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LOAD SHARING AND STRUCTURAL RESPONSE OF TIMBER-FRAMED HOUSE

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ABSTRACT

Contemporary houses in many parts of Australia are brick veneer structures with metal or tile clad roofs that are built by trained builders using skilled labourers working to engineering design specifications. However, windstorms can cause significant damage to houses hence; there is a need to study the load sharing and response of these structural systems to assess their vulnerability. A full-scale test was carried out on a representative brick veneer contemporary house to assess the loading effects on roof to wall connection and load sharing. Tests were carried out at each stage of construction: bare frame followed by the installation of roof battens and cladding, wall lining, ceiling etc. These construction stages were used to assess the contribution of the structural and non-structural (i.e. ceiling, ceiling cornice and wall lining) elements to the load sharing and response of the timber-framed house structure to wind loading. The full-scale test, results show that the vertical load sharing of the timber-framed house through the roof to wall connection depends on the stiffness of the connection and the truss location (i.e. whether located at the end or middle). The contribution of the non- structural elements to the load sharing is about 15% to 20%. The outcome of this study can be used to assess the response (i.e. vulnerability) of these houses to windstorms.

KEYWORDS

Timber-framed structure, full-scale test, load sharing, house construction.

INTRODUCTION

The timber-framed house structure is a complex three-dimensional (3D) structural system, an assembly of several component structures such as the wall structure, floor structure and roof structures. These components are connected at cladding to batten, batten to truss, roof to wall, and wall to foundation connections. These complex structural systems are subject to wind loads but little is known about the structural behaviour and load sharing between each component structure through the inter-component connections. Determining the structural response and load sharing between the components are necessary to assess structural performance of timber-framed houses.

Boughton and Reardon (1982, 1983, and 1984) carried out a range of full-scale tests on houses at the Cyclone Testing Station, James Cook University, Townsville, Australia. These studies qualitatively investigated the performance of Australian timber-framed houses. These tests were focused on the response of wall stud, and roof (uplift strength). Based on the applied load and displacement, Reardon and Henderson (1996) showed improvement in the strength and stiffness of the house system with the addition of various structural and non-structural components such as wall lining, ceiling and ceiling cornice. However, these studies are did not quantify the load sharing within the timber-framed house structure. Morrisson (2010), Gupta and Kuo (1987), and He *et al* (2001) studied the performance of timber- framed houses in North America using full-scale test and numerical model analyses. The structural systems and construction methods of North American houses are different from that of the Australian houses. These types of differences in house structural systems cause differences in the stiffness and deformation of structural system to wind load.

This paper presents a full-scale study on a timber-framed house that determines the load sharing between components through their connections based on the reactions measured at the roof to wall connection and the foundation (i.e. bottom plate). This study also evaluates the effect of the non-structural components (i.e.wall lining, ceiling and ceiling cornice) on the load sharing.

Representative Contemporary House

Contemporary houses in many parts of Australia are brick veneer structures with metal or tile clad roofs that are built by trained builders using skilled labourers working to engineering design specifications. These houses were designed and constructed to wind classifications specified in AS 4055 (2012) and 1684.2 (2010). The metal cladding is fixed to metal top-hat battens, which are attached to timber trusses that are spaced at regular intervals along the walls. The roof trusses are fixed to the wall top plate using various methods, depending on wind loading and building regulations. The schematic diagram of a brick veneer contemporary house structural system is shown in Figure 1.

