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A NOVEL TIMBER CONNECTION WITH EXCEPTIONAL PROPERTIES

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SUMMARY

Connections are mostly the weakest link in a timber structure. The last decade a novel connection was developed that combined reliable high strength and stiffness with excellent ductile properties, the so-called tube connection. The steel tube fit on over-sized holes that ease the assembly of the timber members. By expanding the diameter of the steel tube a perfect tight fit is realized. To prevent timber splits when the tube diameter is expanded densified veneer (ply)wood is glued on the timber members as reinforcement. Although mainly tested in monotonic loading conditions recent tests were performed to determine its hysteresis behaviour. Unprecedented energy dissipation capabilities were recorded with equivalent viscous damping ratios (EVDR) up to 0.35 in comparison with other timber connections, which usually have EVDR less than 0.20. Applied in timber frame structures its seismic performance will be enhanced considerably and a more competitive structural timber design in earth quack prone areas is within reach.

INTRODUCTION

One of the important parameters for seismic resistance of a structure is its energy dissipation characteristics. Reverse-cyclic tests can provide a measure of the energy dissipation capacity of a structure. In timber structures the connections are the only structural parts where energy dissipation will occur as the timber itself behaves elastic. On the other hand the timber connections are the weakest link of the structure and therefore the strength, stiffness and ductility of the connections is of great importance. In heavy timber structures the use of dowel type fasteners like dowels and bolts are very popular. However, for all dowel type fastener connections pinching of the hysteresis loops are commonly observed when the loads reached moderate levels. The pinching phenomenon can be attributed to the enlargement (usually elongation) of the original hole in the wood occupied by the dowel as it reacts against the wood causing non-recoverable embedment deformations. Pinching is an undesirable characteristic because it magnifies the reduction of the structure's capacity to dissipate energy. There is no escape from this draw back unless special devices are used such as friction dampers, Duff et al.[1]. Not withstanding the excellent energy

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dissipation of these friction dampers they have a limited applicability and require a special technique to incorporate them into the structural timber elements. One of very many examples of pinching is shown in Figure 1 for a connection with slotted in steel plates and slender dowels, Schreyer [2]. These types of timber connections are currently very popular because of the high strength capacity. Still, comparing the bending moment capacity of the connection with the connecting timber members shows values not higher than about 40%, Mischler [3]. Also heavy reinforced high capacity connections with dowels where the strength capacity is close to the strength capacity of the timber members are no exception as shown by Kasal et al. [4], Figure 2. The solution of this problem is definitely the use of the solid steel dowels.

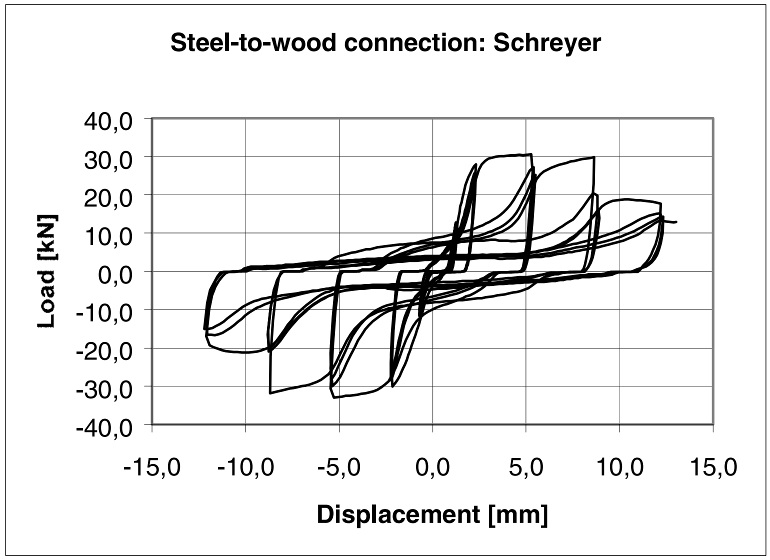

Figure 1: Example of pinched hysteresis loops, Schreyer [1]

Another reason why dowel-type connections should better not be used as moment transmitting connections of statically indeterminate structures is the unreliable stiffness. This is caused by the fact that easy assembly requires some hole clearance. Consequently, the stiffness properties vary a lot. The development of a novel timber connection better known as the tube connection showed not only exceptional mechanical properties in monotonic loading conditions, Leijten [5], but also higher and more reliable strength, stiffness an ductility properties. Therefore tests were carried out to assess its behaviour for reversed cyclic load tests.

