For example, for non-bracing walls with returns and cornices it was observed that the failure mode is by crushing of plasterboard at diagonal corners. Furthermore, if no ceiling cornices are present, the same type of walls may fail by out-of-plane buckling of the plasterboard rather than crushing. This latter failure mode was demonstrated by tests conducted by Golledge et al [20].

As part of the research aim to develop an appropriate test set-up and loading regime for plasterboard-clad wall frames, a number of walls with different configurations have been tested at The University of Melbourne. The objectives of these tests were to study the influence of different supplementary restraints and to examine the possible contribution and associate failure modes of simulated return walls. Details of part of these tests and relevant results follow.

# 6. Testing of different restraints

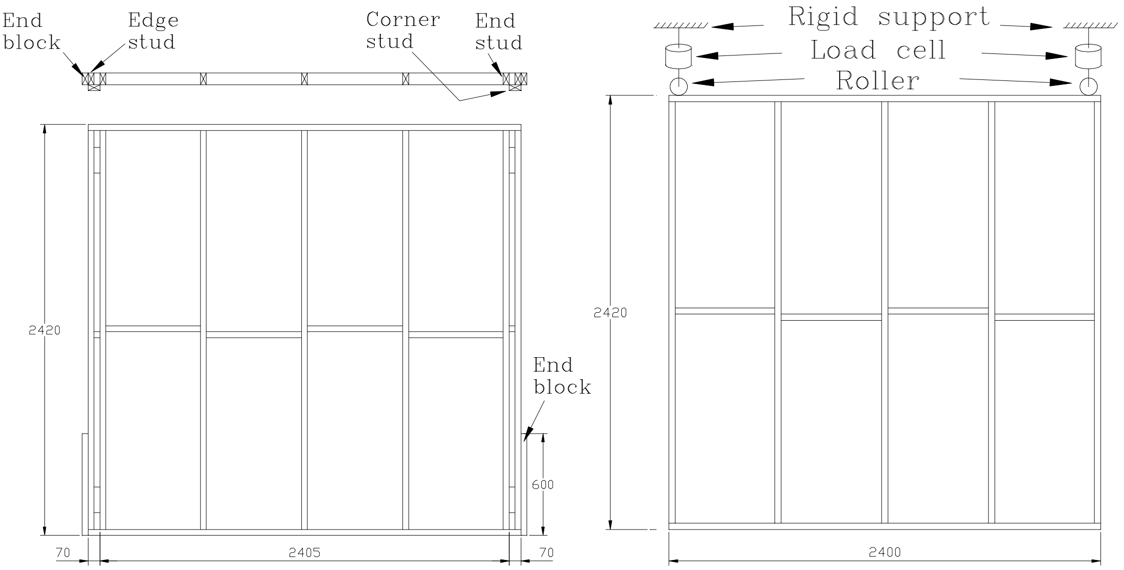
## 6.1 Details of tested walls

Tests on three different walls are reported in this paper. All walls are timber framed (F5 timber with 70 ´ 35mm sections) constructed in a typical manner (i.e., framing members connected together using 75 ´ 3.75mm bullet head nails). Each frame was connected to a simulated rigid foundation using 10mm bolts located at 1200mm centres. The plasterboard was 10mm standard core fixed to the frame using 30 ´ 2.8mm nails located at 150mm centres along the perimeter of the frame and at 300mm along the intermediate studs. No glue was used in fixing the plasterboard to the frame. The specifics of each wall are as follows:

- Wall 1: A 2400 ´ 2420mm wall with supplementary timber end blocks similar to those suggested by the P21 test method. The end blocks are 70 ´ 35mm in section and 600 long, and fixed to the two end studs of the frame by three 75 ´ 3.75mm bullet head nails.
- Wall 2: A wall similar to Wall 1, but it had at each end two extra studs (named herein edge and corner studs), which were attached as shown in Fig. 13a. The edge studs were added to facilitate fixing of the corner studs that simulate the end studs of perpendicular walls. The end blocks in this case were fixed to the edge studs.
- Wall 3: A wall identical to Wall 2, but without the end blocks and edge studs. Vertical restraints were provided by a roller at each end that in turn was connected to a rigid frame via a load cell as shown in Fig. 13b.

