Experimental and Analytical Validation of a Fastener Bearing Test as a Means of Evaluating the Bracing Characteristics of Plasterboard

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Abstract: The beneficial bracing characteristics of plasterboard have recently been incorporated into Australian design standards for residential structures. There is a need to develop control procedures, commensurate with these enhanced design guidelines, to control the quality of plasterboard such that its manufactured properties conform with the bracing characteristics assumed. This paper reports the findings of a study into the adequacy of existing plasterboard quality tests as a measure of its bracing capacity. The paper also reports the development of a new test method, described herein as fastener bearing test, as an alternate quality control method for bracing capacity of plasterboard. This fastener bearing test is subsequently validated through an extensive experimental program and analytical modelling. The paper concludes that the proposed test is a reliable method to assess the bracing capacity of plasterboard. It has also established the validity of a simple closed-form mathematical approach to ascertain the lateral capacity of clad framed walls.

Key words: light-framed structures, plasterboard, gypsum, timber construction, shear resistance, bracing.

1. INTRODUCTION

Plasterboard is a generic name for a family of sheet products consisting of non-combustible core primarily of gypsum with paper surfacing. It is also known as gypsum board, gypsum wallboard, gypsum panel and gypsum sheathing. The term sheathing describes the material used to cover framing members in domestic structures. Other similar common terms include cladding or lining. In Australia, the term lining is generally used to describe the material covering the interior side of frames, while the term cladding is often used for exterior side. The terms cladding and sheathing are frequently used interchangeably in the literature. Cladding, sheathing and lining all perform essentially the same function, i.e. they provide enclosure and possibly in-plane (lateral) bracing to the wall frames.

In Australia, the residential house construction industry has traditionally treated plasterboard as a non-structural component when designing houses. There is a growing body of research demonstrating that plasterboard provides significant bracing capacity, even with nominal fixing. These research findings were first explicitly incorporated into the 1999 version of the Residential Timber-Framed Construction Standard (AS 1684–1999) (Standards Australia 1999) where a lateral bracing allowance is allowed to account for the contribution from plasterboard. The inclusion of the bracing strength of plasterboard into AS 1684–1999 was

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done without any associated changes or controls being put in place to ensure that the assumed structural properties of plasterboard are available. As a result, plasterboard manufacturers may modify the properties of plasterboard without any requirement to ensure the bracing performance of the plasterboard. It is understood that modifications are frequently made to plasterboard by way of the paper lining and plaster mix constituents of the board.

Plasterboard manufacturers would require additional tools and knowledge on the structural behaviour of plasterboard if they are required to meet the expectation of designers of residential structures in Australia and to guarantee the structural strength of their product. This paper reports the findings of a study that has investigated ways to improve the understanding of the relationship between plasterboard properties and its bracing performance when subjected to lateral wind loading. Specifically the study has:

1) investigated the adequacy of existing quality control tests as methods for ensuring the bracing performance of plasterboard;
2) developed a test method which can be applied on the production line to assess the quality of plasterboard for bracing performance; and
3) developed a simple analytical model to predict the lateral load-displacement response of plasterboard clad walls under monotonic loading.

2. LITERATURE

As part of this research, a detailed literature review along with field works conducted in plasterboard manufacturing plants in Sydney and Melbourne, an extensive experimental program as well a comprehensive analytical assessment have been conducted. Their findings are presented and discussed in detail in the following sections.

From the literature review and the interviews with the plasterboard manufacturers, it has been found that:

- National and international standard test methods for plasterboard, i.e. AS/NZS 2588-1998 (Standards Australia 1998), ISO 6308-1980 (ISO 1980) and ASTM C473-2000 (ASTM 2000), do not provide any provisions related to the bracing quality of plasterboard.
- To safely utilise plasterboard as a bracing material, a representative test for quality control must be developed. Current quality control tests for plasterboard have primarily been developed for transportation and handling issues, with no attention to the bracing performance of plasterboard.
- Detailed analysis of load transfer mechanisms in typical light-framed structures indicates that all walls (both structural and non-structural) parallel to the applied lateral load contribute to the lateral capacity of the structure (Liew *et al.* 2002, 2004; Gad *et al.* 1999a, 1999b). The specific strength and stiffness contribution of each wall vary significantly depending on wall length, bracing material and building system.
- The lateral bracing performance of houses is directly related to the performance of in-plane (racking) walls. It is well established that the performance of an individual racking wall is directly related to the load-slip characteristics of sheathing-to-framing connections (shear connections) on the wall, which are highly influenced by the material properties of the sheathing. To understand the relative performance and contribution of plasterboard to the overall house response, full-scale racking tests of isolated walls combined with shear connection tests are concluded to be an appropriate methodology.