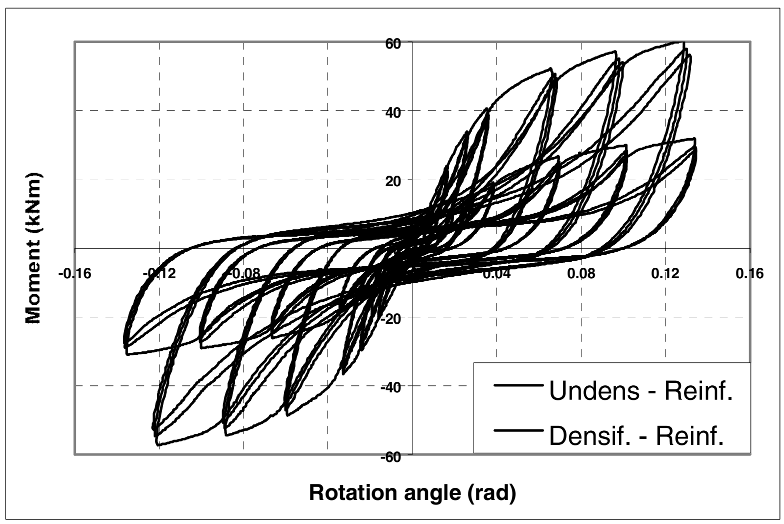

Figure 2: Hysteresis of two types of reinforced timber

A NOVEL TIMBER CONNECTION

Recent advances in timber engineering connections have been reported by Larsen and Jensen [6] and mentioned a novel heavy timber connection the so-called tube connection developed by Leijten [5]. This Two main features, which clearly distinguish the tube connection from bolted or other dowel-type connections is the use of reinforcement, DVW and a special fastener, the expanded steel tube.

Denisified veneer wood, DVW

Leijten [7] was the first to proposed densified veneer wood (DVW) to locally reinforce the timber in the connection area by gluing sheets on the timber members. Main reason for the reinforcement is to prevent timber splits, which in most cases lead to failure of the connection. The DVW can be regarded as high strength plywood.

In short the production of DVW is characterised by the heating and compression of stacks of cross-wise layered veneers up to density of 1300-1400 kg/m^3 and followed by cooling down to normal temperatures resulting in proportional increase of the strength properties. The Austrian Pfleuner brothers invented the commercial production process still in use since 1922. Familiar trade manes for this material are Staypack and Lignostone. An important key for high strength connections with dowel type fasteners is a high bearing or embedment strength. Not only is the splitting strength of DVW very high due to the cross-wise layered veneer structures of the plywood also the embedment strength is no more than seven times higher than the embedment strength of structural timber. Evaluation of the embedment test data revealed that the density significantly affects the embedment strength while other influences such as load to grain angle and bolts diameter can be neglected, Leijten [5], Figure 3. For a maximum density of 1400 kg/m^3 a mean embedment stresses of 155 MPa are attained. Another advantage as a result of the high resistance against splits is that edge and end distances can be smaller than used in bolted connections. To glue DVW to the structural wood requires no new techniques are required as DVW is wood based and therefore easy to glue with standard type adhesives. It is glued at the spot were otherwise the first cracks appear namely at the interface of the individual timber members. Figure 4 shows a typical column-beam assembly with one middle member and two side members.

