Wind Loading Effects on Roof to Wall Connection in a Timber Frame Structure

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ABSTRACT: Load sharing and structural response of contemporary representative houses to loading are investigated using numerical model analysis and full scale test in this study. The structural system of the contemporary representative house is obtained from a field survey by Cyclone Testing Station, James Cook University. In Australia, Contemporary houses are generally brick veneer structures with metal or tile clad roofs. Previous studies on damage to timber framed houses show that the roof structure of a house is vulnerable to windstorms. This indicates the need to study their structural response to mitigate their failures in windstorms. The roof to wall connection is an important inter-component connection for the structural stability of a house during strong winds, by providing a continuous load path from the roof to the foundation. The aim of this study is to assess the loading effects on roof to wall connection of a typical brick veneer contemporary house. A numerical model of the contemporary representative house was developed which provides load sharing and the structural response. This result also shows that the structural system stability will improve with elements such as ceiling and ceiling cornice sharing the load. Full scale tests will be carried out and the numerical model will be validated from the full scale test results. Full scale tests carried out on the bare truss frames gives results that agree with the numerical model analysis.

KEY WORDS: House structural system, Roof to wall connection, Wind load, Full scale test, Load sharing, Numerical model.

1 INTRODUCTION

Windstorms are one of the major causes for severe damage to houses and other infrastructure. An assessment of previous studies on damage to timber framed houses by [1], [2], [3], [4], [5], [6] and [7] show that the roof structure is the most vulnerable part of a house and that failures take place at their inter component connections (i.e. cladding to batten, batten to truss connection and truss or rafter to top plate connection). The failure of roof structure during extreme windstorms gives emphasis the need to enhance their performance. The stability of the roof structure mainly depends on their inter-component connection response to wind loading.

The cladding to battens connection, battens to truss connection and roof to wall connections are the most important connections in the roof structural system. Roof to wall connection is a potential source of vulnerability in the load path of a house structural system as that experiences high loads compared to other connections. This connection should be designed to transfer the total uplift and lateral load from the roof structure as well as the lateral load components from the wall to foundation through the wall structure. Several experimental studies and numerical analysis by [8], [9], [10], [11], [12] and [13] evaluated the performance of roof to wall connections, based on North American styles of house construction. The roof trusses, in non cyclone regions of Australia, are generally fixed with triple grip connections to the wall top plate but in non-hurricane regions of North America they are toe-nailed to the wall top plate. This will result in differences in the stiffness and deformation of the structural systems to wind loading. House structural systems use a range of approaches to account for the way timber framed structures respond to wind loading. However, only limited data is available on the load distribution in inter-component connections and progressive damage due to cascading connection failures, subject to wind loading. Construction defects also increase the probability of structural failures to windstorms.

In a timber frame structure, connections are commonly made by either nails, nail plates, bolts and nuts, screws and straps or a combination of these elements. The uplift capacities of these connections are given in the Australian standard [14] and manufactures specifications. These uplift capacities are based on results of individual component tests subject to static or cyclic loading and that do not simulate the multi axial loading effects. This study focused on developing a better understanding of the loading effects and load sharing on the roof to wall connections of a typical house.

2 REPRESENTATIVE CONTEMPORARY HOUSE

A field survey of contemporary houses under construction as shown in Figure 1 near Brisbane, Australia was conducted by a team from the Cyclone Testing Station to determine their structural system. The survey features were the overall dimensions of house, roof slope, shape, type of connections and type of construction. In addition construction defects were also recorded in this field survey. 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. 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 2.

Figure 1. Contemporary house under construction.

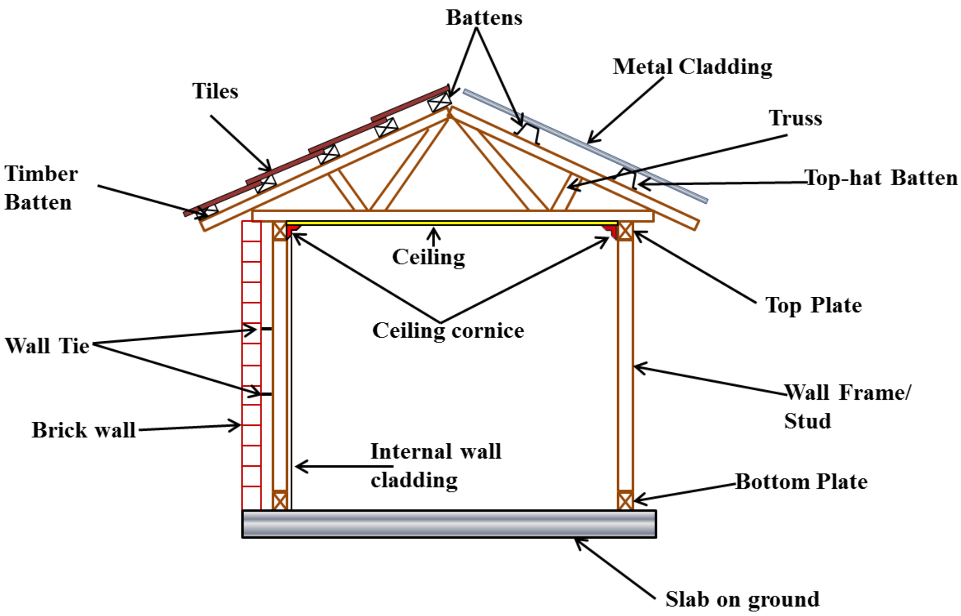


Figure 2. Schematic diagram of a brick veneer contemporary house structural system.