Based on the knowledge gained from a detailed literature review (Liew *et al.* 2002; Liew 2004), information gleaned from the field works conducted in plasterboard manufacturing plants and correlation of data on the existing quality control test methods with the density of plasterboard, a new test method, described here as fastener bearing test, to control the quality of plasterboard for bracing purpose has been proposed, developed and verified (Liew *et al.* 2004). Figure 1 illustrates the apparatus for the proposed fastener bearing test. In this test setup, a plasterboard specimen (400mm × 300mm) is restrained vertically and laterally

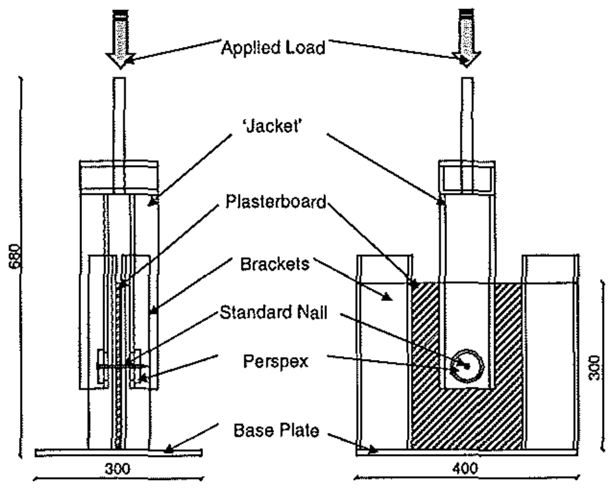

Figure 1. Schematic details of the full test setup of the proposed fastener bearing test apparatus (dimensions are in mm)

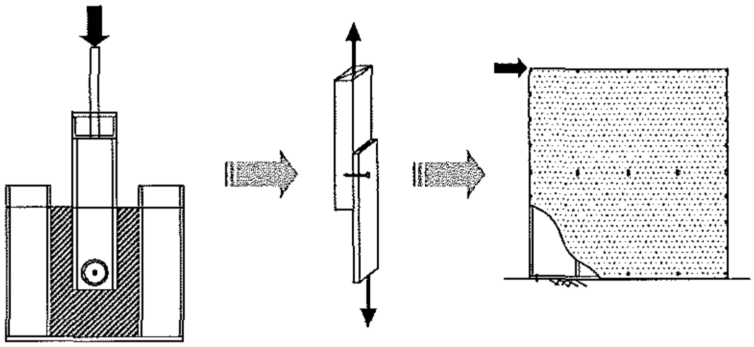

Figure 2. Summary of experimental program

using a set of brackets while a single nail is driven into the plasterboard through a U-shaped jacket. A vertical load is then applied to the jacket which results in the nail tearing through the plasterboard in a similar manner to a shear connection.

3. EXPERIMENTAL PROGRAM

The experimental program of this study, as summarised in Figure 2, was developed to evaluate and verify the proposed fastener bearing test. It comprised two phases with the first phase involving the conduct of a large number of density tests, fastener bearing tests and shear connection tests on plasterboard. The shear connection test is used to obtain characteristics such as strength, stiffness and load-deflection relationship of cladding-to-framing connections in shear (it is also known as monotonic shear test and cladding-to-framing connection test). This phase sought to correlate and verify the proposed fastener bearing test against the current shear connection test. In the phase two of the testing program, full-scale, isolated wall racking tests and some supplementary shear connection tests were performed. This phase was aimed to further verify the fastener bearing test against a full-scale isolated wall racking test as well as to determine the load-slip curves for typical shear connections on plasterboard clad walls. Such curves were then used to facilitate the development of analytical models, which will be discussed in Section 4. It should be noted that this study is concerned with light-framed structures built in low seismicity and non-cyclonic areas which include the majority of Australian cities and many other parts of the world. A monotonic loading regime, which is typically adopted by industry testing facilities and manufacturers (for example, TR440 (Experimental Building Station 1978) and ASTM-E72 (ASTM 1998)), was thus employed in this study.

Table 1 summarises the results obtained in Phase 1 of the testing program. To reduce the variability of the plasterboard specimens, four batches of 10 mm thick plasterboard sheets, named here as Types A to D plasterboard, with different plaster mix but identical

Table 1. Summary of results from Phase 1 which comprised density tests, fastener bearing tests and shear connection tests

			Mean Ultimate Load (N)	
Plasterboard	Sample Size per Test	Mean Density (kg/m^3)	Fastener Bearing	Shear Connection
Type A	36	640 (0.65)	315 (3.7)	365 (4.4)
Type B	36	674 (0.84)	407 (5.7)	480 (5.4)
Type C	36	824 (0.70)	561 (4.1)	683 (7.1)
Type D	36	872 (0.79)	644 (4.1)	806 (12)

Note: Values in parentheses represent Coefficient of Variation in percentage.

Table 2. Summary of Phase 2 results: full-scale isolated wall racking tests

	Nail Spacing (mm)			
Plasterboard Type	Perimeter Studs and Plates	Intermediate Studs	Displacement at Ultimate Load (mm)	Ultimate Load (N)
Wall 1: Type A	150	300	19.2	5414
Wall 2: Type A	300	300	26.2	3011
Wall 3: Type D	150	300	12.7	9491
Wall 4: Type D	300	300	20.9	5644

linerboard supplied by a single manufacturer, were used for testing throughout Phase 1. Details of the setup for the tests conducted in this phase can be found in Liew et al. (2004). Analyses of the results of these tests led to the following conclusions:

- A very strong correlation exists between fastener bearing test and shear connection test, refer to Figure 3. (Note: The error bars in Figure 3 represent the maximum and minimum results of each test.) This finding substantiates the assumption that density tests alone are insufficient to determine the bracing performance of plasterboard. For example, the influence of linerboard is very significant on the bracing strength of the plasterboard but relatively insignificant on the plasterboard density.
- The error bars in Figure 3 show that the simplicity of the fastener bearing test presented in this study achieved higher consistency of experimental results compared with that of the shear connection test results.
- For all the plasterboard specimens, their ultimate failure modes in both the fastener bearing tests and shear connection tests were very similar, in which the maximum load was associated with excessive tearing of the face linerboard.
- Both the plaster mix and linerboard play a significant role in providing the bracing capacity of plasterboard. While gypsum provides the medium to transfer the applied load, the linerboard confines the gypsum from expanding and breaking outwards.
- To effectively utilise the proposed fastener bearing test, plasterboard manufacturers need to set their acceptance criteria in order to suit the different products and their designated performance.