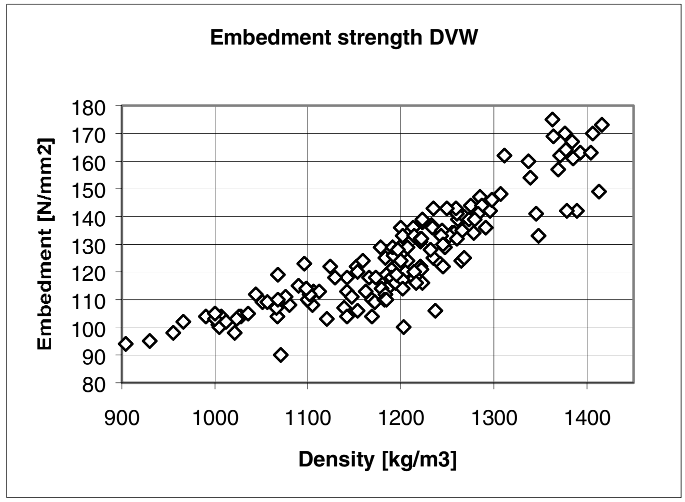

Figure 3: Embedment results of densified veneer

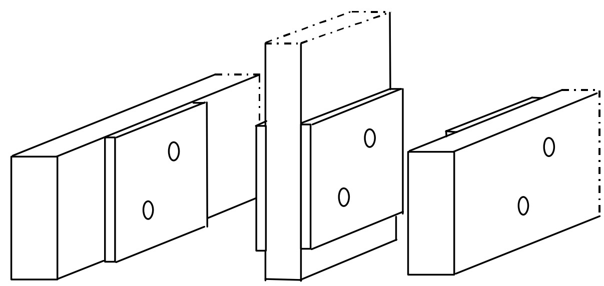

Figure 4: DVW glued on timber column-beam

Expanded tube fasteners

Instead of solid dowel-type-fasteners like bolts or dowels a steel tube is used. The steel tube has a particular over-length, which means that its length is more than the total thickness of the assembly and fit into oversized holes. Specially, the oversized holes ease the assembly of the members in practise. After the tube is inserted the diameter of the tube is increased. This result in a perfect tight fit and immediate load take up, Leijten [8]. In this respect the use of a steel tube is essentially different from the tubes proposed by Guan and Rodd [9]. They adopted the concept of DVW reinforcement but used rein injection to fill up the voids between the oversized hole and the steel tube, which was not expanded in diameter. However, the quality production control procedure appeared to be a drawback of this method. Besides this connection using the resin-injected tubes behaves quite similar as the connections with the expanded tubes Guan and Rodd [9]. Figure 5 shows two stages in the production of the expanded tube connection. A three-timber member assembly each having a DVW sheet glued to the interfaces of the connection is shown. The ends of the over-length tube fit into dies, which are pushed inwards by the hydraulic jack. Due to a central rod the tube can only buckle outwards by expanding in diameter. The material surrounding the hole resists this motion and is pre-stressed specially were high strength DVW is located. Diameter increases of 1 to 2 mm for tubes of 17 and 33 mm diameter have been observed. Typical was the higher degree of expansion perpendicular to grain compared to parallel to the grain direction. As mentioned earlier the monotonic tests revealed that proper expansion lead to immediate load take up, high and reliable strength, stiffness and excellent ductility. Figure 6 shows a cut open tube after assembly where all clearance is vanished.

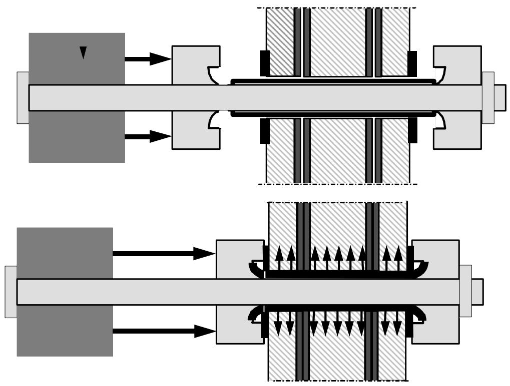

Figure 5: Expansion of the tube diameter

Figure 6: Cut open specimen

CYCLIC TESTS

Moment transmitting T-shape specimens were considered with four tubes located at each of the connection corners, Figure 7. Truss Joists Macmillan, a Weyerhaeuser Business supplied structural composite lumber (SCL) as test material: LSL (Laminated Strand Lumber) and PSL (Parallel Strand lumber). The vertical member of the T-shape specimens consisted of a double (side) member while the horizontal (middle) member was single member. Lignostone International Inc. supplied the DVW (densified veneer wood) sheets that were glued onto all separate elements at the interface of the connection. The largest specimens had DVW sheets of 480x600mm while for the smaller specimen 280x280mm sheets were used. For the large connection 28 mm diameter zinc coated mild steel tube were used for the smaller 18 mm diameter tubes. With four tubes in the connection corners the bending moment transmitting capacity would stay below the bending strength capacity of the members and to check for the loaded edge distance. However, with four tubes the bending capacity already came close to the design bending capacity of the LSL and PSL members. A purpose build measuring device specially tailored to measure accurately small relative rotation and translation of the connection members was used. With three transducers on each side all movements of the side members with respect to the middle members could be detected, one rotation and two displacements.