Based on the filed survey a representative house was obtained, which is a single storey, timber framed brick- veneer construction with 21.5o pitch hip-end roof as shown in Figure 3. The spacing of timber trusses was at 600mm and the metal top-hat battens at 900mm. The roof cladding was metal sheet which is attached to battens and the trusses are fixed to wall top plate with triple grips. This study investigates the loading effects and load sharing on roof to wall connection of the general truss region of representative house. This consists of five general trusses, ten top hat battens, corrugated steel roof cladding, two ribbon top plates, twelve wall studs, two bottom plates, wall lining, ceiling and ceiling cornice.

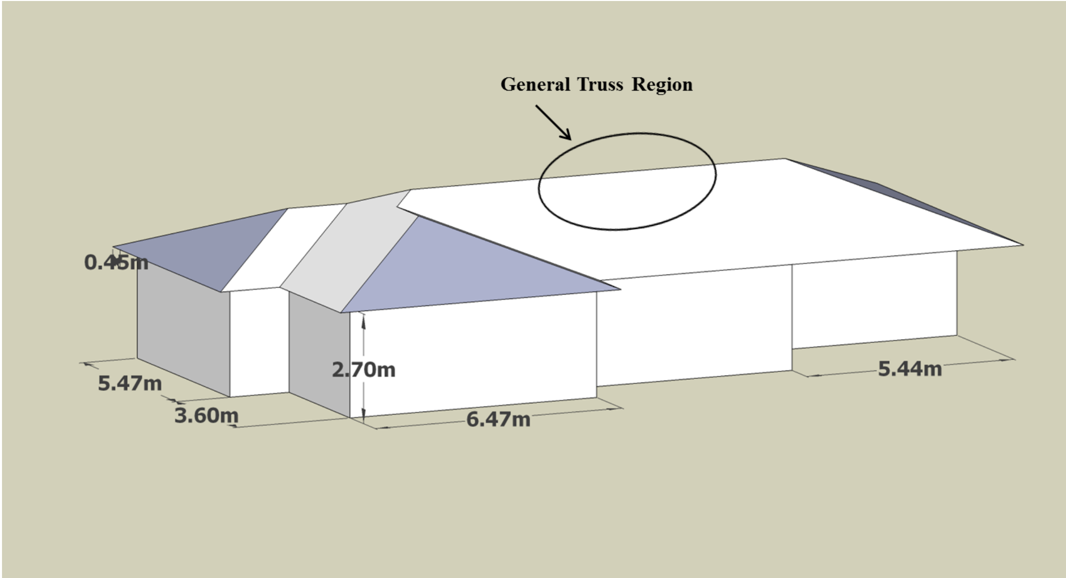


Figure 3. Representative contemporary house

3 ROOF TO WALL CONNECTION

In accordance with the field survey, the triple grip is widely used to connect the wall top-plates and trusses or rafters in house structural system of non-cyclonic regions of Australia, and missing nails are a most common construction defect in this connection. Design of this connection is mainly based on the uplift capacity as specified in Australian standard [14] but this standard does not account for construction defects or gun nailed connections. In addition, little is known about the interdependencies between uplift capacity and constructions defects. Experimental tests were conducted to study the response of roof to wall triple grip connections to loading by [15], which identified the critical nails and their locations to mitigate failure of the roof to wall triple grip connection subject to wind loading. It also showed that nails located near the centre line of the loading action greatly affected the stiffness of the triple grip connections. The response of these nails dominated the uplift capacity and failure types of the triple grip connection. That study also predicted the uplift capacities of triple grip connections with construction defects (i.e. missing nails) and gun nailed connections and showed how this can be used to assess the vulnerability of houses to windstorms.

3.1 Numerical model of the representative contemporary house

A three dimensional (3D) general truss region of the representative contemporary house model as shown in Figure 4 was assembled and subjected to load using ABAQUS (6.12-3) finite element software. To simplify the development of this model, material properties within each model component is assumed to be isotropic. The model was used to predict the roof to wall connection stiffness variation, structural response and the load sharing of the house structure with or without additional elements (i.e. roof cladding, wall cladding, celling, and celling cornice) being added.