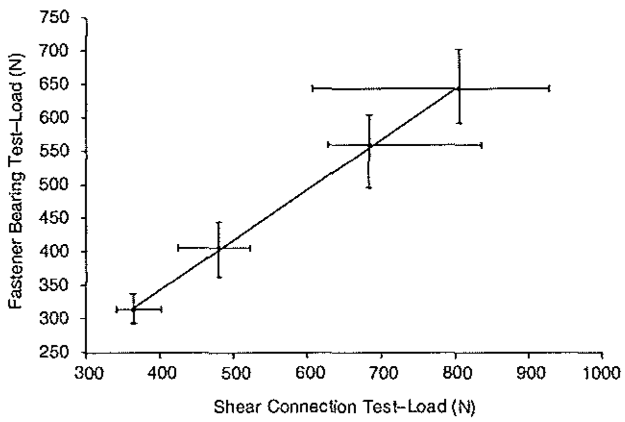

Figure 3. Mean ultimate loads from shear connection tests versus mean ultimate loads from fastener bearing tests

Table 3. Loads measured at serviceability displacements

	Load at + 8 mm (N)	Load at −8 mm (N)
Wall 1: Type A	4343	−4814
Wall 2: Type A	2781	−2774
Wall 3: Type D	8467	−9187
Wall 4: Type D	5063	−4638

Tables 2 and 3 summarise the results of the full-scale isolated wall racking tests conducted in Phase 2 of the experimental program. A total of four walls were tested, named here as Walls 1 to 4. Walls 1 and 2 were clad with normal density (Type A) plasterboard, while Walls 3 and 4 with high density (Type D) plasterboard. These plasterboard sheets were nailed to timber frames using 2.8 mm × 30 mm plasterboard nails with various spacing as listed in Table 2. Adhesive was not applied to these wall specimens as its durability, over the actual design life of the structure, may be questionable. The purpose of employing various nail spacing for the same type of plasterboard was to cover a range of typical nailing patterns and to examine the effect of the number of nails used on the ultimate racking capacity of a plasterboard clad wall.

The test setup and loading protocol adopted in these full-scale isolated wall racking tests were based on the recommendations by TR440 (Experimental Building Station 1978) for lateral wind loading, with the inclusion of uplift restraints to simulate the continuity of top plates, return walls and other boundary conditions which are often provided in actual houses. In this testing program, the uplift restraints were provided in the form of five steel rollers on the top of each stud as shown in Figure 4. The steel rollers were pushed snug tight to the top plate, thus, only a minimum amount of load was applied vertically. Each of these rollers was connected to a load cell to monitor the load imposed on the rollers. In addition, each wall specimen was prevented from out-of-plane movement by employing four rubber rollers which were fitted snug tight on each side of the wall. The specimen was pulled (North) and pushed (South) to complete a full cycle at serviceability displacement (Δ_s – typically equals Height/300 which is 8 mm for 2400 mm high walls) before pulling to failure. A wall was considered to have failed when the applied load decreased below 80% of the maximum load recorded or when a sudden rupture occurred leading to a significant loss of load, whichever happened first. Details of the test setup for these fullscale isolated wall racking tests are reported in Liew (2004).

The findings obtained from the above described full-scale isolated wall racking tests are summarised as below:

- The ultimate load of Wall 4 (clad with highest-density plasterboard, i.e. Type D) was approximately 1.8 times that of Wall 1 (clad with lowest-density plasterboard, i.e. Type A). This compares with the results of the shear connection tests and the fastener bearing tests conducted in Phase 1, in which the ultimate load of Type D plasterboard was found to be approximately 2.1 times that of Type A plasterboard. The limited number of full-scale isolated wall racking tests conducted in this study had an error of approximately 15% between the predictions from the fastener bearing tests and those from the full-scale isolated wall racking tests and, as a result, can be considered in good agreement. This not only demonstrates that the results from the fastener bearing tests are consistent with the shear connection test results but also with those obtained from the full-scale isolated wall racking tests.
- Adding twice the number of nails at the perimeter of the wall increased the ultimate load by 80%