The loading on these two walls was applied at the top plate level using a hydraulic jack. The loading regime involved pulling the frame by 8mm in one direction, then pushing it in the opposite direction by 8mm and finally pulling it in the first direction to failure. The 8mm cycle represents the serviceability limit state, which is 0.33% drift. [28]

The lateral (in-plane) and vertical displacements were monitored at both ends of the wall. The wall was prevented from moving in the out-of-plane direction by a set of rollers.



**(a)** **(b)**

**Fig. 2** Configurations of (a) Walls 2 and (b) Wall 3.

## 6.2 Experimental results

While the results from three walls are not statistically adequate to quantify the strength of walls with different configurations, the difference of behaviour and failure patterns can be appreciated.

The load-deflection curve for Wall 1 is shown in Fig. 14. The load path for this wall was similar to Mechanism A described in Section 4.2. It was observed in this test that the tearing of the plasterboard around the nails connecting it to the frame was not symmetrical (i.e., at the top and bottom of the wall). Indeed, the damage was concentrated at the top of the wall. The studs experienced excessive deflection at the top of the wall as shown in Fig. 15.

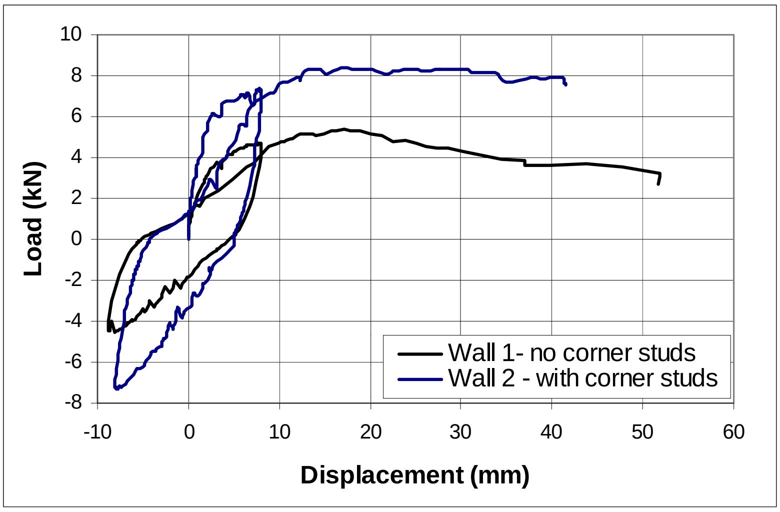


**Fig. 3** Load-deflection curves for Walls 1 and 2.

**Fig. 4** A photo of a top corner of Wall 1 at displacement of about 35mm showing deflected shape of the end stud and failed plasterboard nail connections.

The load-deflection curve for Wall 2 is shown in Fig. 14. Wall 2 exhibited load transfer similar to Mechanisms A and C, which were described in Section 4.2. When the plasterboard was installed, a gap of approximately 2-3 mm was left between its vertical edges and the corner studs. Hence, the initial load path involved the lateral load being transferred from the frame to the plasterboard only though the connecting nails. As the frame deformed and the plasterboard rotated, the gap closed and the plasterboard started to bear against the corner stud at two diagonal corners, as shown in Fig. 16. This led to crushing of the plasterboard at these corners, as depicted in Fig. 17. Wall 2 achieved a maximum load approximately 50% higher than that for Wall 1.

It should be noted that if Wall 2 had larger segments of the return walls (not just a single stud at each end) with plasterboard fixed to the return walls and taped and jointed at the corners, the ultimate load would have been even higher. In addition, the presence ceiling cornices would have also increased the ultimate load further.

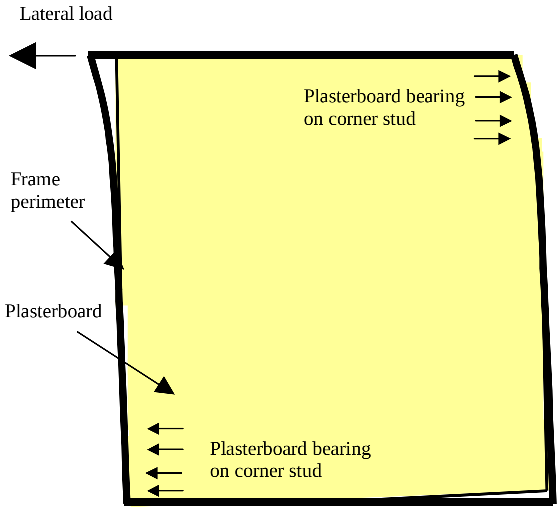


**Fig. 5** Schematic deformed shape of the frame and plasterboard for Wall 1.

**Fig. 6** A photo showing the plasterboard bearing on the corner studs for Wall 1 (as per bottom left corner of Fig. 16).