The model consists of nine separate parts: corrugated steel roof cladding, top hat battens, truss, top-plate, wall studs, bottom plate, wall lining, ceiling and ceiling cornice. A two-node linear beam element (B31) was used to assemble the truss, wall studs and battens. An eight-node linear brick element (C3D8R) was used to assemble the top plate, bottom plate and ceiling cornice. Roof cladding, wall lining and ceiling were assembled with a four node shell element (S4R). Non-linear spring elements were used to represent each roof to wall triple grip connection and linear spring elements were used to represent cladding to batten and batten to truss connections. The stiffness of the nonlinear spring elements in x, y, and z directions were obtained from the experiments of triple grip connection [15] and the linear spring stiffness was obtained from previous studies ([16] and [17]). Table 1 shows the material parameters and the member sizes that were used in this model.

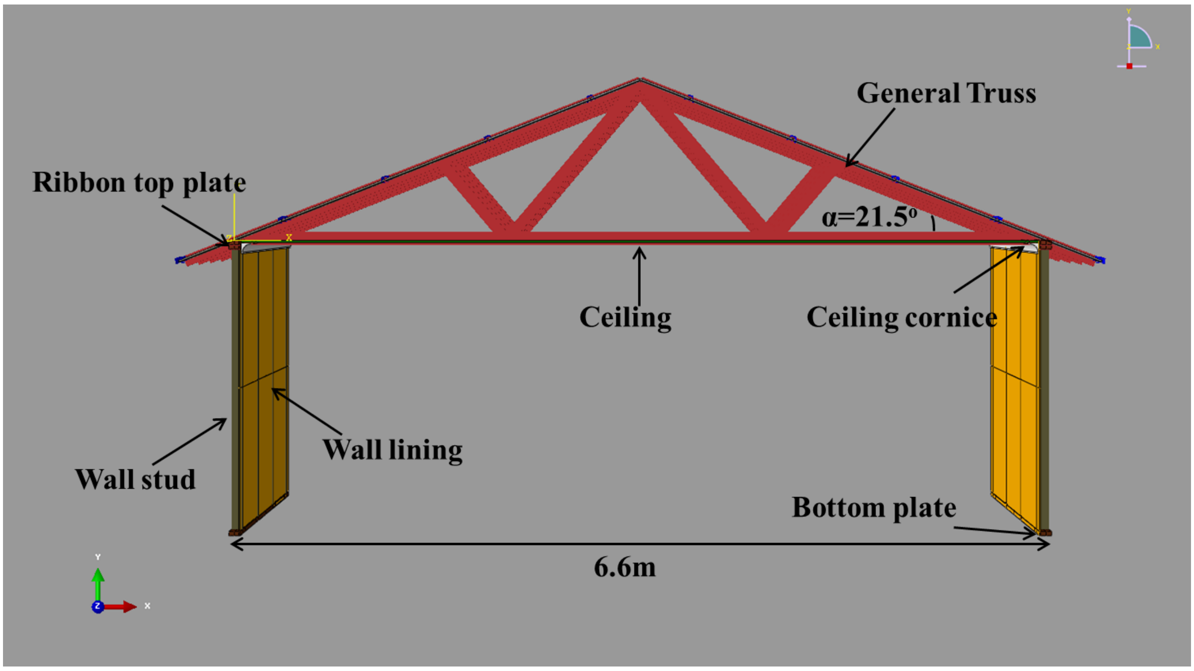


Figure 4. Front view of the numerical model of representative contemporary house

Table 1. Material parameters and member sizes of the numerical model

Member	**Quantity**	**Sizes, (mm)**	**Material**	**Young`s Modulus, (N/m^2)**	**Poisons Ratio**	**Density,(kg/m^3)**
Roof cladding	15	760 x 2700 x 0.8	Steel	200 x10^9	0.3	7850
Top hat battens	10	40 x 40 x BMT 0.55	Steel	200 x10^9	0.3	7850
Truss	5	90 x 35 x 6600	Timber (MGP 10)	10x10^9	0.37	510
Top plate	4	90 x 35 x 3300	Timber (MGP 10)	10x10^9	0.37	510
Stud	12	90 x 35 x 2295	Timber (MGP 10)	10x10^9	0.37	510
Bottom plate	2	90 x 35 x 3300	Timber (MGP 10)	10x10^9	0.37	510
Wall cladding	2	3300 x 2400 x 10	Chipboard	3x10^9	0.35	600
Ceiling	1	3300 x6500 x 17.5	Gypsum board	2x10^9	0.2	720
Ceiling cornice	2	90 x 90 x 3300	Gypsum board	2x10^9	0.2	720

3.2 Analysis

Numerical model analyses were run in seven cases (i.e. Case 1 to 7) in order to determine the effects of additional elements (i.e. roof battens, roof cladding, wall structure, ceiling and celling cornice). Details of the numerical model used in each case are shown in Table 2. The loads were only applied to one side of the house structural system because the geometry and structural properties of the house is symmetric. Figure 6 shows the plan view of the numerical model and Trusses A, B, C, D and E. This figure also shows the battens numbered 1 to 10 and loading directions.

