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Ductile Timber Connections for Earthquake Resistant Design

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ABSTRACT

The energy dissipating characteristics of a heavy timber structure are almost entirely centered in the connections, which is fundamentally different from steel and concrete structures, where plastic hinges are designed to occur in the members. An added complication of timber connections is the fact that wood is highly non-isotropic and non-homogeneous, which necessitates the use of special techniques to assure adequate ductility levels in the connections to provide good structural performance during an earthquake. This paper summarizes some results from research conducted at the University of British Columbia on the behaviour of timber connections. The main emphasis is placed on composite wood products, such as glue laminated timber and parallel strand lumber.

Reinforcing techniques were applied to low-ductility bolted connections, which significantly enhanced the ductility of the connections. Promising results were achieved through the surface application of fibreglass layers in the connection region. Other techniques including the gluing of a layer of plywood or the application of a truss connector plate. Another very effective technique to avoid splitting in a highly loaded connection is the insertion of glued-in or threaded rods through the wood, transverse to the grain and loading direction.

INTRODUCTION

Timber structures have the reputation of generally performing well during earthquakes. This reputation should not be generalized as it is largely based on the performance of single family residential domestic buildings, which are generally not engineer designed. From many observations in the laboratory and in the field, it has been shown that the connections are typically the weak elements in timber structures and therefore deserve special attention, especially in the case of earthquake loading. Since timber is inherently a brittle material, except when loaded in compression, brittle failure modes in connections are very common and must be avoided in applications where seismic action is expected.

Ductility in connections is important for two main reasons, namely to achieve a reasonable amount of deformation and therefore energy dissipation, and also a more even distribution of load in multiple fastener connections, which can lead to higher strength levels and reduced stress concentrations.

To achieve ductility in timber connections, proper detailing is of utmost importance. By providing adequate end distances for connectors, for example, splitting of the wood can be avoided. It has been observed that in most cases, splitting still is the ultimate failure mode, which typically happens soon after the ultimate load has been reached. For earthquake resistant design, ductility is the prime objective, however, and the post ultimate load deflection behaviour plays an important role. Since earthquake actions typically have a certain deformation demand rather that a load demand, displacement capacity is often more important for seismic applications than strength.

As it is not always possible or feasible to provide ductile connections, the principle of capacity design must be followed. This implies that if a connection or member can be expected to fail in a brittle manner, it must be protected from such an occurrence by the presence of a weaker and more ductile component in the load path that will limit the load that can be imposed on such a non-ductile component. This procedure is clearly intended to prevent any brittle failures, keeping in mind that in an earthquake the inertia loads are very unpredictable and a structural component will attract loads proportional to its stiffness. An example where capacity design is applied is in a shear wall. The hold down devices are typically very brittle and it must be assured that the nailed panel connections will fail or displace before a hold down fails. Because of the large variability in strength of wood components, a relatively large margin must be allowed between the strength of brittle and ductile components to assure that the ductile elements fail first.

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To assess the level of ductility in a connection, hysteresis curves from cyclic load tests on the connections are a good indication. Not only the amount of energy dissipated is of importance, but also the displacement capacity. The ductility ratio is often used to gauge the resilience of a connection. This is the ratio between the ultimate displacement (typically the displacement at 80% of the maximum load after ultimate) and the yield displacement (many definitions for this value exist presently, but the displacement at 50% of ultimate load is often used). A comparison of hysteresis curves for a connection with large bolts (20 mm dia) and glulam rivets clearly shows the difference (Fig. 1).