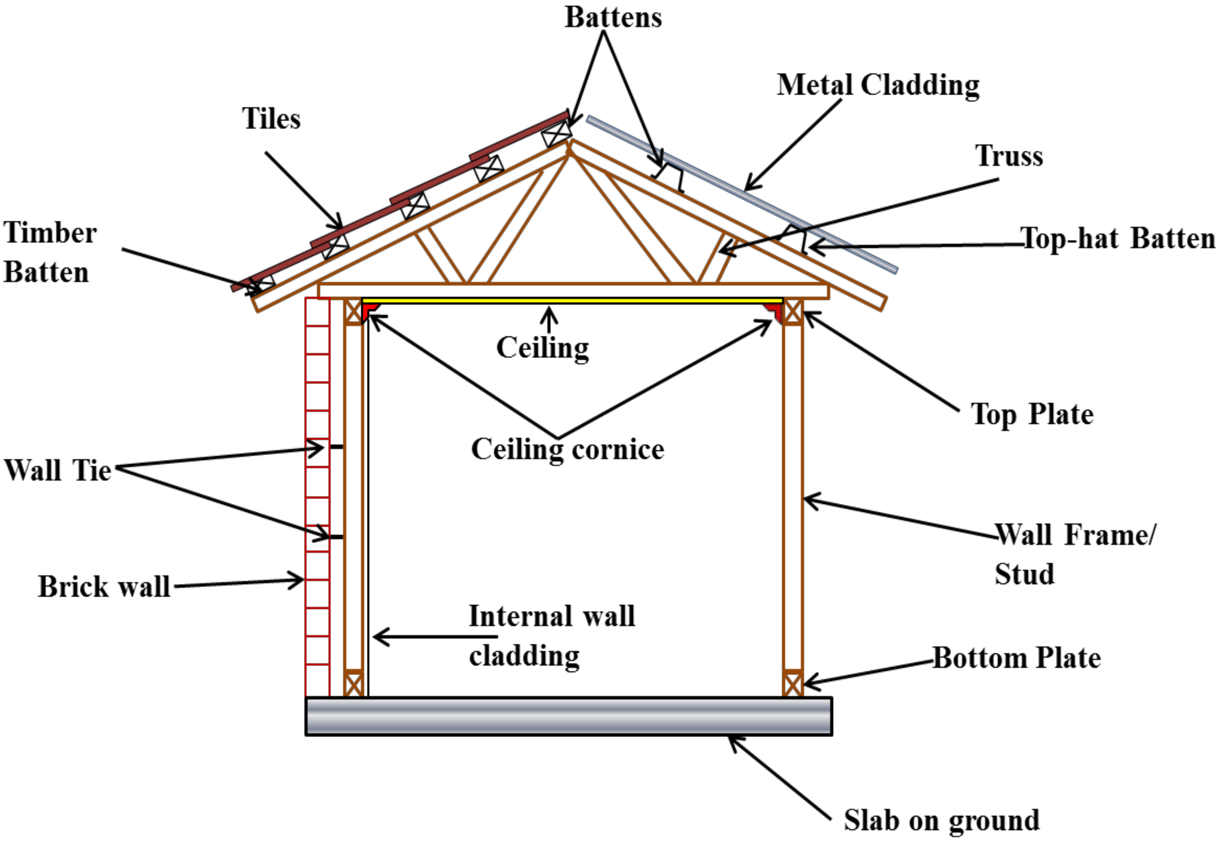


Figure 1 Schematic diagram of a brick veneer contemporary house structural system

This study involved a field survey of contemporary houses under construction around Brisbane, Australia (Figure 2) by a team from the Cyclone Testing Station to determine houses' structural system. Based on the field survey a contemporary representative house was obtained, which is a single storey, timber framed brick- veneer construction with 21.5^{o} pitch hip-end roof. The spacing of timber trusses is at 600mm and the metal top-hat battens at 850mm. The roof cladding was metal sheet, which is attached to battens and the trusses are fixed to the wall top plate with triple grips.

This study investigated the loading effects and load sharing of the general truss region of the representative house by conducting a full-scale test. The test house consists of five general trusses, top hat battens, corrugated steel roof cladding, ribbon top plate, wall studs, bottom plate, wall lining, ceiling and ceiling cornice.

Figure 2 Contemporary house under construction

FULL-SCALE TEST HOUSE

Tests were conducted at seven different stages of construction, described in Table 1. Figure 3 shows the initial stage, full-scale test set-up, with five MGP 10 grade timber trusses, ribbon top plate, bottom plate and wall studs. Triple grips with hand nails are used to connect the truss and the top plate. The aim of testing for Stages 1 to 4 was to evaluate the load sharing within the roof structure and obtain the truss hold down forces, as well as evaluate the contribution of the ceiling to the response of the roof to wall connection. Testing from Stages 5 to 7 evaluated the whole house response and load sharing through the wall structure. Figure 3 also shows the loading beam attached to the steel reaction frame.

Table 1 The detail of each Stage of the full-scale test

Stage	Construction details	Location of applied load	Location of the reaction force measurement
	Roof Structure		
1 (S1)	Five trusses, two ribbon top plates, twelve wall studs and two bottom plates were installed	Loads were applied along the Truss at the batten to truss connection position	At the roof to wall connection on the top plates position which are connected to load cells via rods (i.e. LA, LB, LC, LD, LE, RA, RB, RC, RD and RE)
2 (S2)	Twelve battens were added to the construction Stage 1	On the battens at the same positions as Stage 1	Same as Stage 1
3 (S3)	Roof cladding was added to the construction Stage 2	On the roof cladding at the same positions as Stage 1	Same as Stage 1
4 (S4)	Ceiling was added to the construction Stage 3	Same as Stage 3	Same as Stage 1
	Roof and Wall Structure		
5 (S5)	Steel rod joint was disconnected from the top plate of the Stage 4	Same as Stage 3	Reaction forces measured on the bottom plate at the same location in Stage 4 (i.e. LA, LB, LC, LD, LE, RA, RB, RC, RD and RE)
6 (S6)	The wall lining was added to the Stage 5	Same as Stage 3	Same as Stage 5
7 (S7)	Ceiling cornice was added to the Stage 6	Same as Stage 3	Same as Stage 5

