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Load Sharing Between Batten to Rafter Connections under Wind Loading

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Abstract

Single nailed batten to rafter connections of non-cyclonic region houses were tested under quasi-static ramp loads and under fluctuating dynamic loads determined from a wind tunnel study. Dynamic connection testing showed that nails of connections slip during intermittent 'peak events' in the wind load time history with connection failure occurring after several peak events. Non-linear time-history structural analysis was performed on a system of batten to rafter connections where connection testing data were used to model the nominal force-displacement relationships of the nailed connections. This preliminary computer analysis was able to capture the effects of load sharing and redistribution during nail slips and progressive failures.

Introduction

Batten to rafter connections of light framed timber houses are subject to rapidly fluctuating spatially and temporally varying loads during severe wind events. These connections can fail in a progressive or cascading manner where, upon the failure of one connection, loads are redistributed resulting the overload and failure of neighbouring connections. Recent damage surveys have also indicated that the re-roofing of tile roofs with new corrugated cladding using existing battens can make houses especially vulnerable to wind damage during a storm [3] as original connection uplift requirements are lower due to the tile self-weight. Additionally, newer metal cladding is sometimes fastened to every 2nd or every 3rd existing batten, significantly increasing the tributary area of each batten to rafter connection. This paper presents a study of the performance of aged timber batten to rafter connections under fluctuating wind loads experienced when supporting corrugated metal cladding.

A 1/50 scale wind tunnel test was used to determine fluctuating wind loads on batten to rafter connections which were then applied to individual connections using a servo-hydraulic universal testing machine to determine the connection's response to these loads. Additionally, a structural analysis model of a system of batten to rafter connections and cladding was used to determine the load paths, load sharing and the sequence and direction in which failures are likely to propagate.

Connection Specimens

The Cyclone Testing Station (CTS) surveyed a group of 1960's houses in Adelaide to record data for vulnerability modelling. The survey was conducted in the Bedford Park area of Adelaide in collaboration with the Department of Planning, Transport and Infrastructure (DPTI) and the University of Adelaide. Sixteen houses were surveyed, and the structural systems and connection details of the roof and walls were recorded.

Most of the houses surveyed were single storeyed with double brick walls and pitched frame hip and valley roofs. Figure 1 shows a typical 1960's single storey double brick house with hardwood pitched roof framing and concrete tile cladding that was surveyed.

During a second trip to Adelaide, batten to rafter connections from two houses were extracted and sent back to the James Cook University materials testing laboratory for testing.

One of the houses was constructed with hardwood rafters and the other with softwood. Timbers were identified by a specialist using appearance and microscopy of the cell structure. Hardwood rafters were identified as Karri (*Eucalyptus diversicolor*), softwood rafters as Douglas fir (*Pseudotsuga menziesii*) and battens of both houses as Tasmanian Oak (*Eucalyptus obliqua*).

Connections were securely braced (Figure 2) before they were cut away from the roof structure so that they could be interlocked and transported safely via road freight. Rafters and battens were named such that connections on the same rafter and the same batten could be identified. A comparison to moisture contents taken of samples inside the roof spaces of neighbouring houses with the same material indicated that the levels of moisture had not changed significantly during transit.

Figure 1 An example of the typical double brick pitched framed construction surveyed

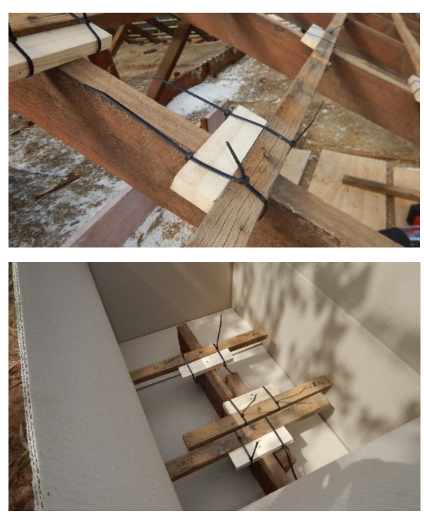

Figure 2 Connections being prepared for extraction (top) and being packed for transit (bottom).

Connection Testing

Laboratory tests were conducted on the hardwood batten to rafter connection specimens. The tests provided data on the performance of in-service nailed connections and enabled quantification of age-related deterioration. Tested samples consisted of:

- Approx. 300mm length Karri Harwood rafter – 120 × 35 mm
- Approx. 300mm length Messmate batten – 25 × 35 mm
- Single flat head plain shank nail – 50 × 2.8 mm

The strength of nailed connections can be influenced by a number of factors; these were recorded for each specimen: 1) moisture content, 2) edge distances, 3) angle of nails, 4) initial gap between batten and rafter, 5) embedment depth of the nail, 6) ring size of rafter timber, 7) orientation of the rings of rafter timber, 8) condition of the nail, 9) any splits in the timber. However, no one factor could be attributed to the performance of the connections upon examination of the testing results.