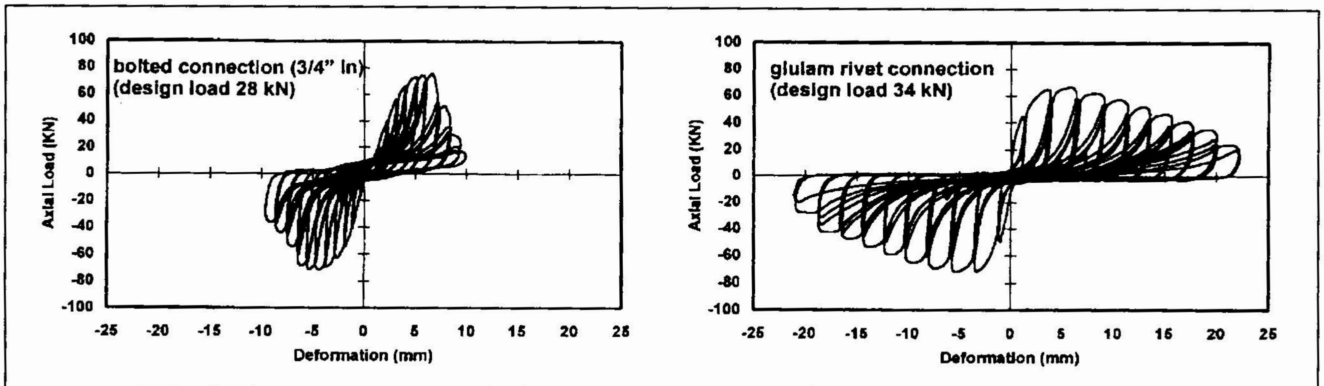


Fig. 1: Hysteresis behaviour of brittle and ductile braced connections

TIMBER CONNECTORS

Nails

The most common connector for wood construction is the nail, which also produces one of the most ductile connections. Because of the relative small diameter of the nail, bending of the nail and crushing of the wood typically occurs before splitting. This is a very effective energy dissipating mechanism with relatively large displacement capacity. Nails are widely used in wood frame construction, where shear walls are the primary lateral load resisting elements. When the proper sheathing is used and nailing patterns are such that wood failures are avoided, shear walls are highly effective in resisting loads and dissipating energy through large deformation excursions. Because of the high level of redundancy, load sharing among the fasteners provides for a very forgiving structural system.

Timber Rivets

Timber rivets, also known as glulam rivets, are oval shaped high strength nails that are always used with steel side plates (Fig. 2). They are driven directly into the wood, with the flat edge parallel to the grain, and the tapered heads lodge into the steel plate, creating a fixed ended dowel. Timber rivets are used for heavy timber construction where high loads need to be transmitted. Because of the relatively close spacing of the rivets, it is possible that a brittle wood failure can occur. Tests on rivet connections have shown that a very ductile behaviour is achieved when a wood failure mode is prevented. This is assured by choosing certain rivet patterns and spacings. The Canadian Code provides two resistance formulae, one for rivet failure and one for wood failure. For seismic design the engineer should assure that the rivet failure capacity is well above the wood failure capacity. Recent tests on rivet connections in braced frames, subjected to dynamic loading on a shake table, have shown that rivet connections provide a reliable means of constructing braced frames. A force reduction factor of R = 2 seemed to be appropriate, based on the tests and analyses using a large variety of earthquakes as input (Popovski et al, 1999).

