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Finite element modelling of the structural response of roof to wall framing connections in timber-framed houses

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ABSTRACT

The structural response and performance of connections are particularly important to assess the vulnerability of timber-framed structures to windstorms. Finite element (FE) analysis using ABAQUS (6.12-3) software is used in this study to determine the structural response and uplift capacities of typical roof to wall connections. Results (i.e. force-displacement relationship and failure modes) of the FE model were compared with experimental tests and the model validated from the test results. The FE model accounts for large deformation as well as the contact between nail and timber through the elastic and post-elastic phases up to failure. The dominant failure modes observed are nails and framing anchor bending, and nail pull out. The FE model produced structural responses and uplift capacities that generally agree with the experimental results. Construction defects (i.e. missing nails) in a roof to wall connection influences the design uplift capacity. Nails located near the centre line of the loading action in a triple grip connection (i.e. common roof to wall connection used in the timber-framed house of Australia) significantly affect the stiffness of this connection. The response of these nails dominated the uplift capacity and failure types of triple grip connection to loading. Missing a nail in both truss and top-plate in the triple grip connection reduces the design uplift capacity by 40% of the "Ideal" triple grip connections. The roof to wall connection subjected to a combination of lateral and vertical loads, gave a connection capacity of about 55% less than the uplift capacity specified in the standards.

The outcome of this study shows that the FE model analysis methods used in this study can be used to assess and predict the structural response and design uplift capacity of the roof to wall connection.

1. Introduction

In the recent past, various windstorms have occurred in Australia such as Cyclone Yasi, Cyclone Larry (2006), Cyclone Yasi (2011) and Brisbane Thunderstorms (2014). They caused severe damage to houses due to high wind loads, construction defects and increased internal pressure. Connections between the structural elements of a timber-framed structure (i.e. cladding to batten connection, batten to truss connection, truss or rafter to top plate connection, top plate to wall frame connection and wall to foundation connection) are critical for ensuring stability and transferring forces from the roof to the foundation. Windstorm damage investigations by Walker [1], Boughton et al. [2], Leitch et al. [3], Morrison et al. [4], Minor [5] and Shanmugasundaram et al. [6,7] have shown that structural failures generally depend on the response and behaviour of connections between structural components. Yet, these connections are generally the weakest components in a timber framed-structure. Load path transfer discontinuity in these connections will result in a reduction in the strength and stiffness of the house structure [8]. Most connection failures can be attributed to construction defects [3] as a result of inadequate quality assurance, missing fasteners, overdriving of nails and improper placement of anchor bolts.

Post windstorm investigations by Walker [1], Boughton et al. [2], Shanmugasundaram et al. [6] indicate an evaluation of the strength, stiffness and the structural response of the inter-component connection is required to assess structural stability of the timber-framed house to windstorms. Response prediction methods should focus on connection stiffness as well as resistance strength (i.e. capacity) to provide reliable and safe connection design and to mitigate failure of houses from windstorms. In

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addition, a full-scale test of a house system is the most reliable method for investigating the structural performance and for validating the sub-assembly testing of houses as well as numerical model that can be used as a cost-effective alternative to full-scale testing. Development of the individual connection model is essential for modelling of a complete house or sub-assembly components (i.e. roof, wall, connections, etc.) ([9–18]). Furthermore, the roof to wall connection of a timber-framed structure experiences tri-axial loads (i.e. vertical, lateral and horizontal directions loads) when it is subjected to wind loads ([12,19,20]). The effect of this tri-axial loads on the roof to wall connection structural responses would be difficult to investigate in laboratory tests. Therefore, this study developed a FE model to evaluate the strength, stiffness and structural response of the roof to wall connection subjected to combination loads (i.e. vertical and lateral loads).

By using the FE model analysis, this paper analyses the response of typical roof to wall connections (i.e. triple grip connections, as shown in Fig. 1) used in Australian house construction, subject to loading. The FE model enables a wide-ranging parametric study (i.e. the effect of construction defects, tri-axial loading of the connections, deformed shape and size of nails and framing anchors) that would be difficult to achieve in laboratory tests. The main features of this paper are:

(1) Developing the FE model with and without construction defects (i.e. missing nails) and validating from the experimental test results. This will enable economic simulation of the various triple grip connections, including locations of fastener installation, with the aim of developing probabilistic distributions of connection strength.
(2) Predicting the design uplift capacity of connections with or without construction defects. Being able to make these predictions would greatly assist experimental tests and result in significant savings in time and cost.
(3) Accounting for the combination of vertical and lateral loading response of the roof to wall connection.