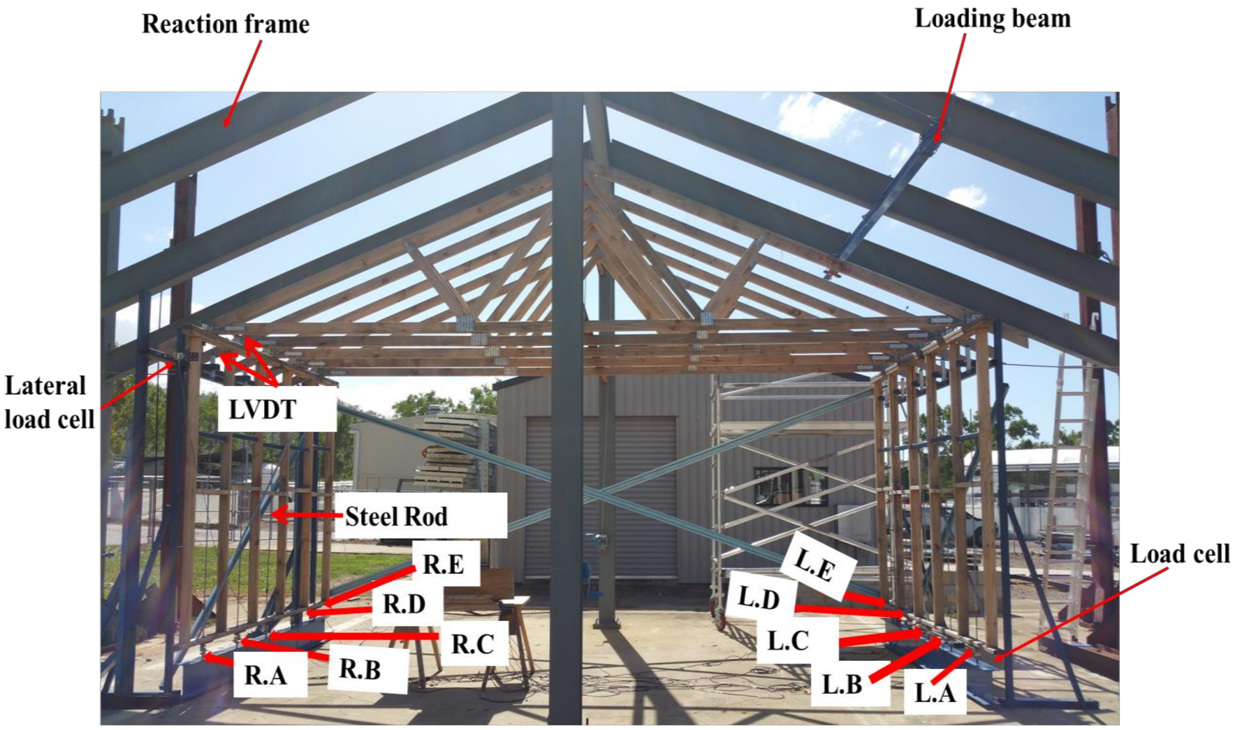


Figure 3 Full-scale test house at Stage 1 and the load cell locations

Figure 4 is a schematic diagram of the plan view of the test house. The structural system of the test house was symmetric; therefore, the loads were only applied to one side of the roof. Loads were applied normal to the roof surface at batten to truss connection locations with a hydraulic ram, which was connected to the loading beam located parallel to the batten as shown in Figure 3.

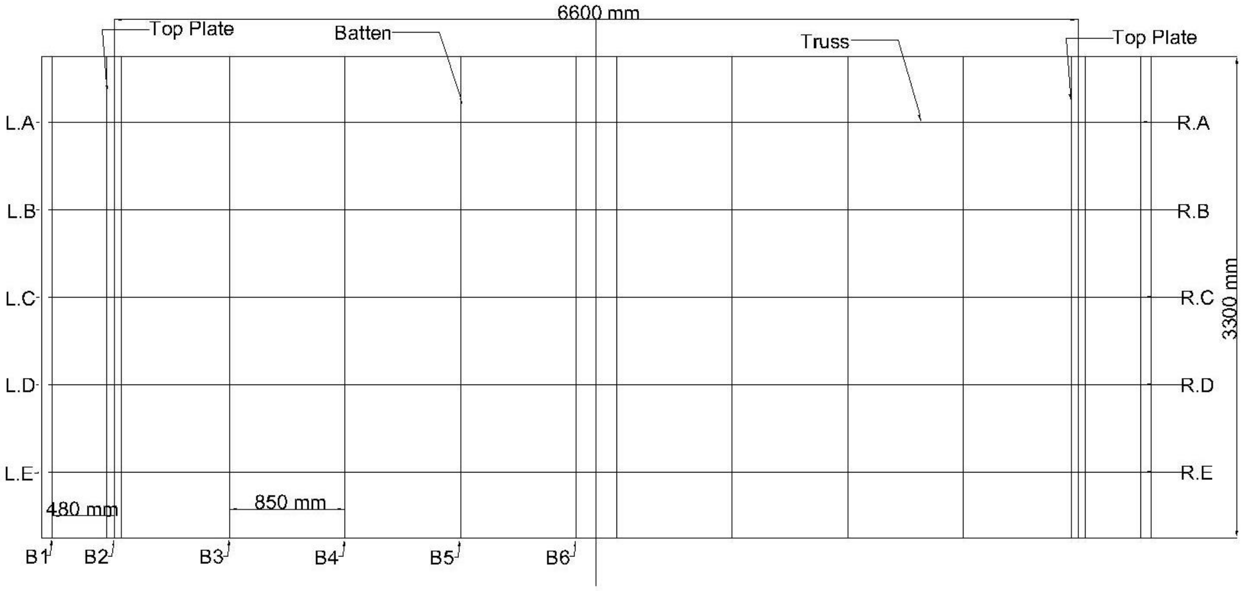
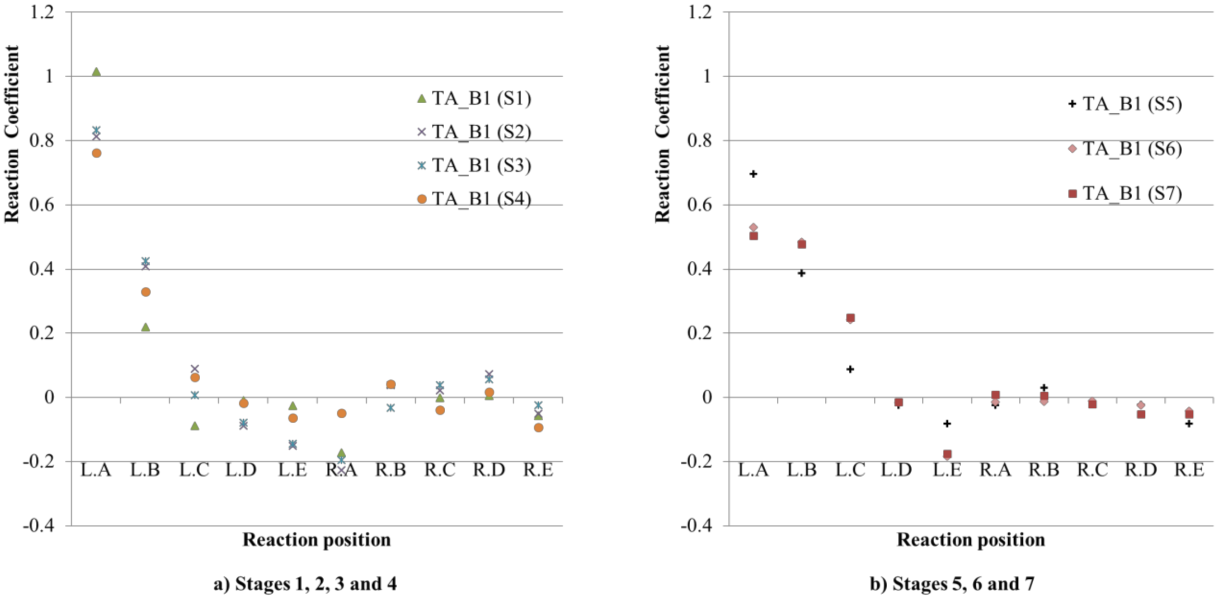