Static testing

Displacement controlled pull-out tests at a rate of 2.5mm/min were conducted to determine the mean strength of the connections under a slow load rate. A representative load vs. extension plot of a hardwood connection with a strength close to the mean strength is shown in Figure 3.

The connection behaves elastically up to a load of approx. 500 N and reaches a maximum load of approx. 600 N. Connections then display a plastic region where the nails withdraw while maintaining the same load for 5 to 10 mm after which the connection quickly loses its strength with further withdrawal of the nail.

Dynamic testing

Dynamic tests of single batten to rafter connections were undertaken to characterize incremental failure of connections under fluctuating wind loads.

Batten to rafter connections are subject to fluctuating uplift loads due to turbulence of the atmospheric boundary layer and building induced turbulence from flow separation. A 1/50 scale wind tunnel model test was conducted on a gable roof house with a 22.5° roof pitch as described in [2]. For cornering winds, connections near the ridgeline at the gable end experience especially high uplift loads. Load fluctuations at one of these connections are shown in Figure 4. High loads occur in 'peak events' where the load can be more than 3.5 standard deviations from the mean.

Preliminary testing showed that the connection specimens experienced damage only during peak events with low-level fluctuations causing only elastic deformation of the connections. To reduce testing time and for added consistency, a 'synthetic' load trace was created consisting of several peak loads of the same magnitude repeatedly.

The results of the dynamic tests still showed large variability in connection performance, with some connections able to survive only 2 or 3 peaks and some able to survive more than 100 peaks. All showed some ductility as they were able to sustain loads at deformations much higher than their elastic limit.

Figure 5 shows an example of connection behaviour under dynamic loading. The vertical bands in this plot indicate the loading and unloading paths during low-level load fluctuations between peak events. During peak events, the nail slips causing a permanent withdrawal of the nail. As the pressure fluctuations do not reverse the direction of the load on the nail, the connection deforms elastically resulting in another vertical band in the plot between each peak event. In this case, there was an increase in performance after a slight withdrawal of the nail as the magnitude of each slip decreased near the centre of the plot. After about 7mm of nail withdrawal, the connection rapidly lost strength and failed.

The dynamic tests showed that a connection's elastic stiffness, indicated by the gradient of the loading and unloading paths, does not change with accumulated damage through successive peak events. This indicates that load redistribution to adjacent connections occurs when the load acting on that connection exceeds the yield load of that connection causing nail slip, rather than due to a decrease in elastic stiffness.

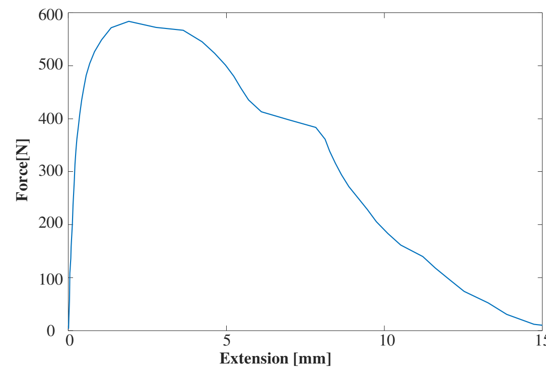

Figure 3 Example of a force vs. displacement curve for static pull-out test of a hardwood batten to rafter connection

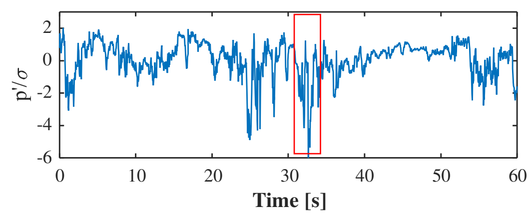

Figure 4 Load time history at a batten to rafter connection showing an intermittent 'peak event'

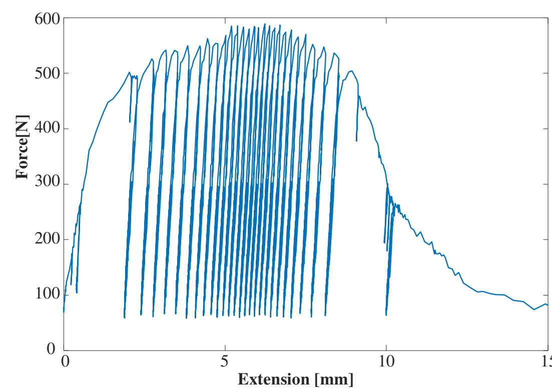

Figure 5 Example of a force vs. displacement behaviour of a hardwood batten to rafter connection under repeated wind uplift peak events

Structural Analysis Model

To determine the characteristics of load redistribution and how a progressive failure may propagate through the roof structure, a non-linear time history analysis using a finite element method structural analysis model was performed. An array of batten to rafter connections representing the connections on a gable roof house were modelled as shown in Figure 6.

