Ductile timber connections: Understanding the factors contributing to their ductility

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ABSTRACT

It is well accepted that ductility in a timber structure is achieved through its connections as the behaviour of timber is inherently brittle. It is thus important to understand the different parameters that contribute to the ductility to optimise this as much as possible and ensure that there is sufficient robustness in the connection design to achieve the target ductility. Timber designers can design ductile connections with relative ease using the European Yield Model. However, what is not well understood is how to control the level of ductility, i.e. the amount of deformation after the onset of yielding. Experimental studies have been conducted to identify what controls the resistance and limits the amount of deformation in timber connections. In this paper, the different factors affecting the amount of deformation in a ductile connection will be presented and discussed. Experimental data validating the effects of these parameters will also be shown. The goal is to empower designers to control the amount of ductility in timber connections.

1 BACKGROUND

As timber members typically fail in a brittle manner, connections are the component of a timber structure dissipating energy through large deformations (Brühl, Kuhlmann, & Jorissen, 2011). This allows the structural integrity of the timber structure to be maintained during earthquakes. The failure modes of timber connections can be described as either ductile or brittle. Ductile connections will undergo a combination of crushing of the fibres and bending of the fasteners ***before*** the timber connection will ***ultimately*** fail in a brittle manner (generally). Thus, an accurate seismic design can't be undertaken in timber structures without the specific knowledge of a ductile connection entire load-displacement behaviour. Up to now, as the crushing of the timber fibres results in a gap and significant loss of stiffness in the structural system, the design philosophy for ductile timber connections has been to use a multitude of small ductile fasteners.

However, as crushing is still involved, pinching will be observed, as shown in Figure 1, which is the result of the residual capacity of the fasteners in bending during the cyclic loading.

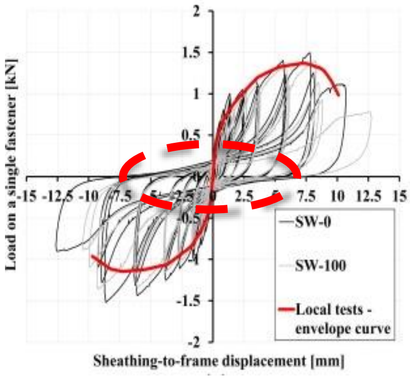


Figure 1: Load-deformation curve for a nailed connection under cyclic loading showing the envelope curve and residual capacity of the fasteners in bending (supplied by M. Popovski).

The ductility of a connection is defined as the ratio of the ultimate displacement at failure to the yield displacement (Δ_u / Δ_y). The amount of deformation that can take place prior to the ultimate failure (not necessarily the one that governs the resistance) is thus the main criterion that dictates the amount of ductility that a connection can offer. These values have traditionally been obtained experimentally, which is not practical on an individual project level.

2 TIMBER CONNECTIONS

In the upcoming version of the New Zealand timber design standard (NZS 2020), the capacity of connections is defined as the minimum of the ductile and brittle failure resistances. However, this design approach considers the behaviour up to the ultimate capacity and does not account for the amount of deformation that can be observed. A brittle failure occurs when stress concentrations exceed the wood fibres resistances in shear or in tension and lead to sudden rupture of the timber. The brittle failure modes of connections can be characterised as row shear, group tear-out, splitting, block tear-out and net tension failures (Quenneville and Mohammad, 2000). A timber connection ductile failure is best described by the European Yield Model (EYM), assuming that plastic deformation of the wood fibres to occur through crushing of the members in bearing (Modes I and II) and the formation of plastic hinges in the fastener (Modes III and IV), as shown in Figure 2 for a fastener in double shear. Different ductile failure modes are possible for fasteners in single shear but to simplify the discussion in this paper, the double shear case will be referred to mostly. The EYM equations predict the ductile capacity of connections, based on these four modes.