Figure 4 Schematic diagram of the plan view of test house

TEST RESULTS AND ANALYSIS

In the full-scale test, the loads were applied in the perpendicular direction to the roof surface, in order to represent wind loading. The applied loads were within the serviceability limit state of the house structure. This serviceability limit state load did not cause failures of the structural, non-structural components and the inter-component connections at each stage of testing. The response (i.e. the measured reaction forces and displacements) to applied loads ranging between 0.7kN and 1kN at batten to truss connections along Trusses A, B and C, are presented in this paper. A reaction coefficient, a normalized reaction force, is defined as the reaction force divided by the applied load.

Figures 5, 6, 7 show the vertical reaction coefficient (i.e. vertical reaction force divided by the vertical applied load) variation of the roof to wall connection support (i.e. L.A, L.B, L.C, L.D, L.E, R.A, R.B, R.C, R.D and R.E) at construction Stages (S1), (S2), (S3) (S4), (S5), (S6) and (S7), when the test load was applied along Truss A (i.e. TA), B (i.e. TB) and C (i.e. TC). Figure 5a shows the variation of the reaction coefficient for construction Stages 1, 2, 3 and 4, whilst Stages 5, 6 and 7 are shown in Figure 5b, when loading at Batten B1 on Truss A. Figure 5a shows that the reaction coefficient of the roof to wall connection Truss A at the loading side support (i.e. L.A) was high at Stage 1. This is because, in Stage 1, the ribbon top plate is the only structural element available to share the load to the adjacent trusses' supports. About 20% of applied loads were shared to the adjacent trusses through the wall top plate. The reaction coefficient at Truss A roof to wall connection (i.e. L.A) at Stage 1 is reduced by about 20% at Stages 2 and 3, whilst about 25% of the reaction coefficient was reduced at Stage 4 when compared to Stage 1. Figure 5b illustrates that Stages 6 and 7 produced similar reaction coefficient magnitudes, indicating that the contribution of ceiling cornice on the vertical load sharing is less compared to wall lining.