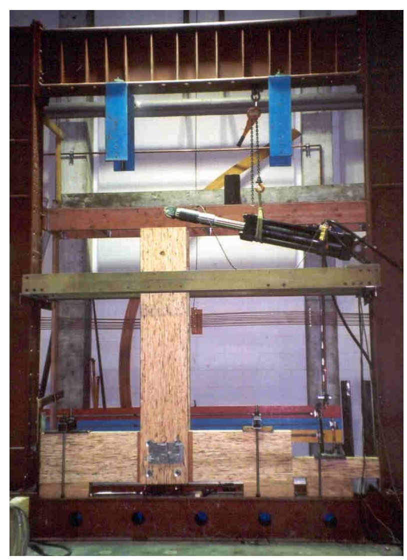

Figure 7: Test frame with T-shape specimen

Test procedure and load protocol

Standardized reverse-cyclic load protocols for hysteresis tests such as the European load protocol CEN-EN 12512 (2000) and the ASTM D 5652-95 (1995) are available. They based the applied deformation increments of subsequent cycles on the yield deformation Vy derived from monotonic tests. Derivation of this parameter according to these standards revealed large differences. It was decided to use the CEN standard definition of Vy as a starting point. The loading rate was arbitrarily chosen as 1 cycle per 90 seconds. In order to prevent any hydraulic problems a sinus rate of load application was introduced in contrast to the triangle-loading rate proposed by the CEN standard. The effect of this change was considered negligible.

TEST RESULTS

The test results are presented by evaluation of key parameters including ductility level, impairment of resistance and the equivalent viscous damping ratio. Regarding the failure it is noted that none of the specimens failed in a brittle way. The tests terminated after a considerable decline in the resistance associated with large rotations. Finally, steel failure occurred in one or more tubes caused by low cycle fatigue. The highest bending moments at the centre of the connection in the connection elements were 29.1 kNm and 120 kNm resulting in bending stresses of 21.6 MPa and 26.0 MPa for the 18 mm and 28 mm tube connections, respectively. These are close to the design bending stress of LSL and PSL.

Reduction of resistance

The average drop in bending moment (resistance) in every second and third loop compared to the first loop for a given cycle, the so-called impairment in resistance, is in many design codes limited. Usually a boundary line at 20% impairment is specified. Only in the cycle where failure occurred the reduction in resistance was more than 20% in all other cycles the reduction was less than 20%, figure 8.

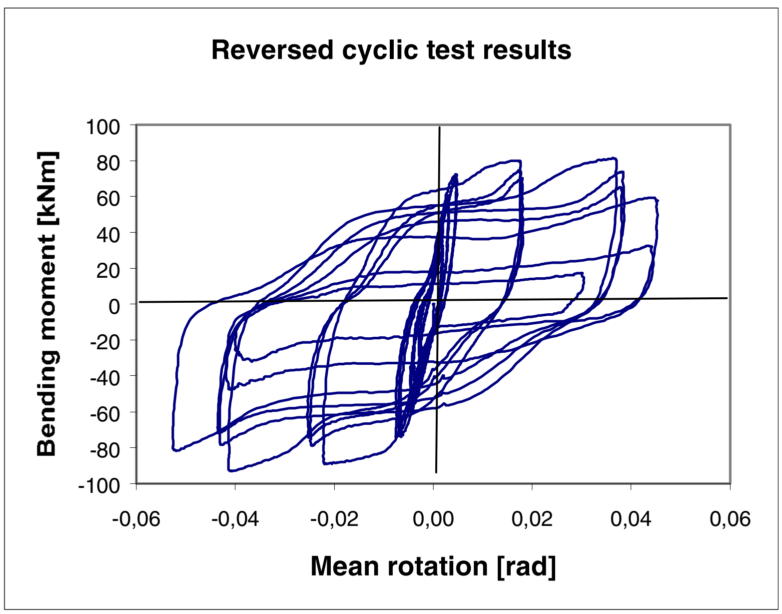

Figure 8: Moment rotation behaviour of connection with 28 mm diameter tubes

Ductility

Ductility is defined as the ability to undergo large deformations beyond the elastic stage without substantial reduction of resistance. One way to measure durability is by the static ductility ratio D = Vtest/Vy. In the European design standard prEN1998-1 (2000), three ductility classes are introduced Low, Medium and High. The medium class M requires D > 4 while for highest class H, D > 6 without more than 20 % reduction of resistance. Evaluation of the data, show the highest ductility class H can be justified as average D values of 10 to 23 were observed for the connections with 18 mm and 28 mm diameter tubes, respectively. The beneficial consequences of using connections with high ductility are small values for the Action Reduction Factors (ARF) or q-factors (CEN). For ductility class H, Eurocode 8 (prEN1998-1) proposes ARF factors of 0.2.