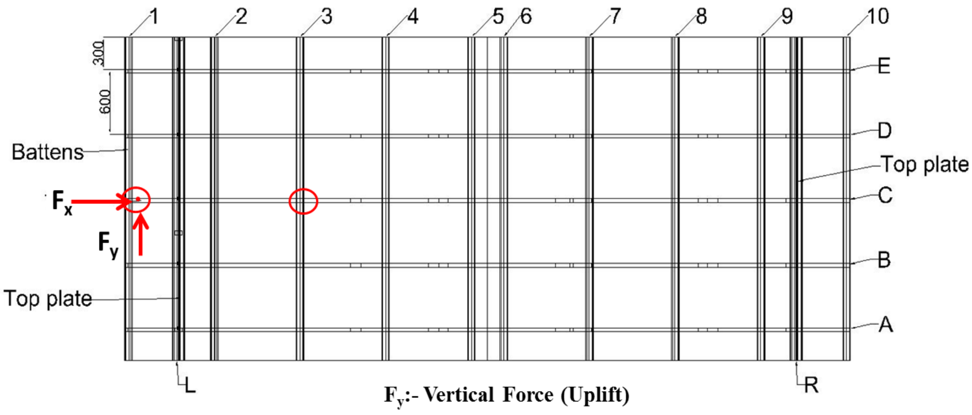


Figure 6. The plan view of the numerical model of representative contemporary house

Table 2. The detail of the each case numerical model.

Case	**Model detail**	**Location of the applied load**	**Location of the reaction force**	**Location of the vertical displacement**
	Roof Structure			
1	Model assembled with the Truss C and two ribbon top plates located along the lines L and R. A fixed boundary condition was subject at the bottom surface of the top plate	Uplift loads were applied along the Truss C on the batten to truss connection position (i.e. C1, C2, C3, C4 and C5).	At the bottom surface of the top plates on the roof to wall connection position (i.e. LA, LB, LC, LD, LE, RA, RB, RC, RD and RE)	At the truss on the location LC and RC
2	Model consists of five trusses, 10 battens and two ribbon top plates. The boundary condition is similar to Case 1	On the battens at same positions as Case 1	Same as Case 1	At the truss on the location LA, LB, LC, LD, LE and RA, RB, RC, RD, RE
3	Roof cladding was added to the Case 2 model	On the roof cladding at same positions as Case 1	Same as Case 2	Same as Case 2
	Roof and Wall Structure			
4	The wall structure was added to the Case 3 model. A fixed boundary condition was subject at the bottom surface of the bottom plate and there is no horizontal movement (x direction) on the top plate along the line R (U1=0)	Same as Case 3	Reaction forces measured on the bottom surface of the bottom plate at the same location in Case 3	Same as Case 2
5	Wall lining was added to the Case 4 model and the boundary conditions is similar to Case 4	Same as Case 3	Same as Case 4	Same as Case 2
6	Ceiling was added to the Case 5 model and the boundary conditions is similar to Case 4	Same as Case 3	Same as Case 4	Same as Case 2
7	Ceiling cornice was added to the Case 6 model and the boundary conditions is similar to Case 4	Same as Case 3	Same as Case 4	Same as Case 2

3.3 Results

In the initial stage of this study, the model was subject to 1kN uplift loads that are perpendicular to roof surface. This analysis is used to determine the load sharing and distribution within the house structure. Simulated wind load will be applied to the model in the next stage of this study. Figures 7, 8, 9 and 10 illustrate the y (vertical) direction reaction coefficient that is the ratio of the reaction force to the applied force obtained in each case of numerical model subjected to 1 kN load at position C1 and C3. Figures 7 and 9 show the reaction coefficient variation when the load was applied at C1, and Figures 8 and 10 when the load was applied at C3.

Figures 7 and 8 show the roof to wall connection reaction coefficient when adding additional elements to the roof structure. They show a decrease of reaction force at Truss C with the addition of elements (i.e. battens, roof cladding). This clearly indicates that the loads are shared between the adjacent trusses and their connections through the battens, roof cladding and top plates. The reaction coefficient of roof structure also decreases when the position of applied load moves from C1 to C3, indicating that the roof to wall connection experiences larger stresses when the load acts at the edge regions of the roof structure.