Roof cladding was modelled as a thin shell with the thickness selected to give the same flexural rigidity (*EI*) as a 0.42 BMT 'custom orb' cladding profile. A 'stiffness modifier' of 0.1 was applied to the *EI* of the sheeting in the direction parallel to the battens to represent the lower bending stiffness in the direction perpendicular to the cladding corrugations. Battens were modelled as frame elements and batten to rafter connections were modelled as multi-linear plastic link elements, with their force-displacement behaviour determined from laboratory tests. These links were assigned a proportional limit of 0.5kN, plastic deformation for 10mm at 0.5kN and complete failure at 15mm extension. The roof structure below, such as the rafters and roof to wall connections are not modelled.

Quasi-static pull-up analysis

As described in [1], non-linear time history analysis was performed with a quasi-static ramp load (1kN/min) applied at the location of connection T2-B7 (Batten 7 fastened to rafter/truss 2 as shown in Figure 6). The ramp load is continued as the first connection fails and loads are redistributed to neighbouring connections. Selected time steps of colour scale plots showing the redistribution of load are shown in Figure 7**.**

As load is applied above T2-B7, the system behaves as a set of springs in parallel, with part of the load being resisted by the connection T2-B7 itself and the remaining resisted by the batten and the cladding in flexure as well as extension of the neighbouring connections. Uplift loads are thus shared among neighbouring connections even when T2-B7 is undamaged and in the elastic range.

Before connection T2-B7 yields as shown in Figure 7(a), a total of 27% of the load is shared among connections immediately to the left and right on the same batten (T3-B7 and T1-B7). Loads are also resisted along the corrugations of the cladding, with a total of 21% shared with connections T2-B8 and T2-B6. Finally, 15% is shared among connections diagonally away from the loaded connection. These proportions of load sharing continue to the point where connection T2-B7 yields.

After connection T2-B7 yields the proportion of load borne by this connection decreases and the amount of load sharing at all neighbouring connections increases. After connections to the left (T3-B7) and right (T1-B7) yield, shown in Figure 7(b), the loads borne by connections on the same batten reduces and load transferred along corrugations increases. Loads are then redistributed along corrugations to connections T2-B8 and T2-B6.

Once all connections adjacent to the loaded connection yield as shown in Figure 7(c), loads are shared equally among all the adjacent connections including the loaded connection. However, when the loaded connection fails completely as shown in Figure 7(d), loads are redistributed to diagonal connections.

The next connection to fail completely is T1-B7, to the right of the loaded connection. Loads are again redistributed to connections along the corrugations. At this stage a cascading failure commences with loads being rapidly redistributed as connections fail in succession resulting in the failure of all the connections in the study area.

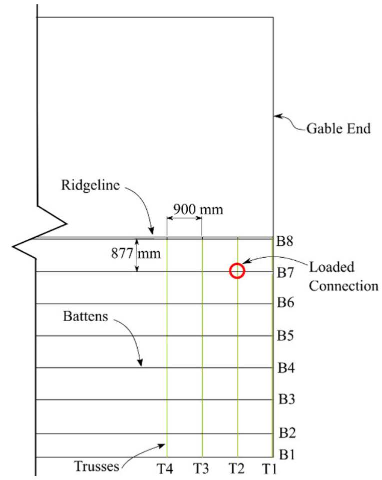

Figure 6 Plan view of batten to rafter/truss connections on the gable roof house modelled in the finite element model. [1]

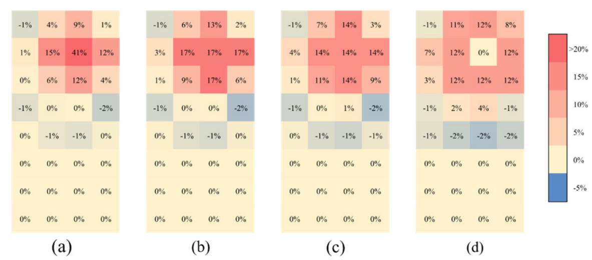

Figure 7 Colour scale plots of batten to rafter connection loads at five time steps showing percentage of the applied load borne by each connection. From left to right: (a) at and before yield of loaded connection, (b) at yield of connections along battens, (c) at yield of connections along cladding corrugations, (d) at failure of loaded connection. [1]

Time history analysis with peak events

Connection T2-B7 was subjected to a repeated peak event as per the dynamic connection testing. A single connection on its own could not be modelled in the structural analysis program as the structure would become a mechanism when a nail slip occurs causing the immediate failure of the connection. Multiple nail slips could be observed during laboratory testing as the hydraulic ram of the testing machine would lose pressure and 'drop load' slightly during each nail slip.