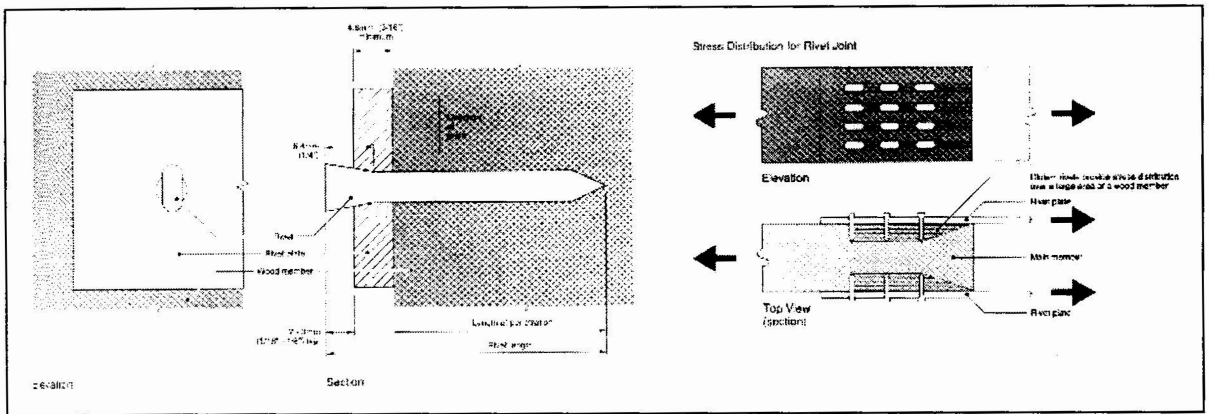


Fig. 2: Glulam Rivet (from Wood Reference Handbook, 1997)

Bolted and Dowel Connections

The design of bolted connections in the Canadian Code (CSA, 1994) is governed by equations that are based on ductile behaviour (European Yield Model) with rules on minimum edge and end distances to avoid splitting of the wood before the ultimate load is reached. Nevertheless, bolted connections almost always fail in a brittle manner, often with very little or no ductility. This is particularly the case for multiple fastener connections where high stress concentrations cause premature splitting or shear failures. The Canadian code prescribes reduction factors for connections with more than two fasteners in a row and for fasteners in more than one row. These reductions are very conservative compared to rules in codes in the US and Europe, which prompted an extensive study into multiple bolt connections (Quenneville, 1998). The aim of this study is to provide rational design equations that reflect the true behaviour of bolted connections.

In Europe tight fitting dowels are often used with embedded steel plates to achieve tight connections with very high force resistance, a pleasing appearance and sufficient fire protection. A more recent development is the use of small diameter high strength dowels to produce high efficiency connections for heavy timber construction. Because of the large number of dowels required, fabrication precision is of utmost importance, which is achieved through the use of numerically controlled fabrication plants. Recent tests have shown that the use of regular steel is preferable when ductility of the connections is an important requirement.

REINFORCED CONNECTIONS

A cost-effective method of achieving ductility in a connection is to reinforce the wood around the connector for added strength perpendicular to grain. This can be achieved with different means, keeping in mind the specific application, fire resistance and aesthetics. Many different methods have been tried and results are typically published in conference proceedings. A few of these are described below to provide designers with guidelines and ideas.

A study at the University of British Columbia has shown that the ductility and resistance of a bolted connection in parallel strand lumber (PSL-Parallam®) tested in static tension can be enhanced significantly by adding reinforcement in the form of a truss plate, fibre glass or a layer of glued-on plywood (Fig. 3).

This study was extended to the use of truss plates in single and ten bolt (2 rows of 5) connections in various sizes of PSL. Combinations of bolt and PSL sizes tested included 12.7 mm bolts in 38x140 mm PSL, 15.9 mm bolts in 89x140 mm PSL, and 22.2 mm bolts in 133x191 mm PSL. The multiple bolt connection for the 133x191 PSL size consisted of four 22.2 mm bolts (2 rows of 2). Average load displacement plots for single bolt connections and 10 bolt connections in the 89x140 mm PSL can be found in Fig. 4. The shapes of these curves are similar to what was found for the 38x140 mm specimens. Average load displacement curves for single and four bolt connections in 133x191 mm PSL can be found in Fig. 5. The results from this study show that for the reinforced single bolt connections, there were gains in average ultimate strength as the reinforcement changed the failure mode from wood splitting wood crushing (Fig. 4a). As well, significant improvements in residual strength after failure were realized, creating a far more ductile connection than the unreinforced connections. Average ultimate strengths did not improve significantly with the multiple bolt connections, as the reinforcement did not change the failure mode of the connection (the dominant failure mode of group shear prevailed in the unreinforced and reinforced ten bolt configurations). This is reflected in the nature of the average load-deflection curve, as the abrupt brittle failures show up as spiked peaks (Fig. 4b). Significant improvements in ductility did occur though, with the residual strengths of the reinforced connections substantially higher than the unreinforced connections.