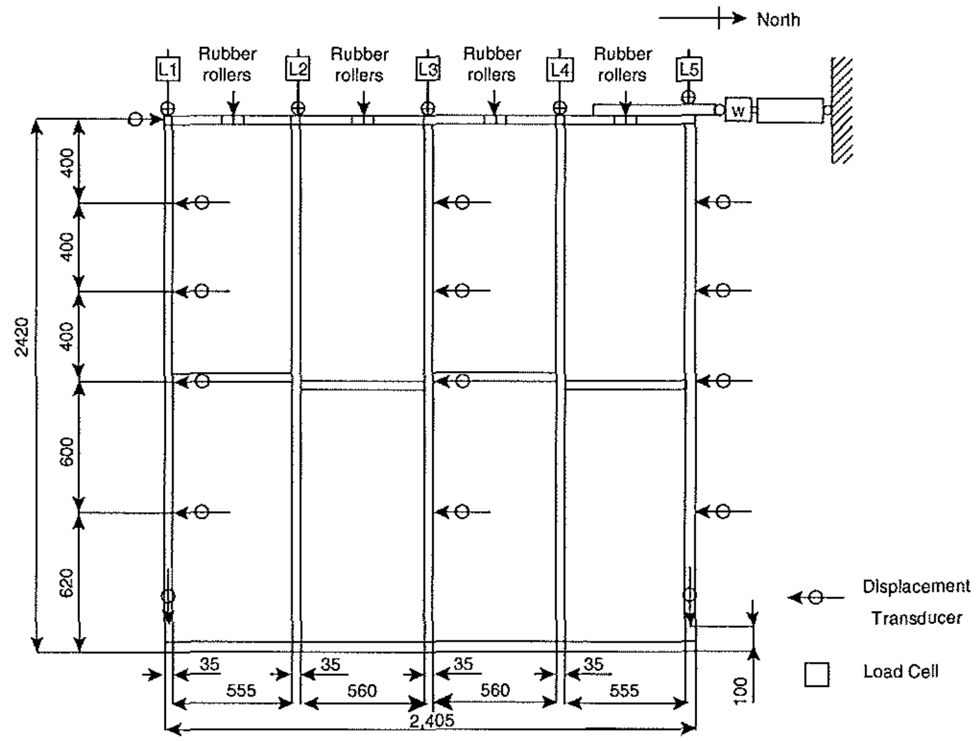

Figure 4. Schematic diagram of full wall test setup (Rubber rollers are to prevent lateral sway while the vertical rollers above the studs are to prevent uplift, the displacement transducers on the plasterboard are not shown for clarity)

and 68% for Type A (lowest density) and Type D (highest density) plasterboard, respectively.

- The ultimate loads for the four wall specimens were only about 10% to 25% higher than the loads measured at serviceability displacement (8 mm), suggesting that plasterboard clad walls may reach their ultimate loads close to their design serviceability deformation. This should be taken into account in the design of light-framed residential structures, in particular when different cladding materials with different load-deflection characteristics are used for the same wall or within the same house.
- The plasterboard sheathings of all the wall specimens experienced significant translation and rotation. These mechanisms are not commonly observed in a full-scale house test where plasterboard is typically restricted from vertical and horizontal movements by ceiling cornices and return walls.
- The distribution of lateral forces in the end studs is dependent on the nailing pattern (i.e. spacing of nails between the plasterboard and studs).

4. ANALYTICAL MODELLING

Analytical modelling is important in complementing the knowledge gained from experimental analyses, especially in extending the boundary of results and conducting sensitivity analyses. Although the closed-form mathematical models and Finite Element (FE) models developed by past researchers are able to predict the load-displacement response of walls subjected to lateral loading with acceptable degree of accuracy, the majority of these models were developed and verified for use on walls clad with plywood or wood-based materials (eg. Oriented Strand Board). Furthermore, such models generally assumed that the sheathing is fixed vertically with uniform nailing configurations. These models cannot be applied to study the performance of plasterboard clad walls that are commonly found in Australian light-framed residential structures because:

- Unlike plywood and OSB (Oriented Strand Board) sheathings, as shown in Figure 5, plasterboard exhibits a different failure mode and load-slip characteristics at the connections located around the cut edges of plasterboard compared with those within the board (field) (terminology of typical Australian plasterboard is defined in Figure 6). That is, nailed connections located close to the edges of the board tend to fail by tear out of plasterboard as opposed to elongation of the hole and possible bending of the nail for connections located away from the edges. As depicted in Figure 5, the tear out failure mode takes place at small amount of slip (between the plasterboard and the frame) and the ultimate load capacity of the connection is reduced as the edge distance gets smaller. Hence, existing models which assume the same load-slip characteristics for all the fasteners regardless of their locations are unsuitable for accurate modelling especially that connections close to the corners of the wall contribute the most to the overall wall performance.
- It is common in Australia to have more fasteners located along the vertical edges of plasterboard compared with those in the field and along the top and bottom plates. Hence, any closed-form mathematical model to be applicable in