Wall 3 exhibited almost identical behaviour to Wall 2. The load-deflection curves for Walls 2 and 3 are compared in Fig. 18. Both walls reached almost the same maximum load and both failed in the same manner, that is by tearing of the plasterboard around the nails at the top of the wall. The failure mode of Wall 3 is depicted in Fig. 19. It was observed in walls 2 and 3 that some intermediate stud uplift was taking place, however this was not large enough to cause premature failure.

The load cell measuring the uplift on Wall 3 (refer to Fig. 18) recorded a maximum force of approximately 5 kN which occurred at the ultimate racking load (approximately 6 kN). It is expected that the end block on the tension side for Wall 2 experienced similar uplift force and it was able to sustain that level.

It should be noted that the end blocks used in Wall 2 and the restraining rollers used in Wall 3 will not always produce the same results. For the given wall configurations (stud spacing, plasterboard thickness and fastener spacing) the uplift force could be sustained by the end block. However, if more perimeter nails are used to attach the plasterboard to the frame, the ultimate racking capacity would be expected to be higher which would lead to higher uplift forces. In this case the lateral capacity of the whole wall becomes a function of the capacity of the end blocks. If the uplift force exceeds the capacity of the end blocks, stud uplift as shown in Fig. 11 would take place and premature failure would occur.

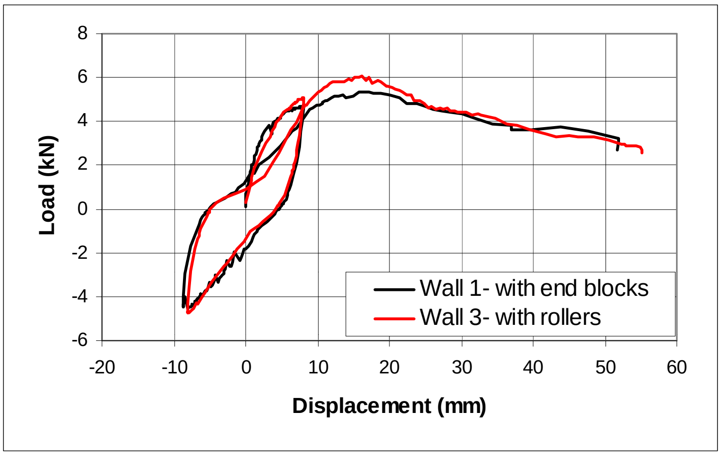


**Fig. 7** Load-deflection curves for Walls 2 and 3.

**Fig. 8** Photo depicting the failure of Wall 3 (wall is pulled to the left).

## 7. Conclusions

The paper has highlighted the structural significance of plasterboard in residential structures even when it is only used as a non-structural component. While the house construction industry generally considers plasterboard as a non-structural material, there are inherent assumptions embedded in the design procedures that a significant proportion of the lateral loads are resisted by plasterboard clad non-bracing walls. Consequently, the bracing capacity of the plasterboard needs to be maintained as it develops to become more and more cost efficient.

The paper has presented in detail the possible load transfer mechanism to typical walls within the house. Within a single wall, there could be several load paths depending on the connectivity to adjacent walls, roof and ceiling. Most testing procedures only consider isolated walls with only one load path. It has been demonstrated through presented experimental results that the failure mode may be dependent on the load transfer mechanism and boundary conditions. By just adding two extra studs at either side of the plasterboard cladding the lateral capacity increased by almost 50%. This is due to the failure mode being the crushing of the plasterboard along the extra studs rather than tearing of the plasterboard around the fixing nails.

Experimental results have also been presented for two walls with two different uplift restraints for testing isolated walls, namely roller and end blocks similar to those utilised in the New Zealand test method (P21). Both walls produced very similar load-deflection curves and reached almost the same ultimate load. This suggests that the lateral behaviour and failure modes for such walls are not sensitive to the form of vertical restraint, however, the end blocks have limited capacity which when exceeded would result in premature failure of the whole wall panel. Thus, end blocks must be made to replicate as much as possible the real boundary conditions.

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