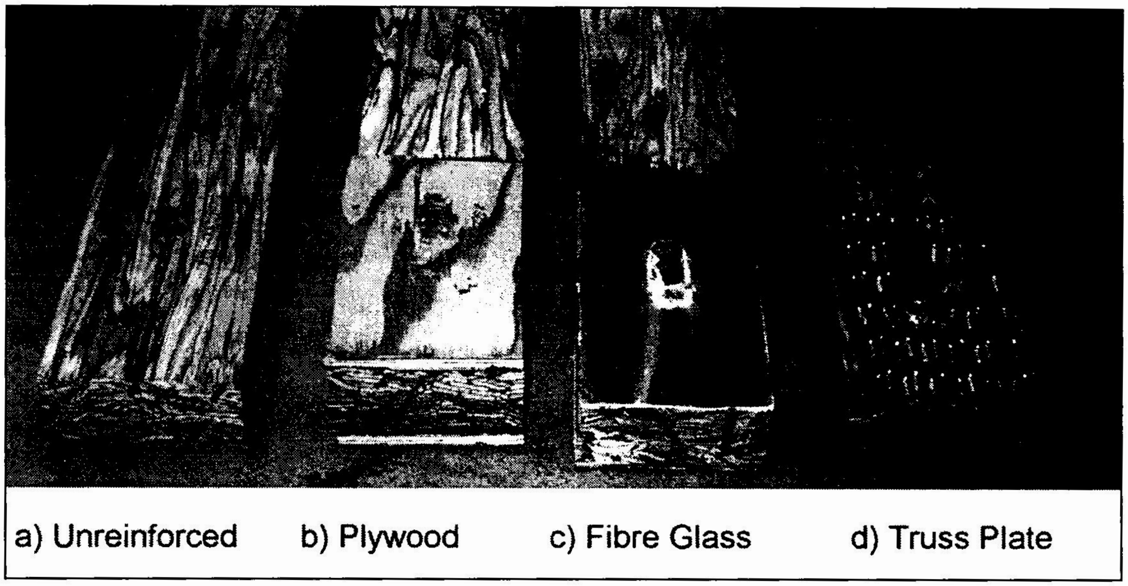


Fig. 3: Reinforced bolted connections in parallel strand lumber

For seismic design this is a very important issue, especially when these connections are chosen to be on the critical path for failure in a capacity design approach. It is therefore not necessary to reinforce all the connections, only the ones that are expected to undergo significant deformations and are expected to be energy-dissipaters.

As Fig. 5b shows, the average load displacement curve for the four bolt connection specimens is less jagged than the multiple bolt average curves in the 89x140 mm PSL specimens (Fig. 4b), as the failure mode consisted of wood bearing and splitting rather than group shear. Each connection was designed according to CAN/CSA 086.1-94, with end distances of 10 bolt diameters and spacing of 4 bolt diameters. As Fig. 4 and 5 show, the code connection strengths are well below the average test values.