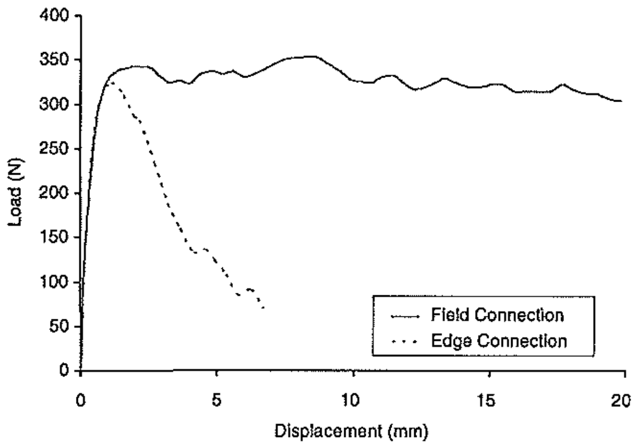

Figure 5. Typical load-slip curves from shear connection tests

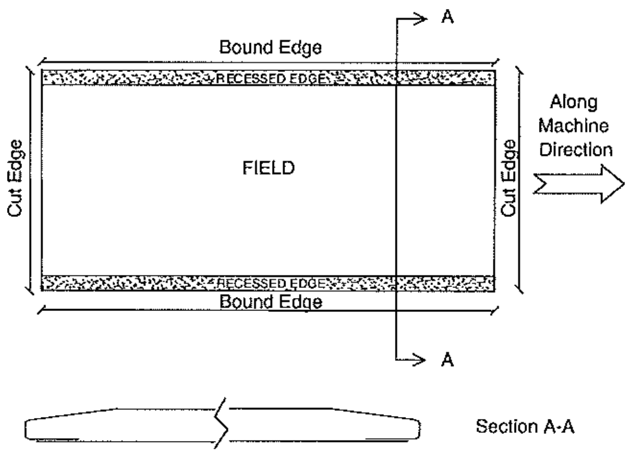

Figure 6. Typical plasterboard with recessed edges used in Australia residential construction

Australia must allow different fastener spacing for the vertical edges, plates and intermediate studs. Most of the existing closed-form mathematical models do not allow for this flexibility and cannot be easily modified.

- Existing closed-form mathematical models assume different shapes of stud deformation such as parallelograms by Tuomi and McCutcheon (1978); sinusoidal shape (S-shape) by Gupta and Kuo (1985); and vertical cantilevers by Salenikovich (2000). To date, the S-shape stud deformation presented by Gupta and Kuo (1985) seems to be the most reasonable assumption as such a deformation is observed in most full-scale isolated wall racking tests. However, this model assumes the same magnitude of deformation and profile for all the studs in a wall. This assumption is not applicable for plasterboard clad walls because edge studs normally undergo more deformations than intermediate studs, due to a different failure mode (tear out) of plasterboard connections along the edges (i.e. end studs) compared with the connections on the intermediate studs.
- In Australia, wall plasterboard is usually connected to ceiling plasterboard via ceiling cornices. The ceiling cornices prevent the plasterboard from rotating but allow lateral (in-plane) movement. This type of wall behaviour is not observed in isolated wall racking test since the cornices are omitted. Furthermore, boundary restraints such as skirting boards and cornices provide significant additional racking resistance to the plasterboard clad walls as they prevent out-of-plane buckling of plasterboard and also restrict the relative rotation between the plasterboard and the frame (Gad *et al.* 1999b; Reardon 1990). Hence, analytical models which are based on the behaviour of isolated walls without such restraints would not be appropriate in predicting the load-displacement response of walls which are in use in Australia.

Based on the abovementioned unique features of plasterboard clad walls, it was concluded that a new closed-form mathematical model, which incorporates the effects of the cornices and skirting boards, needs to be developed for plasterboard clad walls typically found in Australian residential structures.

In this section, two analytical models for predicting the lateral load-displacement response of plasterboard clad walls in Australian residential structures under monotonic racking load are presented. Conclusions drawn from this analytical study are then discussed.

First, an FE model was constructed to simulate the behaviour of the walls tested in the experimental program as described previously in Section 3. This model was developed by extending the model presented by Gad *et al.* (1999c), using the commercially available FE software ANSYS (SASI 1996), and was verified against the experimental results presented in the previous section. The FE model consisted of linear elastic beams elements to represent the studs, plates and noggings and elastic plate elements to simulate the plasterboard. The nails between the plasterboard and frame were modelled by non-linear springs. Different spring properties were used for different nail locations to represent the various load-slip characteristics as highlighted earlier and illustrated in Figure 5.

It is generally acknowledged that the lateral strength of plasterboard clad walls is directly related to the capacity of the sheathing-to-framing connections (shear connections). Hence, for each experimental wall (Wall 1 to Wall 4), three FE models were created. The first and second models utilised the upper and lower bounds of the load-slip curves obtained from the supplementary shear connection tests, respectively, while the third model used the average load-slip curve.

As shown through the comparison presented in Figure 7, the experimental load-displacement curves fell within the upper and lower bounds of the predicted curves and matched the predicted mean curves with very good agreement. Most importantly, the middle stud deformations predicted by the FE model also corresponded well with the experimental results, refer to Figure 8. This is a very important verification step as it indicates that the FE model predicted both the wall capacity and stud deformations accurately. It can also be noted from Figure 8 that the upper and lower bounds of the middle stud deformations generated by the FE model almost coincided with each other, but the upper and lower bounds of the load-displacement responses generated were significantly different, as shown in Figure 7. Thus, it can be inferred that the load-slip characteristics of shear connections are more dominant in influencing the load-displacement response of the wall when compared with the influence caused by stud deformations, as advocated by Easley *et al.* (1982).