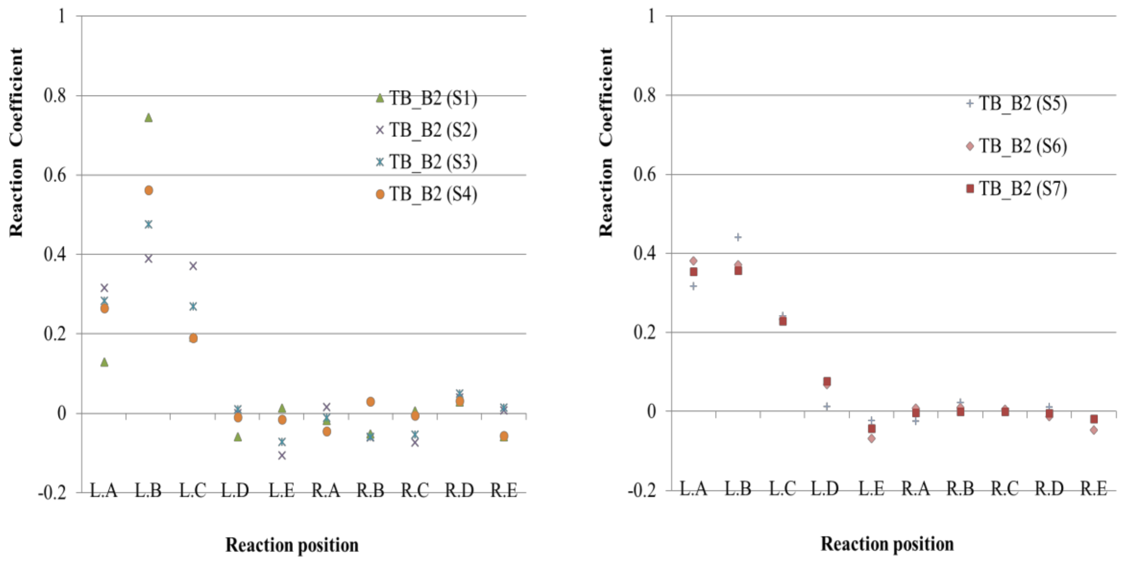


a) Stages 1, 2, 3 and 4

b) Stages 5, 6 and 7

Figure 5 Reaction coefficient variation when loading along Batten B1 at Truss A

Figure 6 illustrates the reaction coefficient variation when the test load was applied along Batten B2 at Truss B. The reaction coefficient at the Truss B support (i.e. L.B) in all the Stages was less than that the reaction coefficient obtained when loading along Batten B1 at the Truss A support (i.e. L.A). This is due to the location of the trusses. The Truss A was located at the end of the top plate and could share the load only on one side of the house, whilst Truss B was located between two trusses (i.e. Truss A and Truss C) and could share more loads between these two truss supports. The reaction coefficients at Truss A (i.e. L.A) were generally higher than the reaction coefficients of Truss C (i.e. L.C) when loading along Truss B. This is due to the stiffness variation of the roof to wall triple grip connections, the roof to wall connection stiffness varies with material non linearity, construction practices and workmanship. This figure indicates that the stiffness of the Truss C connection is less than that of Truss A.

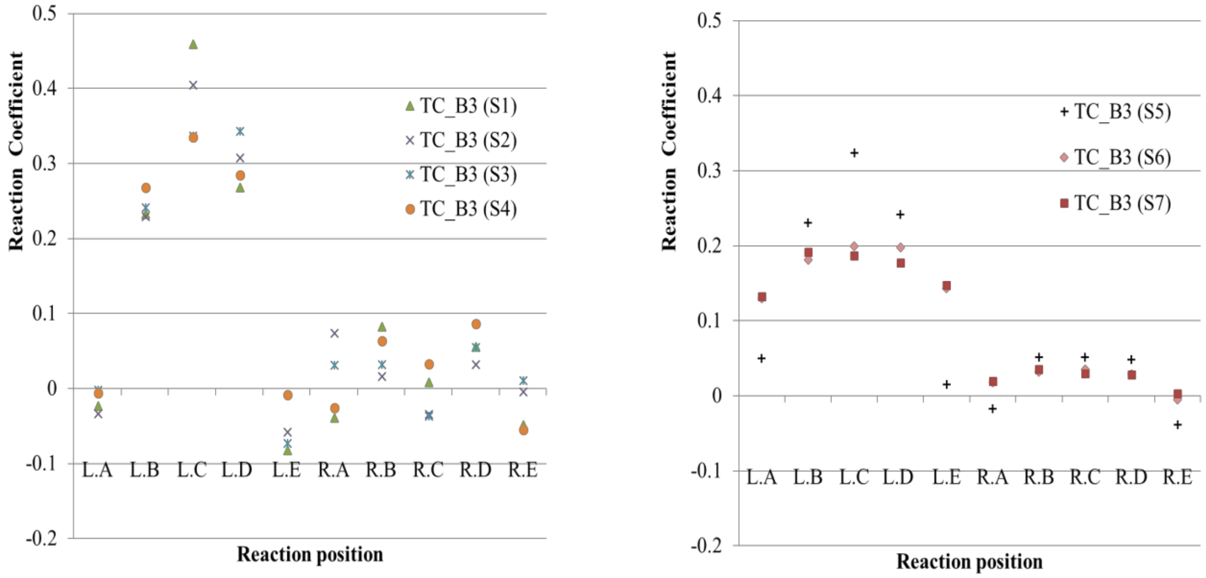


a) Stages 1, 2, 3 and 4

b) Stages 5, 6 and 7

Figure 6 Reaction coefficient variation when loading along Batten B2 at Truss B

Figure 7 presents the reaction coefficient variation when loading along Batten B3 at Truss C. The reaction coefficient of the Truss C support (i.e. L.C) in all the Stages was less than the reaction coefficient obtained with loading applied along Battens B1 and B2 at Trusses’ A and B supports (i.e. L.A and L.B). Truss C was located at the middle of the test house and could share the load to the adjacent trusses’ supports. This could be a reason for the lower reaction coefficient obtained when loading along Truss C. The stiffness of the roof to wall connection of Truss C was less than the other connections when compared to other trusses at Stage1. This lower connection stiffness is also a reason for the reduced reaction coefficient found in all stages when loading along Truss C.



a) Stages 1, 2, 3 and 4

b) Stages 5, 6 and 7

Figure 7 Reaction coefficient variation when loading along Batten B3 at Truss C

The measured roof to wall connection vertical displacement was divided by the applied load to quantify the flexibility of the connection in mm/kN. Figure 8 shows the flexibility of the roof to wall connection on Trusses A, B and C, on loaded side by considering vertical displacement variation at each construction stage. This shows large displacement at Stage 1 then progressively decreasing when the structural (i.e. S2 and S3) and non-structural (i.e. S4, S5, S6 and S7) elements were added to the system. Figure 8 also shows that the vertical displacements of the Truss A connection was high in all the stages compared to other trusses (i.e. Truss B and C). This because, Truss A shared less load to the adjacent trusses (Figure 5) due to their location.