Achieving these features will enable the development of the timber-framed house FE model ([21–23]) and the structural vulnerability assessment of timber-framed housing.

1.1. Roof to wall connection (RWC)

The RWCs connect the roof structure to the wall structure in house structural systems, which is required to resist resultant forces on the roof structure and transfer these forces to the wall top plate and surrounding wall structure. Consequently, for a house structure to survive under extreme wind loading, it is crucial that these connections have sufficient strength to resist these induced actions. A recent experimental study by Satheeskumar et al. [24] has shown that the strength and uplift capacity of the RWC depends strongly on each nail's structural response to loading and the stiffness of the surrounding structure (i.e. framing anchor, timber species).

The performance of roof structure under extreme wind loading conditions mainly depends on the ability of a structure to absorb input loading energy and transfer the load through its elements (i.e. cladding, battens, trusses, and connections). The RWC should be designed to provide continuity in the load transfer path. Discontinuity in the load transfer path may cause severe damage in a windstorm ([4,25]). The response of RWC to loading depends on the framing anchor, nails and the type of timber species. Mechanically fastened joints are the only elements in a timber structure capable of absorbing a large amount of loading energy through plastic deformation of metal fasteners ([26,27]). Thus the behaviour and response of mechanically fastened joints is important for timber-framed structures' responses to wind loading.

The response of a single-nail joint under loading provides a basis for understanding the response of the RWCs. The action of the nail or timber transfers forces in a complex way between the metal nail and the surrounding embedded timber. Foschi [28,29] investigated the behaviour of a connector and the embedment characteristics of the surrounding timber medium by using experimental and empirical models. A single mechanical connector as described in Fig. 2a was used in his study. Foschi [29] found when the connector joint is subjected to load F, there will be a reaction force P from the timber medium. Correspondingly, the connector will deform and adopt a shape $w(u)$, where, u is axial displacement of the cross-sectional centroid of the timber, and w is lateral displacement. The reaction from the timber medium per unit length is assumed to be a function $p(w)$ of the displacement w. $p(w)$ is named as the "embedment" property of the surrounding timber medium. A recent study by Li et al. [30] further developed the embedment function $p(w)$ derived by Foschi [28] and also produced a curve for the response $p(w)$, as shown in Fig. 2b. This embedment function $p(w)$ takes into account the lateral nail deformation, which was not considered in previous study by Foschi [28].

$p(w)$ is expressed as follows,

$$\begin{cases} p(w) = (Q_0 + Q_1 w)(1 - e^{[-K_0 w/Q_o]}) & \text{If } w \leqslant D_{\max} \\ p(w) = P_{\max} e^{\{Q_3 (w - D_{\max})^2\}} & \text{If } w > D_{\max} \end{cases} \tag{1}$$

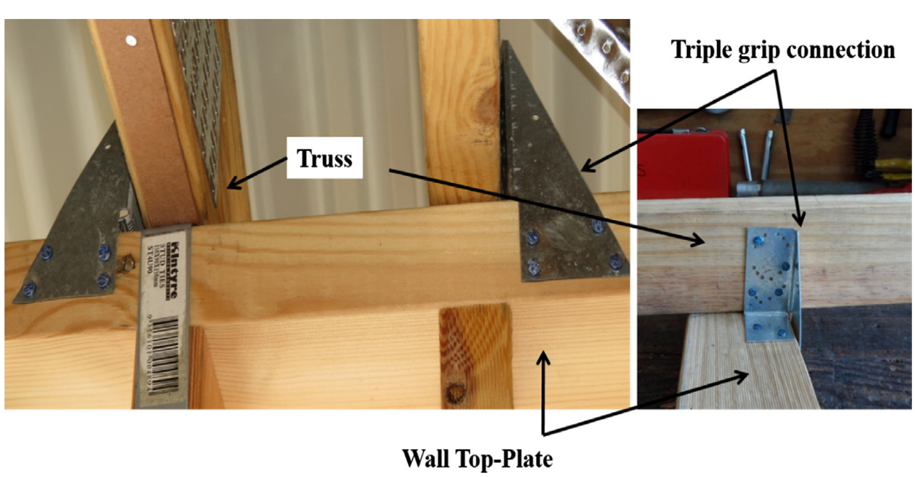

Fig. 1. Roof to wall triple grip connection.