In addition to the FE modelling, a new closed-form mathematical model, described here as 'Modularised' Closed-Form Mathematical (MCFM) model, has been developed. The MCFM model employed the strain energy approach to model the non-linear behaviour of plasterboard clad walls and was developed as two modules. The first module establishes the deformation of studs relative to the plasterboard at each incremental

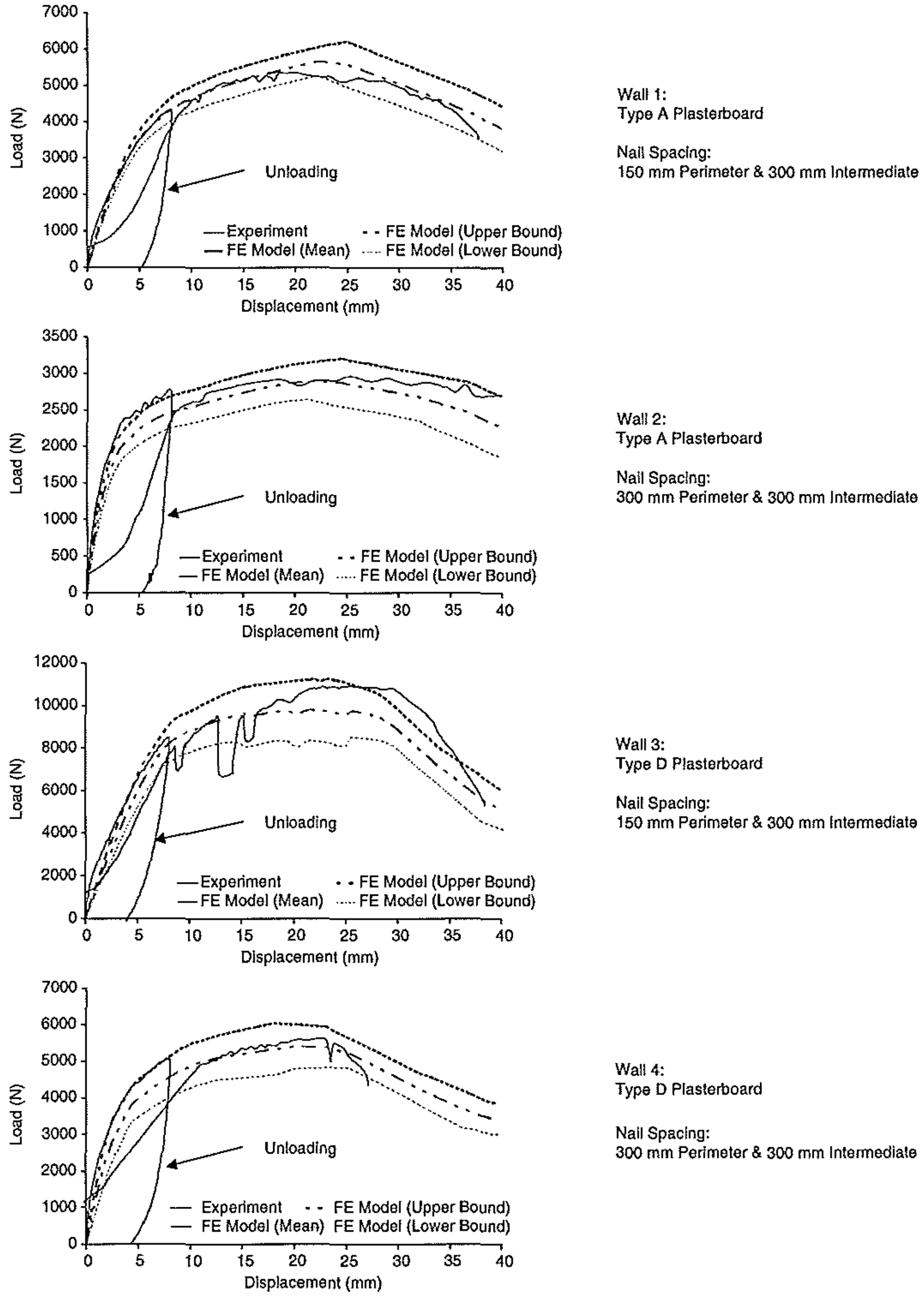

Figure 7. Comparison of load-displacement responses predicted by the FE model and the experimental results, Walls 1 to 4

displacement. Importantly, the MCFM model does not assume the shape of stud deformation, instead, it is generated by using a simple sub-model which calculates the deformation of each single stud according to the load-slip characteristics of the shear connections on the stud and its stiffness. In the second module, based on the computed stud stiffness, the energy stored in each individual shear connection and in each stud is determined based on the load-slip characteristics of the shear connections and the elastic properties of the frame. This enables the 'modularised' formulation to incorporate the different load-slip characteristics of