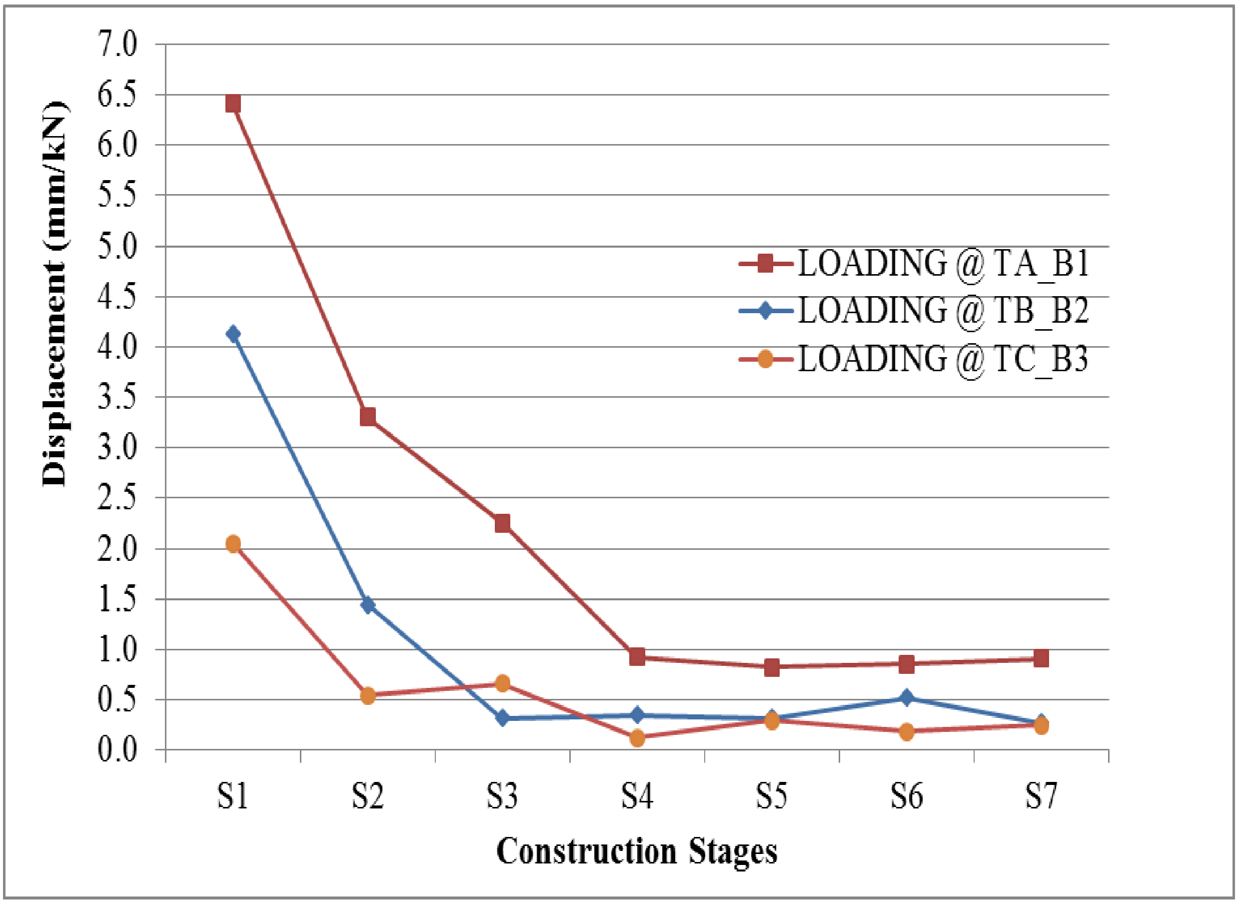


Figure 8 Roof to wall connection vertical displacement at Trusses A, B and C supports L.A, L.B and L.C

Load Sharing

The test results found during in this study provide a clear indication that the load distribution (Figures 5 to 7) and hence, the load-sharing characteristics of timber-framed structure depends on the inter-component connection stiffness. Figure 9 gives the percentages of vertical applied loads that were shared to the adjacent trusses when the loads are applied at B1, B2, B3, B4 and B5 on Truss A. This figure shows 10% to 20% of loads were shared to the adjacent trusses at Stage1, which then increased to 30% to 40% at Stages 2, 3, 4 and 5. About 45% to 50% vertical applied loads were shared to the adjacent trusses at Stages 6 and 7. This indicates that the non-structural elements (i.e. Ceiling, Ceiling cornice and wall lining) increase the load sharing characteristics by about 15% to 20%.