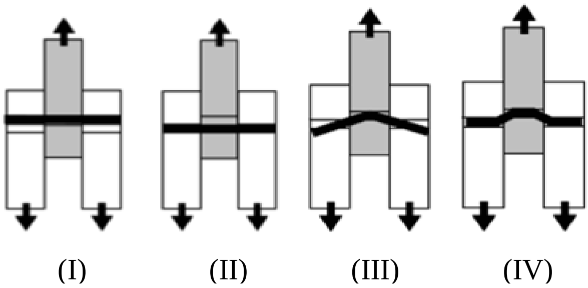
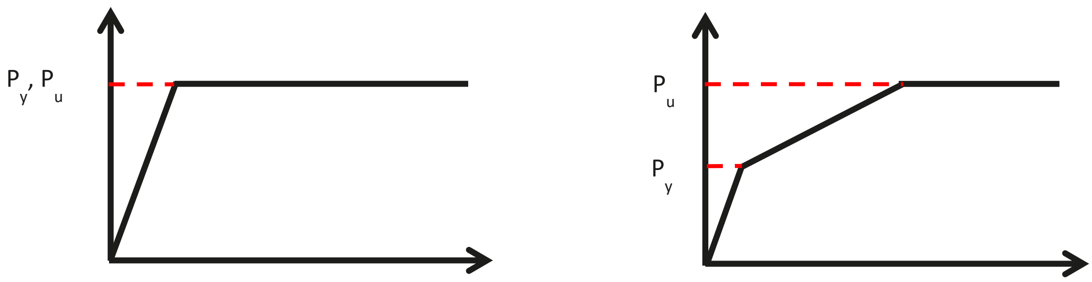


Figure 2: Ductile failures for a timber fastener in double shear (Quenneville & Mohammad, 2008) with their associated load-deformation relationship.

The ductile capacity, dependent on the wood crushing resistance and the connector yielding moment resistance, is taken as the minimum capacity of the applicable EYM modes. A ductile failure is recognised as the ideal primary failure mechanism to control the resistance. A secondary failure may occur in one of the brittle failure mode to govern the amount of deformation. This typically occurs suddenly. An additional set of capacity equations to represent the brittle failure modes are also available for both large and small dowel-type fasteners (Quenneville and Morris, 2009, Zarnani, 2013). The resistance to each brittle failure mechanism is recognised to be dependent on the tension and shear strength of the timber and the configuration of the connection. The capacity of the connection is thus governed by the minimum of all the failure mechanisms; both ductile and brittle. This approach forms the basis of the timber connection chapter in the upcoming version of the New Zealand timber design standard.

2.1 Load-deformation curves and ductile failures

The load-deformation curve of a ductile connection will be as shown in Figure 3. In all of the ductile modes of failure, the design load can be determined using the EYM equations. For modes I and II, the design load is governed by the bearing resistance of either of the connection material where the crushing occurs. For modes III and IV, the design load is governed by the combination of the fastener bending and wood fibre crushing and is identified on the load-deformation curve as the first inflection point. It must be noted that for modes III and IV, this first inflection point does not constitute necessarily the maximum load that the connection can resist. Ultimately, the bearing resistance of either of the connection material can become the maximum load.



(a) (b)

Figure 3: Load-deformation relationships for double shear ductile connections, (a) modes I and II and (b) modes III and IV.

Timber connections are designed with fasteners that are characterised as dowel-type fasteners. Typically, if the diameter or largest cross-sectional dimension is 6 mm or less, the fastener is a small dowel-type fastener. Bigger than 6 mm, then it is identified as a large dowel type fastener. The other important characteristic of timber fasteners is their ability to resist some axial component. This capacity becomes important even in connection configurations where the fasteners are resisting the load in shear. Examples of ductile failures are illustrated in Figure 4.

Figure 4: Typical timber connection ductile failures, from left to right; screw, nails, bolt, rivets.

2.2 Load-deformation curves and brittle failures

When a timber connection fails in a brittle failure, the resulting load-deformation curve will have one of the four different patterns, depending on the governing ductile failure had the brittle failure not occurred. These four patterns are shown in Figure 5.

The occurrence of a brittle failure is normally the result of smaller spacings between fasteners. It can also be triggered by small connection end and edge distances.