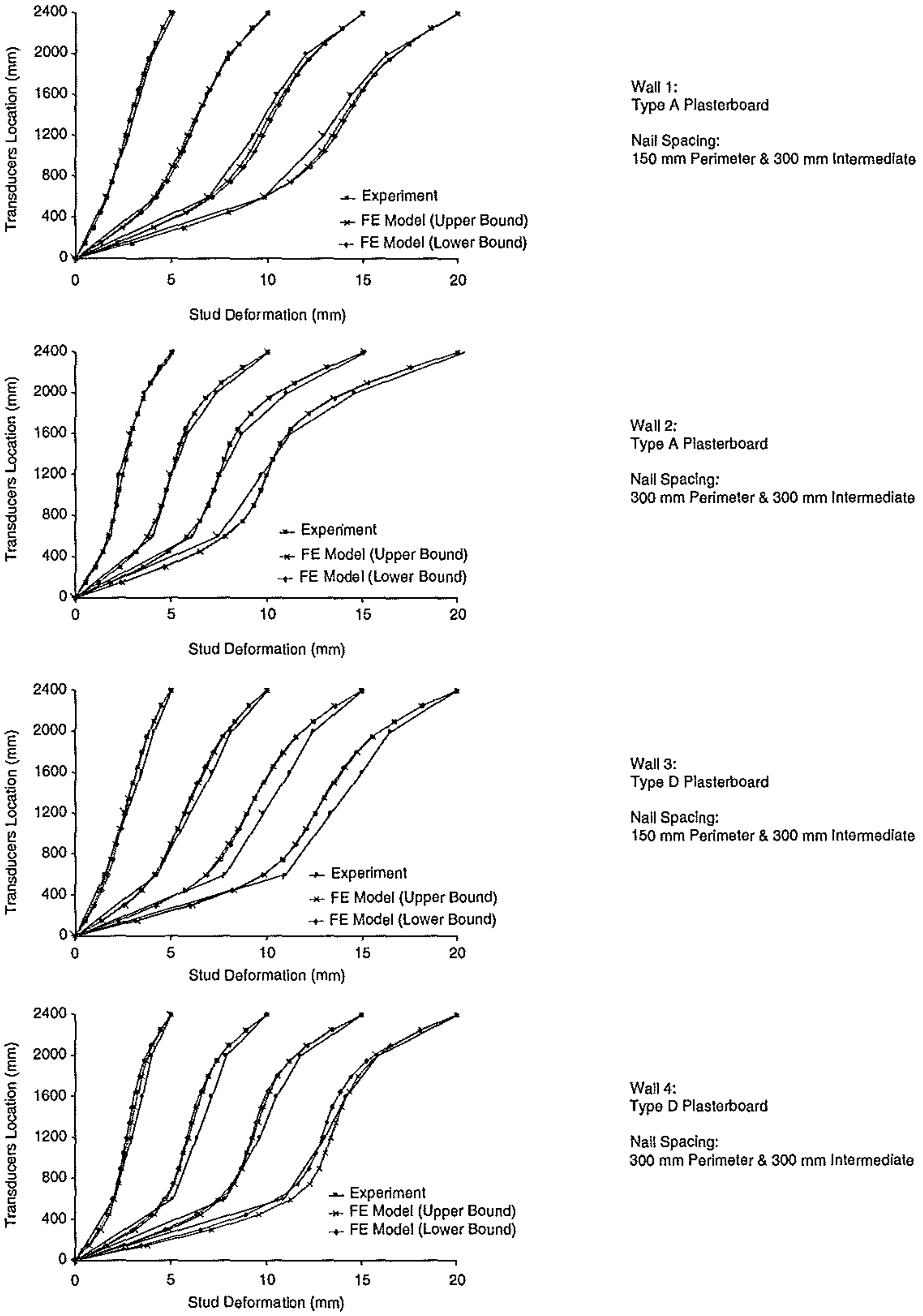

Figure 8. Comparison of middle stud deformation profiles obtained from the FE model and the experimental results, Walls 1 to 4

shear connections into the model. Next, the load-displacement response of the wall model due to frame deformation and nail slip is determined through an iterative procedure. Finally, the additional racking displacement caused by shear in the plasterboard is added to the frame deformation as well as the nail slip