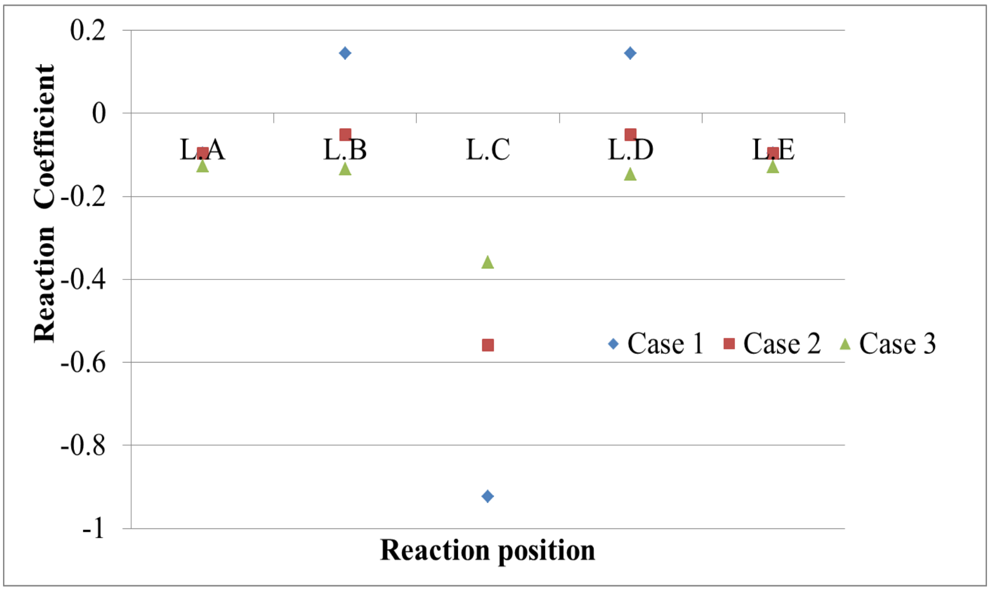


Figure 7. The Y direction reaction coefficient within the roof structure at the top plate along the line L, loading at C1

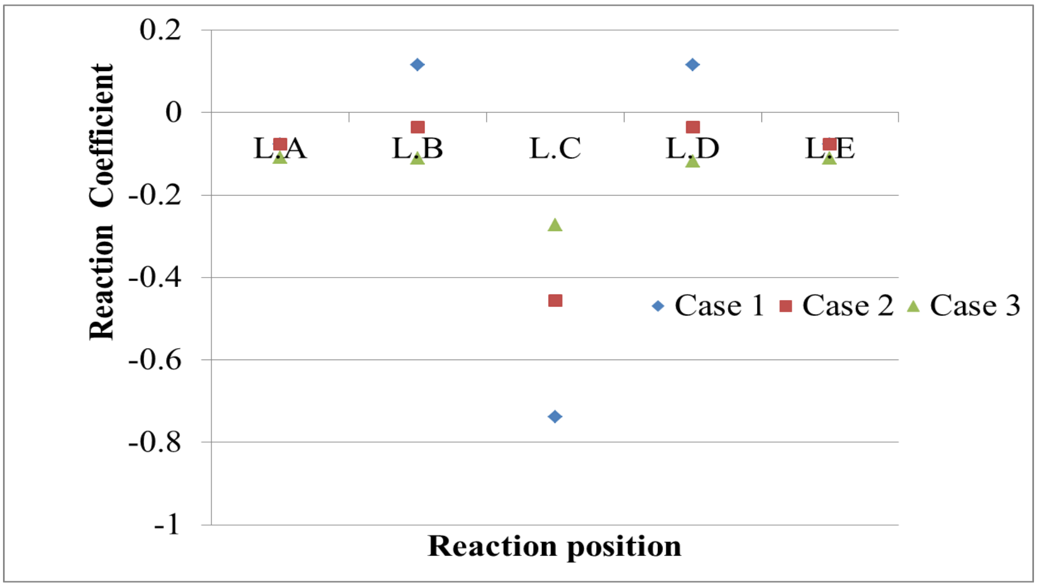


Figure 8. The Y direction reaction coefficient within the roof structure at the top plate along the line L, loading at C3

Figures 9 and 10 show the y (vertical) direction reaction coefficient along line L at the bottom surface of the bottom plate. These figures indicate that the y direction reaction coefficient is high when there is no wall lining, ceiling and ceiling cornice. Installation of the ceiling does not significantly affect the reaction forces if ceiling cornice is not installed, indicating that the wall lining, ceiling and ceiling cornice increase the load sharing capacity from roof to foundation.