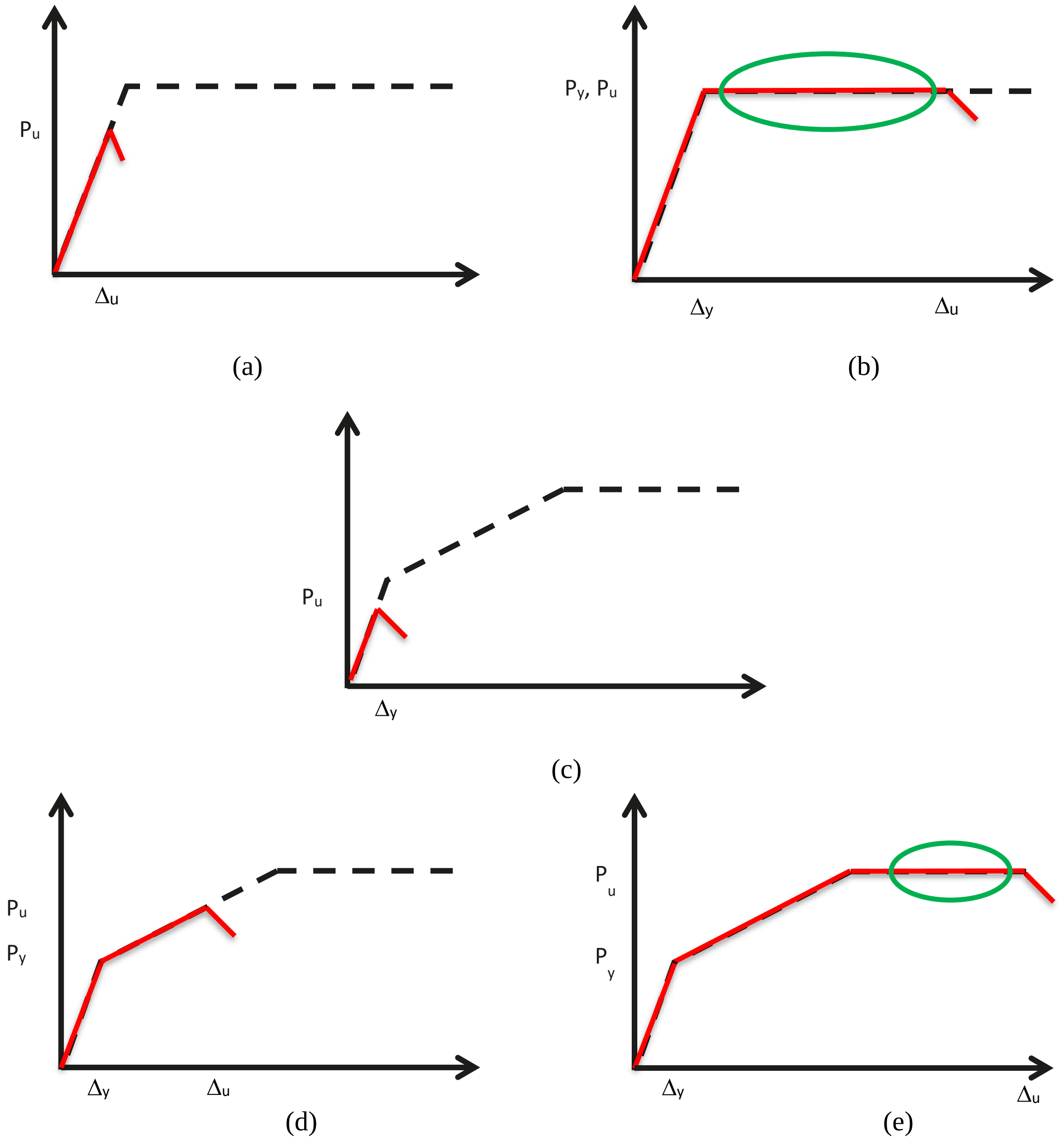


Figure 5: Load-deformation relationships for double shear brittle connections, (a) and (b), modes I and II and (c), (d) and (e) for modes III and IV.