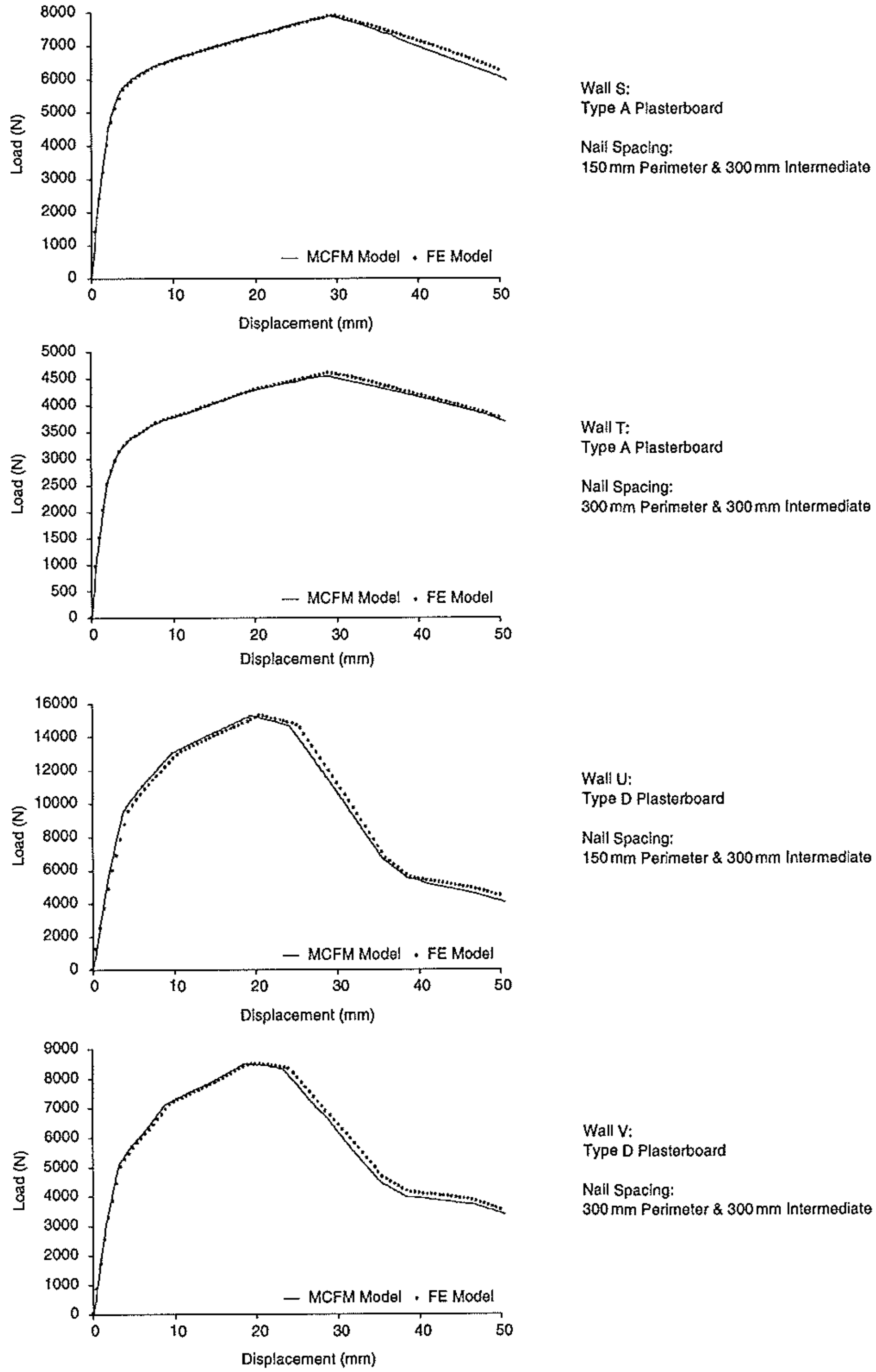

Figure 9. Comparison between load-displacement curves obtained from the MCFM and the FE model, Walls S to V

obtained previously to calculate the actual total displacement. A full derivation of the MCFM model can be found in Liew et al. (2005).

Using the computational algorithm as described above, four walls, named here as Walls S to V, with boundary conditions (i.e. ceiling cornice and skirting board), were modelled. The predictions generated by the MCFM model for the four walls were found to be in excellent agreement with the results obtained from the previously verified FE model as shown in Figure 9. The MCFM model has also proven flexible in accommodating various nailing patterns and different framing member dimensions.

From the analytical study described above, the following conclusions have been drawn:

- Strain energy due to stud deformation is significant and must be included in modelling of the plasterboard clad walls typically found in light-framed residential structures in Australia.
- Deformation of each stud can be independent of the other studs in the wall and the strain energy of each stud is additive to the total internal strain energy of the wall subjected to racking load.
- Inclusions of ceiling cornice and skirting board further enhance the bracing performance of the plasterboard clad wall by preventing the rotation of plasterboard relative to the frame. Also, these components prevent out-of-plane buckling of plasterboard.
- The high consistency exhibited by the ratios of the ultimate loads of the wall specimens clad with Type D plasterboard (highest density) to that of the walls clad with Type A plasterboard (lowest density), as obtained from both the test results and predicted by the FE models, enables direct correlation between shear connection tests or fastener bearing tests with full-scale wall racking tests.
- The results of load-displacement responses predicted by the MCFM model matched remarkably well with those generated by the FE model.
- The MCFM model has the capability of assigning different load-slip characteristics for shear connections to account for the effects of fastener locations on a wall. Such effects are particularly important for walls clad with plasterboard, where the shear connections close to edges of the plasterboard are substantially weaker than those at the recessed edges and field.
- The influence of the various nail spacing at the top and bottom plates is significant in providing bracing capacity for walls clad with plasterboard. However, changes in the framing member dimensions typically adopted in Australian light-framed structures do not have significant effect on the overall bracing performance of plasterboard clad walls.
- The MCFM model has established the basis for developing a spreadsheet-based program to analyse the load-displacement response for plasterboard clad walls. This fulfils the demand for straightforward and cost effective computer programs to perform regular design calculation without the need for complex non-linear FE softwares.

5. CONCLUSIONS

This study has successfully proposed, developed and verified a new test method, described herein as fastener bearing test, through an extensive experimental program and subsequent analyses. The test enables plasterboard manufacturers to reliably control the bracing quality of plasterboard, hence, allowing engineers to safely design the overall bracing capacity of light-framed residential structures. The contributions of each component of plasterboard and its effects on the bracing performance of plasterboard have also been examined and discussed. This was followed by the successful development of the 'Modularised' Closed-Form Mathematical (MCFM) model, which was validated against the results from the verified finite element (FE) model. The findings of this study have significantly contributed to the understanding of the bracing performance of plasterboard, the behaviour of plasterboard clad walls and to some extent, the behaviour of residential light-framed structures when subjected to lateral wind loading. This study has produced reliable and effective analytical models, particularly the MFCM model, which is suitable for developing simple and cost effective computer programs for everyday design.

It should be noted that although this and other studies proves that plasterboard has the capability to provide significant bracing capacity, the deformation compatibility of plasterboard with other types of bracing material has to be studied further. That is, plasterboard clad walls may have higher initial stiffness than other bracing walls in the structure (e.g. those with diagonal cross strap bracing or plywood clad) and may also achieve their full strength at lower deformation. Hence, the direct addition of strengths from all individual walls without regard to the deformation compatibility may not reflect the true lateral performance of the overall structure.

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