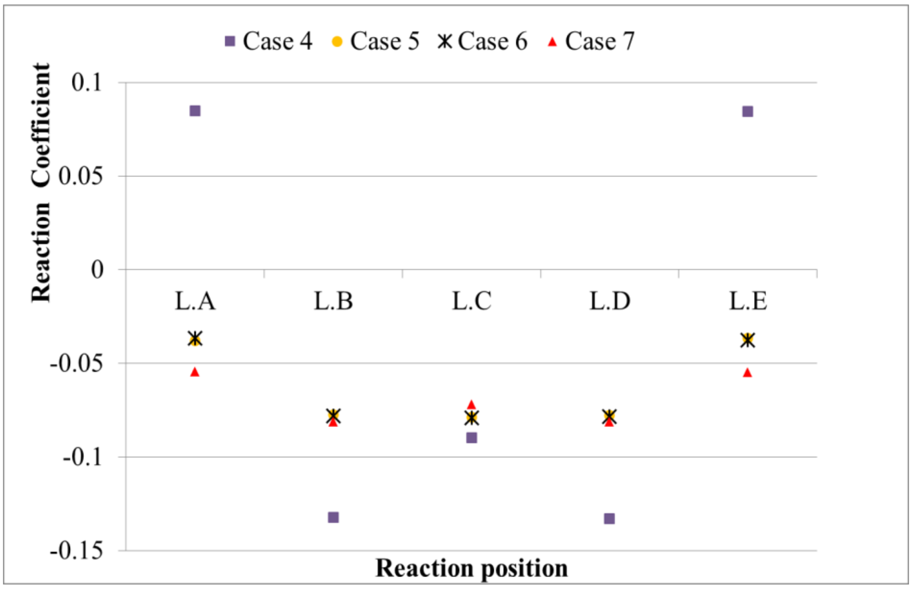


Figure 9. The Y direction reaction coefficient within entire structure at the bottom plate along the line L, loading at C1

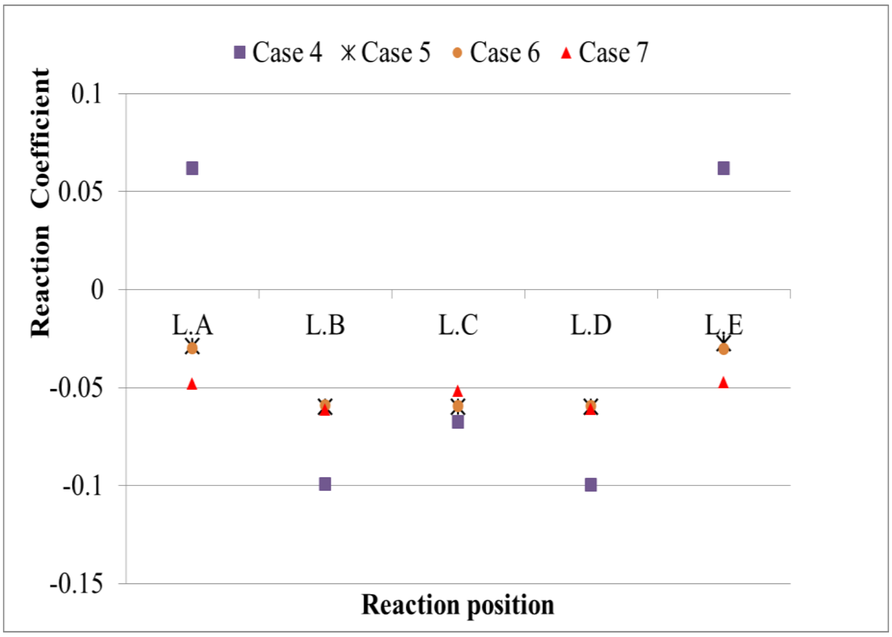


Figure 10. The Y direction reaction coefficient within entire structure at the bottom plate along the line L, loading at C3

Figure 11 shows the vertical displacements (i.e. the gap between the top plate and the truss which is opened up due to the applied load) of the roof to wall connection at Truss C for all seven cases. This figure shows the vertical displacement is significantly reduced when ceiling cornices are installed, an indication that ceiling cornices contribute to an increase of the roof to wall connection stiffness. This figure also shows that the deflection of the roof to wall connection reduces when the applied load is moved from C1 to C3.