In Figure 5(a), the fastener is stocky and stiff enough not to bend. The bearing resistance of the timber is governing the ductile resistance. However, before the onset of the fibre buckling, a shear failure, tension or a combination of both, occurs in the timber. The connection has not shown any signs of yielding.

For Figure 5(b), we have the same fastener and again, the bearing resistance is governing the ductile resistance. In this instance, there is sufficient timber around the fasteners not to create stress concentrations in shear and in tension and the bearing resistance is overcome. The ultimate load is attained and does not increase with increasing deformation. A gap forms between the fastener and the timber as the load cycles from tension to compression. Ultimately, there is insufficient wood material between fasteners and at the end distance and a secondary failure (brittle) is triggered. The ultimate displacement is attained. The connection exhibit a large amount of ductility (looking good for monotonic loading) but this type of load-deformation envelope is not recommended for cyclic loading as the pinching resistance is zero and leads to very low residual stiffness of the connection. It is best to reduce the area circled in green to a minimum.

In Figure 5(c), the fastener is not necessarily stocky but relatively, the shear or tension resistance of the fibres are very low and there is also a sudden failure before any onset of fastener yielding. In both load-deformation curves 5(a) and 5(c), the connection has no ductility.

In Figure 5(d), yielding in the connection is observed and the P_y is observed. The fasteners have yielded and there is portion of the wood that is failing in bearing. Deformation in the connection continues to increase. However, along the axis of the fasteners, not all of the fibres have reached their bearing capacity before the appearance of a brittle failure that limits the connection capacity, triggered by a shear or tension failure in the fibres. Another possibility for this brittle failure is that the fasteners pull out of the timber after exhibiting a significant amount of deformation (see Figure 4 for the rivets). This pulling out of the fasteners is possible for screwed, nailed or riveted connections. The brittle failure governs the connection ultimate load P_u and ultimate deformation Δ_u. The connection exhibits some ductility. Even if research studies have made some significant findings in this area, the state of the art in design equations for brittle behaviour is not yet capable of predicting the ultimate load for this case.

In Figure 5(e), yielding in the fasteners has occurred and the P_y is observed. The load has been able to increase up to the point where along the entire axis of the fasteners, all of the wood fibres have reached their bearing capacity. The connection has reached its ultimate load resistance which is governed by the wood fibres bearing capacity alone (Mode I or II of the EYM). After reaching the load P_u, the resistance does not increase and the connection deforms as much as the demand forces it to. Ultimately, the deformation in the connection results in the quantity of wood fibres between the fasteners and in the end distance to decrease and this results in a decrease of the shear resistance of the wood surrounding the fasteners. The brittle failure that is triggered at that point governs the ultimate displacement of the connection, Δ_u. This scenario depicts a condition where the connection ductility is at its maximum. However, in a cyclic load situation, the portion of the curve where the load does not increase is problematic as there is no residual stiffness and the pinching resistance is zero. It is best to reduce the area circled in green to a minimum.

3 HOW TO INCREASE DUCTILITY IN TIMBER CONNECTIONS

As the ductility of a connection is defined as the ratio of the Δ_u over the Δ_y, it is thus simple to say that to maximise the ductility of a timber connection is to use a very stiff fastener (to have a very small Δ_y) and detail the connection configuration to have the largest Δ_u possible. Once the timber members are sized and graded and a fastener is selected, the Δ_y is more or less set and the remaining detailing decisions will only influence the value of the Δ_u. To obtain the largest ultimate displacement, one has to ensure that a brittle failure triggered by shear and tension occurs at the largest displacement possible. This can be achieved in two ways:

- by detailing large fastener spacings and large end and edge distances, in other word, engage as much wood fibres as possible in resisting the load.

- by using means to avoid longitudinal shear failures in the wood fibres by reinforcing the member in the vicinity of the fasteners. This can be achieved using transverse self-tapping screws, metal-toothed plated, or any other means that will increase the longitudinal shear resistance.