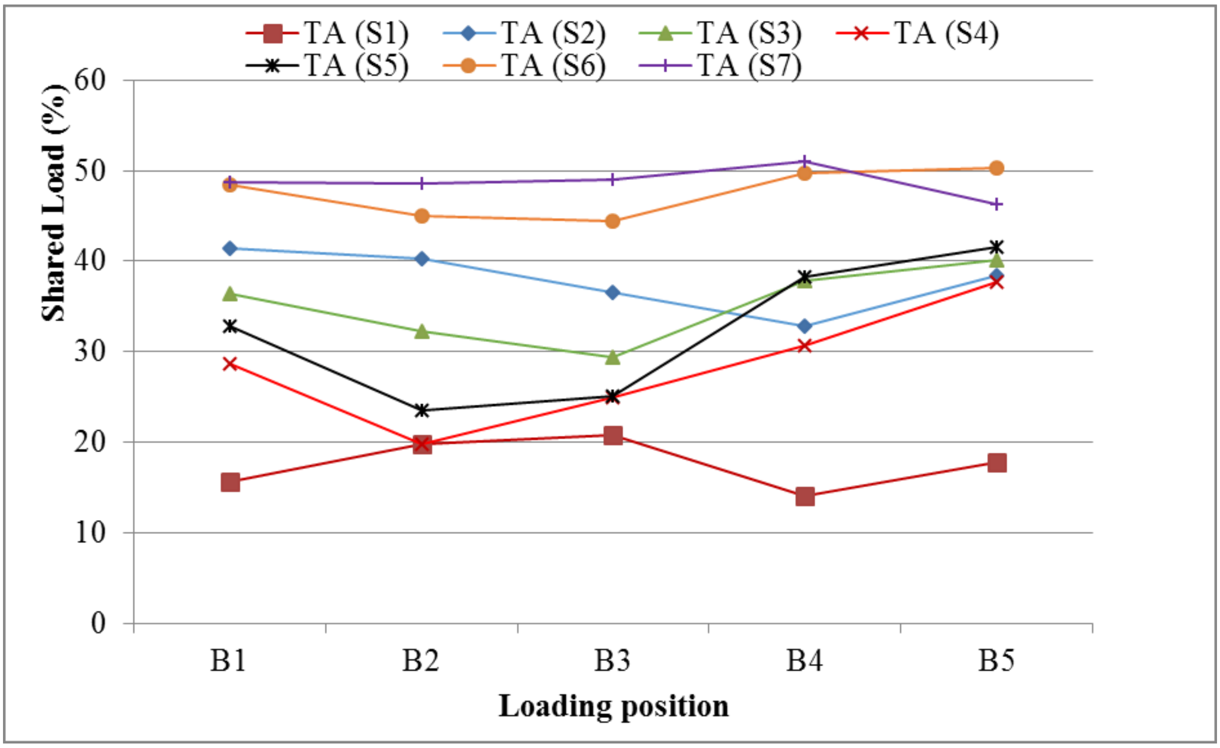


Figure 9 Percentage of applied loads are shared to the adjacent trusses when loading along Truss A

Figure 10 presnts the percentge of vertical applied loads shared by the adjacent trusses when loads were reapplied on Truss B. About 30% to 45% applied vertical loads were shared by the adjcanet trusses at Satge 1, which increased to 55% to 72% at Stages 2 and 3. After the ceilling was added to Stage 3, which is Stage 4, the load sharing was reduced to 50% to 55%. The self weight of the ceiling held down the truss and reduced the vertical displacement of the roof to wall connection, eventually increasing the support stiffness therefore, the percentge of load sharing was reduced at Satage 4. The contribution of non-structral elements to the load sharing was about 15% to 20% when loading along Truss B.