Incremental failure of nails was observed similar to those of the individual connection tests. Each nail slip results in loads being redistributed to neighbouring connections. Figure 8 shows the force-displacement curves of nine connections including the loaded connection with the nail slip behaviour seen in the repeated diagonal bands. Selected time steps when connection T2-B7 begins to slip are encircled and indicate that nail slips at neighbouring connections occur at different times to that of the loaded connection.

Figure 9 shows load time histories at the nine connections showing the increase in loads at neighbouring connections during nail slips at Connection T2-B7. Loads increase at neighbouring connections with little time delay, indicating that loads are redistributed effectively instantaneously to neighbouring connections during nail slips. Additionally, loads are shared and redistributed in similar directions to the pull-up analysis. In this instance the structure becomes unstable after seven peak events, a cascading failure then commences and propagates in a similar manner to that of the pull-up analysis.

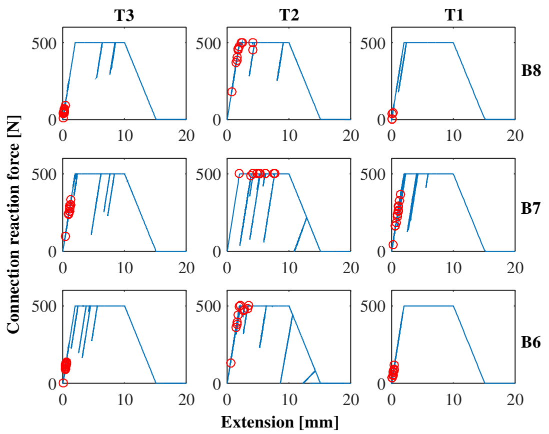

Figure 8 Force-deformation curves of nine connections including the loaded connection showing nail slip behaviour in response to peak events. Time steps encircled indicate instances when connection T2-B7 begins a nail slip. showing that nail slips occur at different times at neighbouring connections.

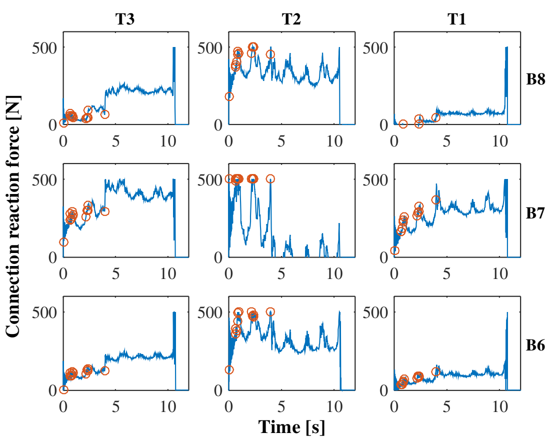

Figure 9 Load time histories at nine connections showing load redistribution during nails slips at the loaded connection. Time steps encircled indicate instances when connection T2-B7 begins a nail slip.

Conclusions

The structural response of aged batten to rafter connections under fluctuating wind loads was quantified by dynamic connection testing using loads derived from wind tunnel data. Dynamic testing showed that connections failed due to incremental nail slip during peak events with their elastic stiffness remaining the same throughout the loading process until failure. Additionally, the connections showed a large variability in performance.

Non-linear structural analysis showed that load sharing and redistribution between batten to rafter connections is a complex process. Loads are shared among neighbouring batten to rafter connections depending on the ratio of stiffness of the battens and cladding as well as the batten and rafter spacing. Additionally, the load path changes whenever a connection yields or fails completely. Connection failure and load redistribution occurs rapidly but in durations similar to pressure fluctuations experienced on the roof surface. Thus, the correlations of wind pressures across the roof surface may play a significant role in the initiation of a progressive failure.

In future work, time history analysis with spatial and temporally varying loads can be used to determine the effects of synchrony of loads at neighbouring connections. Additionally, the effects of variable connection strengths and the presence of defective connections can be examined using the structural analysis model to develop fragility curves for batten to rafter connection failures.

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