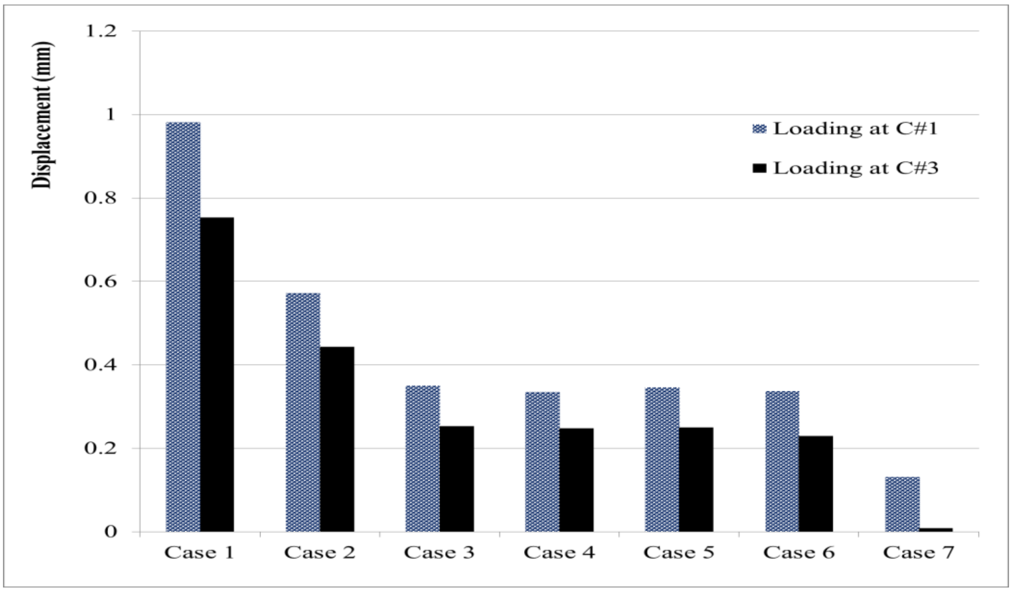


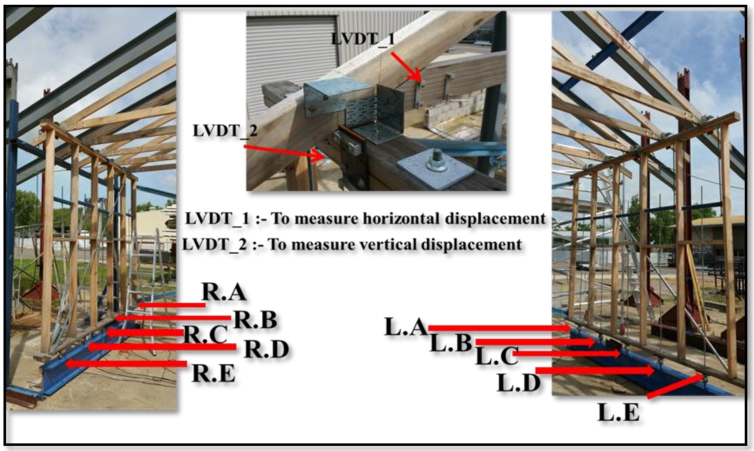
Figure 11. The roof to wall connection y (vertical) direction displacement at Truss C in all cases along line L.

3.4 Comparison between full scale test and numerical model

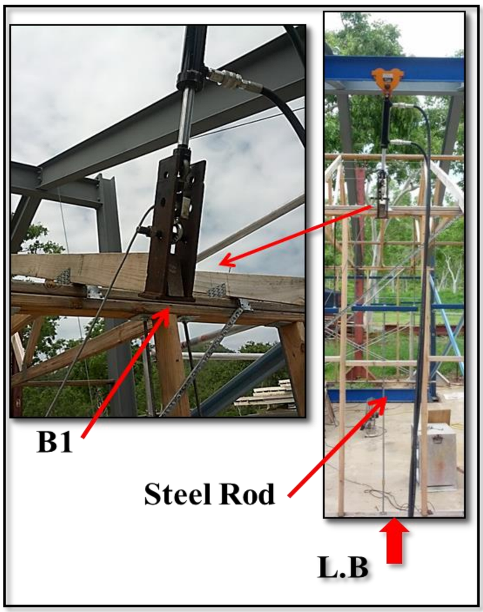
A full scale test house has been built (Figure 12) to validate the numerical model. “S type” load cells were used to measure the applied and reaction forces and LVDT`s were used to measure the roof to wall connections displacements. The entire house structural system is sitting on the load cells located under the bottom plates at the locations of the roof to wall connections, as shown in Figure 13a. Steel rods were used to connect the load cell and the top plate, as described in Figure 13b, to transfer the vertical reaction force from roof to wall connection to load cell. Test will be carried out for all seven cases as described in Table 2 and the results will be compared to the numerical model results.

At the stage only the test of Case-1 construction has been carried out; therefore, this paper only presents the Case-1 experimental results (i.e. load applied to the truss frame). A 1kN load was applied to truss B at location B1 using hydraulic ram as shown in Figure 13b. Reaction forces were measured at the locations of L.A, L.B, L.C, L.D, L.E, R.A, R.B, R.C, R.D and R.E.

Figure 12. Full scale test house



a) Locations of the Measuring devices



b) Loading position

Figure 13. Locations of applied loads and measuring devices

Figure 14 shows the reaction coefficients given by the numerical analysis and the full scale test. This figure shows that the reaction coefficient at the roof to wall connection of Truss B (the load was applied on this truss) is similar to the full scale test results. However, small discrepancies between the reaction coefficients determined by the numerical analysis and that by the full scale tests are observed. Differences of construction quality, connection stiffness and material nonlinearity between the numerical model and full scale test could be the reason for these observed discrepancies.