Moment rotation behaviour, pinching and displacements

The moment-rotation curves are of interest as they can be compared with other tests such as the ones shown in Figure 1 and 2. In Figure 8 a representative moment-rotation graph is shown for the connections with 28 mm tubes. The hysteresis loops exhibit very little pinching in the elastic stage and the load take up is immediate, which indicates a tight fitting connection. The absence of pinching allows the connection to dissipate significant amount of energy during the reverse-cyclic tests. In the plastic stage strength degradation upon repeated loading can be observed although pinching was not significant. In this respect the behaviour resembles more a steel connection than a typical timber connection. There is no doubt that the reason for this behaviour is the fact that the elongation of the holes in subsequent load cycles do not attribute so much to the total deformation as the deformation of the steel tube themselves.

EQUIVALENT VISCOUS DAMPING RATIO

To compare the energy dissipation capacity between different types of connections the so-called Equivalent Viscous Damping Ratio (EVDR) as specified in CEN-EN 12512 (2000) is introduced. It is a non-dimensional parameter expressing the hysteresis damping properties of the connection and is determined as the ratio between the dissipated energy in one half cycle and the work by the applied force. From the literature, braced frames with steel-to-timber dowel connections and nailed wall shear panels typically have maximum EVDR-values of 0.10 to 0.20, Yasumura et al. (1998) & Miyazawa et al. (1999). The EVDR-values of the 28 mm tube connection starts at 0.2 in the elastic stage and increase to 0.35 in the plastic stage demonstrating that the tube connection has outstanding energy dissipation properties. The outstanding energy dissipation properties can be demonstrated by comparing the EVDR values of other connections like the one by Schreyer [2], Figure 1 and Kasal et al. [4], Figure 2. As shown in Figure 9 the tube connections, curve No.1 has EVDR values approximately twice as high as the others.

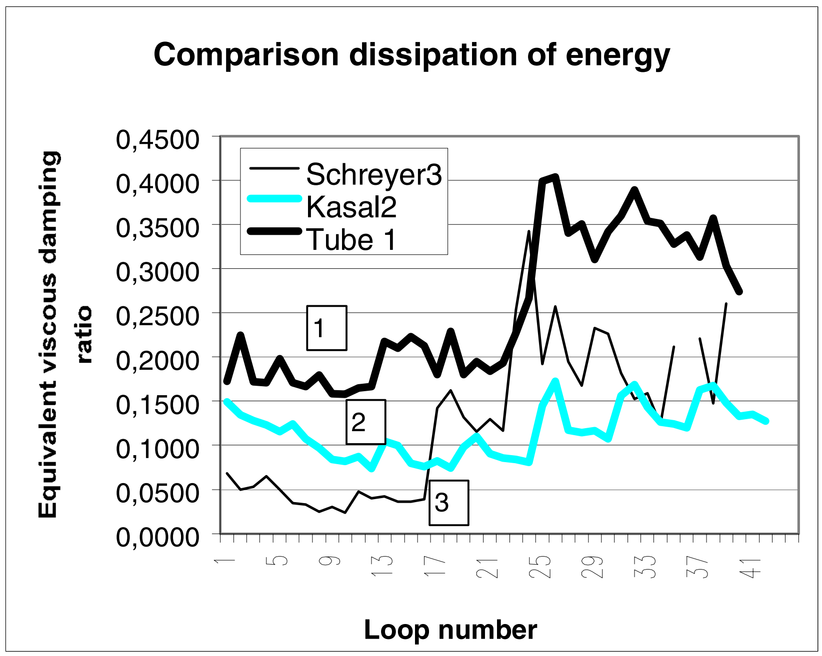

Figure 9: Comparing equivalent viscous damping ratio

CONCLUSIONS

Having analyzed the data and determined the key parameters of the cyclic tests the following conclusions can be drawn:

- The novel tube connection with 18 and 28 mm tubes shows an excellent ductile behaviour without significant reduction of the resistance in subsequent load cycle loops.

- For the test Series with 28 mm tubes equivalent viscous damping ratio (EVDR) values of 0.15 to 0.20 are observed in the elastic stage. For both test Series the EVDR values increase dramatically for plastic deformations with EVDR values of 0.3 and 0.35 for 18 mm and 28 mm tube connections, respectively. Compared to nailed shear walls, the equivalent viscous damping ratio (EVDR) of both test series is twice as high.
- On the bases of these test results Action Reduction Factors are envisaged as low as 0.2. However, such values need to be backed up by more comprehensive studies including computer simulations and dynamic verifications.

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