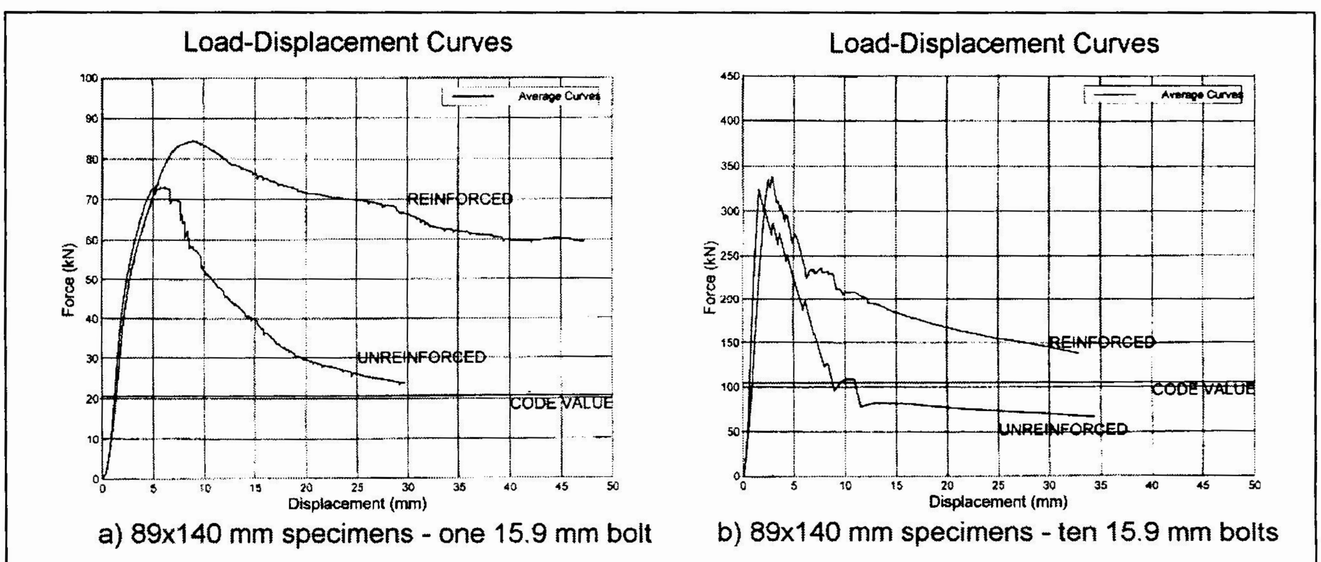
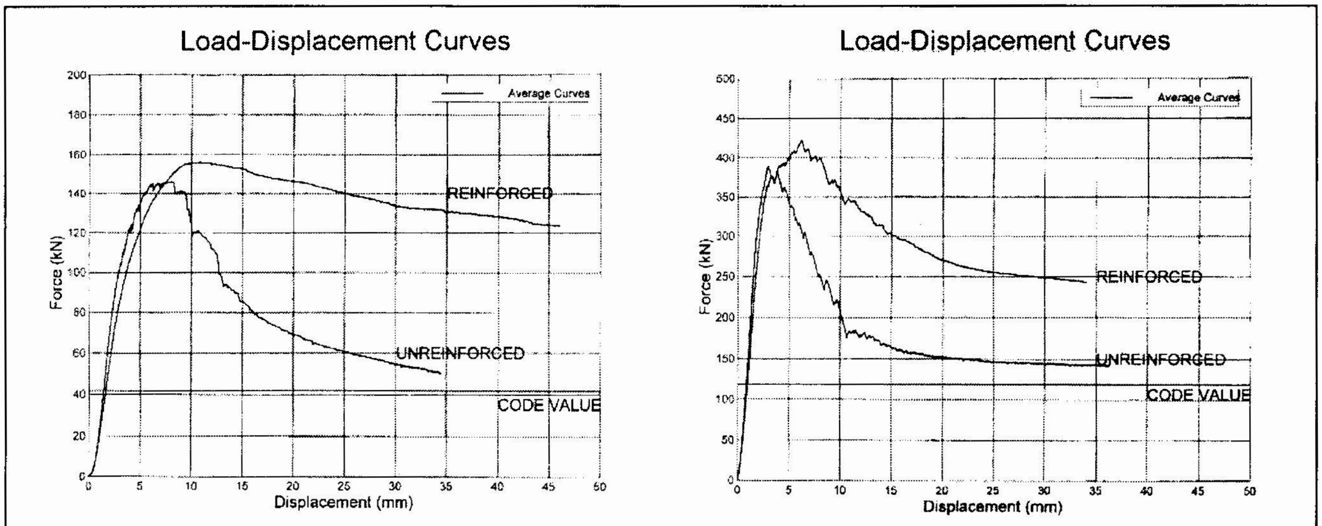