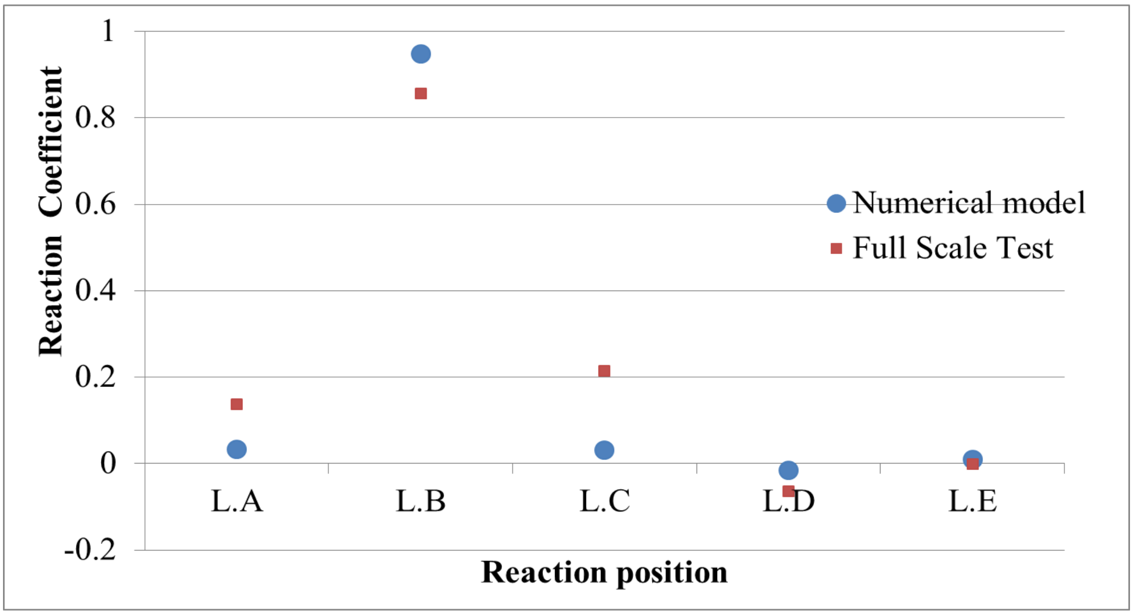


Figure 14. Reaction coefficients determined by numerical analysis and full scale test with load applied to truss B at location B1

The applied load was moved to position B3 on the Truss B and the reaction coefficients are compared with numerical model analysis. Figure 15 showed that the numerical model gives a reasonable representation of the experimental test behavior. Comparison of Figures 14 and 15 indicates that load applied to location B3 induces more load sharing than load applied to location B1.

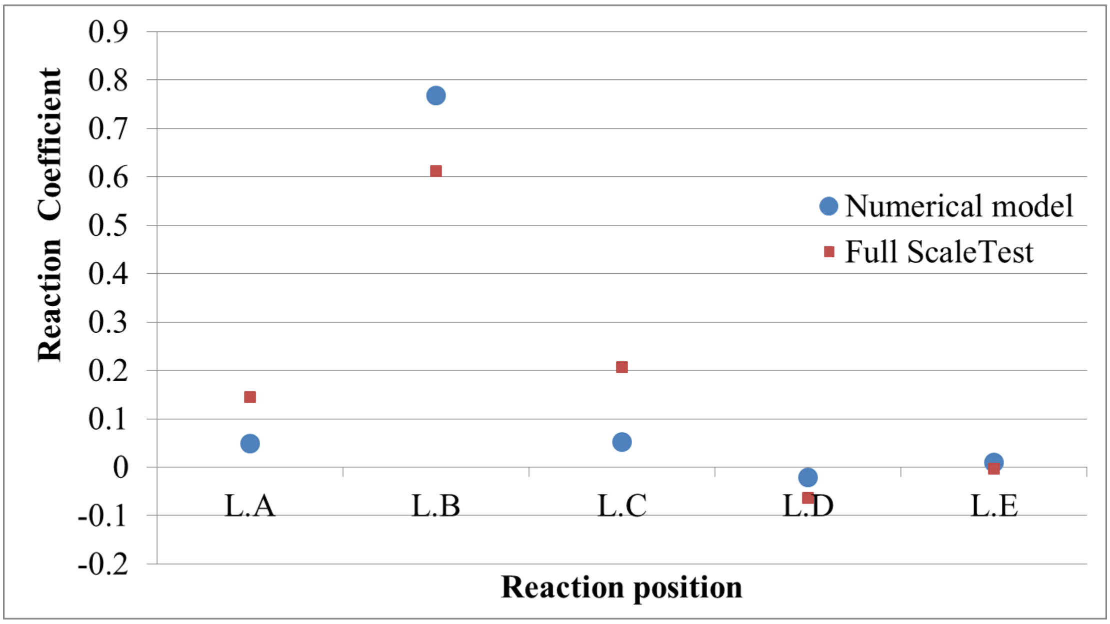


Figure 15. Reaction coefficients determined by numerical analysis and full scale test with load applied to truss B at location B3

3.5 *Conclusions*

This paper focused on understanding the loading effects and load sharing of the roof to wall connection in typical timber framed house structures. A numerical model was developed and the analysis showed that: i) the strength and the stiffness of the roof to wall connection will increase if the structural system has wall lining, ceiling and ceiling cornice installed; ii) adjacent roof trusses share wind loads through connections of roof cladding, battens and top plates, and iii) roof to wall connections are subjected to larger loads if the external load is applied to the edge surface of the roof structure.

Numerical models must be validated by full scale tests. The numerical model of Case 1 produces a good representation of the full scale test load sharing. Both experimental and numerical results will be used as a basis for the development of vulnerability models of timber framed structures subjected to windstorms.

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