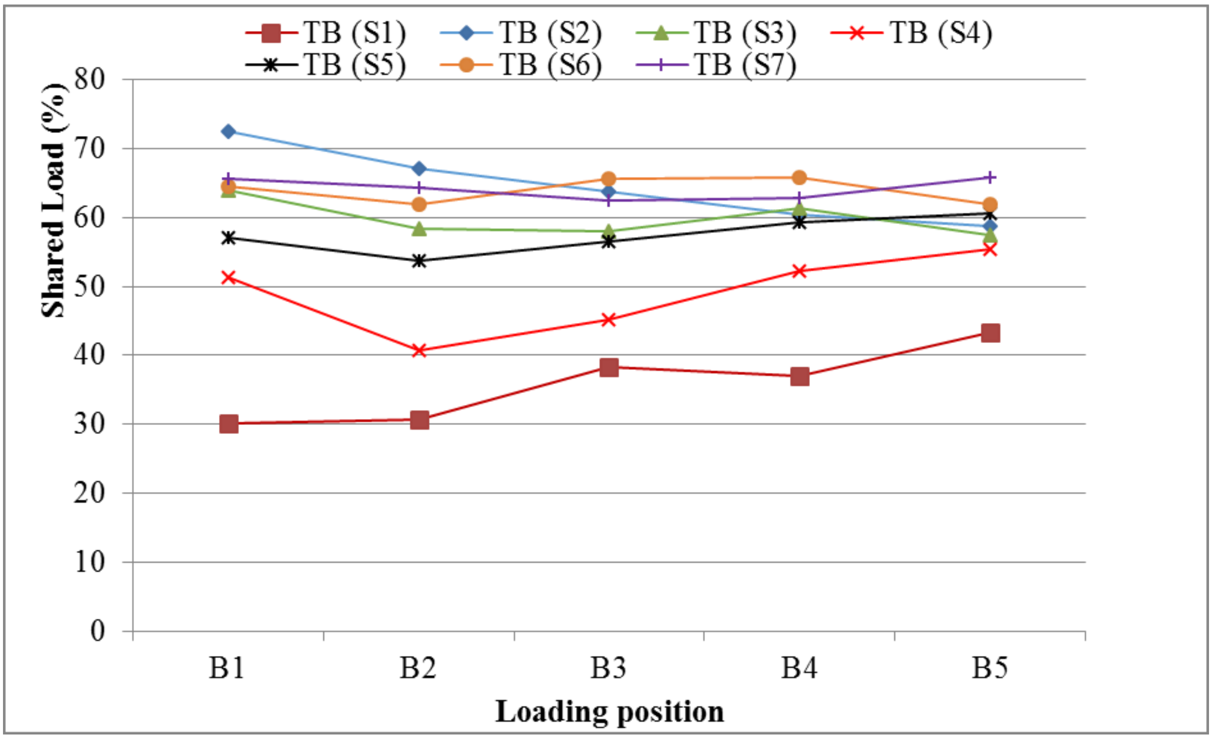


Figure 10 Percentage of applied loads are shared to the adjacent trusses when loading along Truss B

Truss C is a middle truss in the test house, and the stiffness of that truss to the wall connection was less than the other connections. Therefore, compared to other trusses, a higher percentage of loads were shared to the adjacent trusses in all the stages when loading along Truss C (Figure 11).

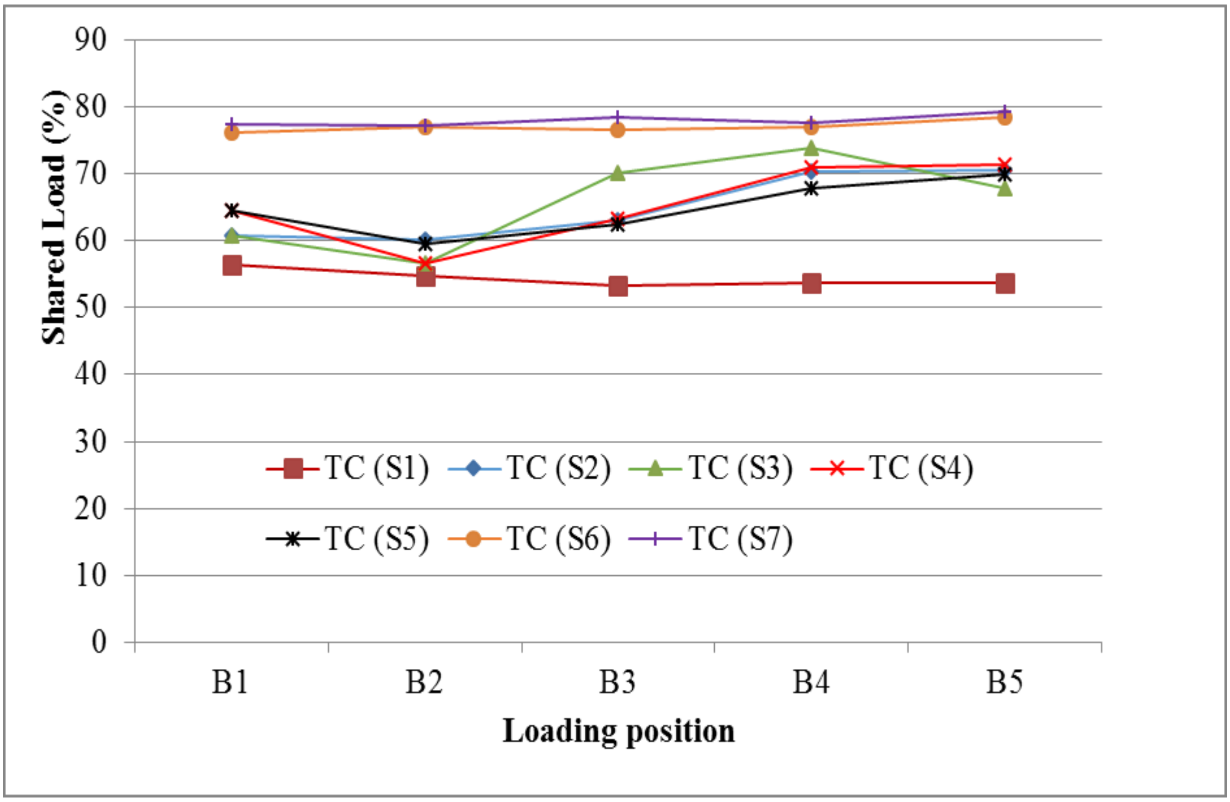


Figure 11 Percentage of applied loads are shared to the adjacent trusses when loading along Truss C

CONCLUSIONS

The determination of load sharing within the structure of timber-framed houses is important for assessing their response (i.e. design and vulnerability) to wind loads. A full-scale test was carried out to determine the response and load sharing of a representative, contemporary Australian timber-framed house. The following observations and conclusions were reached.

- Load sharing characteristics in timber- framed structure is dependent on the inter-component connection stiffness.
- Self-weight of the ceiling increased the roof to wall connection stiffness by reducing the vertical movement of the connection.
- The non- structural elements (i.e. ceiling, ceiling cornice and wall lining) contributed significantly to the load sharing of the timber-framed structure this contribution was about 15% to 20%.
- The reaction force and displacement is high when loading along the end truss, this indicates the end truss should use a high stiffness connection.

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