Fig. 4: Average load-displacement curves of unreinforced and reinforced connections in 89x140 mm PSL (a) single bolt connection (b) ten bolt connection (2 rows of 5 bolts)



a) 133x191 mm specimens - one 22.2 mm bolt   b) 133x191 mm specimens - four 22.2 mm bolts

Fig. 5: Average load-deflection curves of unreinforced and reinforced connections in 133x191 mm PSL (a) single bolt connection (b) four bolt connection (2 rows of 2 bolts)

As previously mentioned, there are limitations to the benefits of external reinforcement depending on connection size and configuration. Larger cross sections or connections with a large number of bolts seem to need a different reinforcing approach. A relatively simple and inexpensive means of reinforcing a connection is to insert reinforcing rods perpendicular to the grain and the bolts. These rods could be glued in with epoxy or one could use threaded rods driven into tight fitting holes. The latter is a less cumbersome method and might be more appealing, while being very effective. A study at UBC with various reinforcement patterns tells an interesting story:

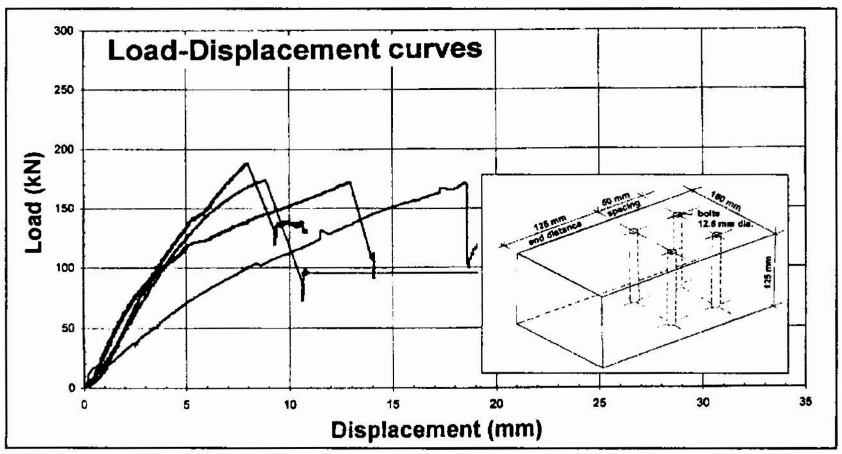


Fig. 6: Unreinforced bolted connection tests in glulam members

A set of four connections with four bolts each were tested without reinforcement and produced the typical response: varying load capacities, little ductility and brittle failure modes (Fig. 6). When threaded reinforcing rods were added halfway between the bolts, a significant improvement was achieved in both strength and ductility (Fig. 7). Furthermore, the test results were more consistent. The reinforcing rods themselves fulfilled only one purpose, namely to strengthen the wood in the perpendicular to grain direction.