3.1 Dowel-type connections in single shear

The following recommendations are applicable to screwed, nailed and riveted connections, where the fasteners are working in single shear.

The diameter of those fasteners is relatively small and the EYM modes III and IV will most likely govern the design. However, the difference between a load-deformation curve 5(d) or 5(e) is set by the length of the fastener. Following the onset of yielding of the fasteners, which occurs in the portion of the fastener closer to the connection shear plane, the tip portion of the fastener is relatively unloaded laterally and anchors the head portion of the fastener. The longer the "laterally unloaded" portion of the fastener is, the more lateral displacement the connection can sustain without the fasteners losing their axial resistance and pulling out. It is also possible that the brittle failure governing the P_u of figure 5(d) is triggered by a block tear-out resulting from stress concentrations in the wood fibres.

3.2 Dowel-type connections in double shear

The following recommendations are applicable to bolts and dowels connections, where the fasteners are working in double shear. Specify fasteners of the lowest grade possible and with a small diameter and determine the required number so that the governing P_y of the connection is higher than the design load. The material grade of the fasteners should allow for as much yielding and reverse cycling as possible. The governing ductile mode of failure should be IV (III is also acceptable). Not all steels will provide this latest capability. Detail the connection so that the brittle failure modes resistances are higher than the P_u of the ductile connection (EYM modes I or II). The variability of this P_u value is very small (5 to 10% maximum) and ensures that the connection over-strength factor is well defined. The resistance of the brittle failure will start to decrease the instance that yielding in the connection is observed (Novis et al., 2016). The target is to obtain a load-deformation curve that will reach the ductile Pu value but not too much beyond. One needs to realise that the higher the values of the brittle failure mode resistances are, the larger the fastener spacings and the more costly the connection will be. Ideally, the load-deformation curve of the connection will be as shown in Figure 6. The resistances of the brittle failures are shown (set constant within the elastic region of the loading) and decreasing following the onset of yielding and should be approximately 10 to 20% higher than the P_u value.

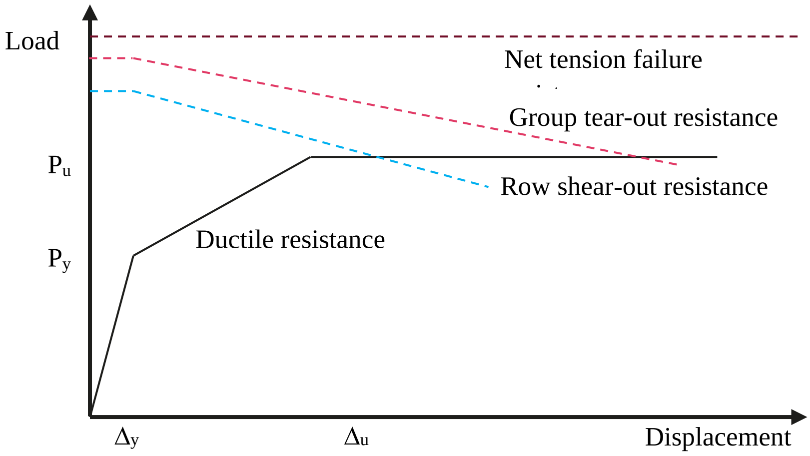


Figure 6: Target load-deformation relationship for double shear ductile connections showing brittle failure modes resistances.

4 CONCLUSIONS

The ductility of timber connections is significantly affected by the amount of wood fibres surrounding the connection fasteners; the more spacing there is between fasteners, the less likely a brittle failure will prevent the connection to reach its intended ductile failure. However, there are additional connection details that can result in higher ductility values. They are:

- Detailing the connection to have brittle failure resistances higher than the P_u of a ductile mode of failure. At this point in time 10% to 20% above is believed sufficient.
- For single shear connections, use longer fastener to increase the fastener axial stiffness and resistance and prevent fastener pull-out. This will increase the P_u without changing the P_y.
- Transverse reinforcement to prevent shear failure planes to occur. This can be done using screws, threaded rods, toothed metal plates, etc…

4.1 References

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