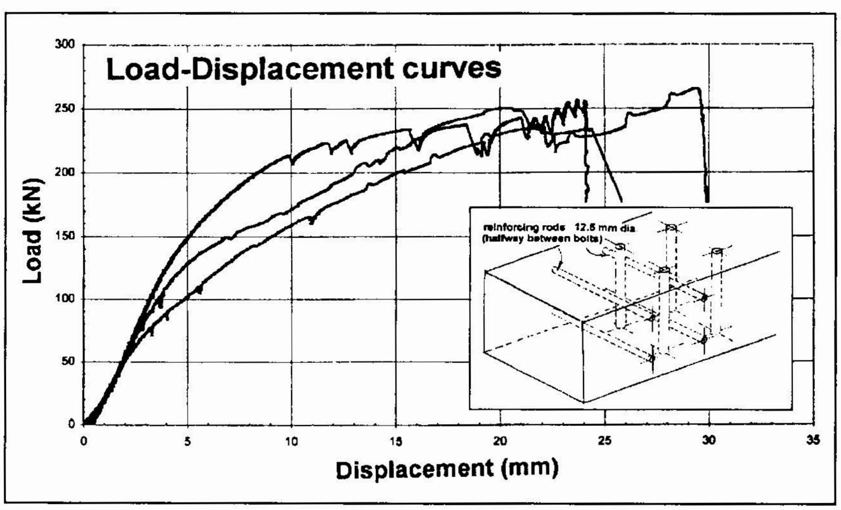


Fig. 7: Reinforced connection response (passive reinforcement)

Another group of similar connections was tested, this time with the rods against the bolts (Fig. 8). In this case the rods not only prevented splitting, but also helped in transferring loads from the bolts into the wood, thus forming a grid of connectors. The resistance of the bolts showed a significant increase, as before, but the failure was a tension fracture across the section at the bolt grid furthest from the end – a typical net-section failure. This is an example where the reinforcement rods were used to enhance the effectivity of the connection by actively participating in the load transfer mechanism. In doing so, ductility was lost and brittle failures dominated the behaviour after the maximum load was reached. This is not a desirable condition for connections that have to undergo significant deformations in an earthquake. This examples serves to reiterate that the engineer needs to be cautious when designing connections for ductility and a good understanding of the material and the load transfer mechanisms is of crucial importance. Cyclic testing of reinforced connections are presently being done to establish energy dissipation capacity and degradation under repeated cycles of displacement. These tests will be followed up by shake table tests of model frames.

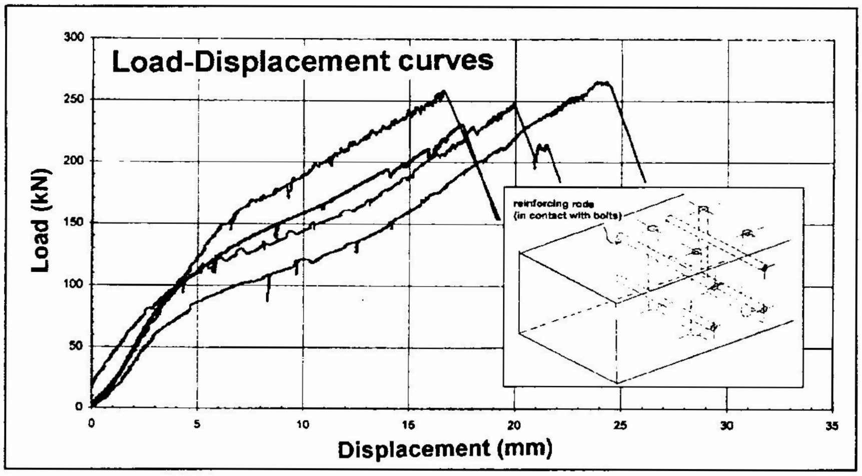


Fig. 8: Reinforced connection response (active reinforcement)

CONCLUSION

The design of connection for timber structures is to a large extent an art of engineering. The designer needs to have a thorough understanding of the materials he/she is working with and utilize the advantages of these (e.g. the ductility of steel and of perpendicular to grain deformations in wood), while avoiding the inherent weaknesses (e.g. the low splitting strength of wood). Ductility of connections is a very important concept, not only for seismic applications, but also to assure more even load distribution and more reliable connections. Designers need to look beyond the stiffness and strength of a connection and seriously consider the potentially brittle failure modes when deciding on a specific product. After all, no design is perfect and the more one can achieve forgiveness in connection response, the better are the chances for load redistribution in a structure when unforeseen events threaten its integrity. With all the science and experience around, we are still repeatedly stunned by the forces unleashed in an earthquake or a hurricane, forcing us to re-evaluate current design practices. Redundant and ductile structures have time and again shown that this is the direction for future development in timber design.

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