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On Protocols for Characterising "Dynamic" Properties of Structural Timber Connections

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ABSTRACT

Typically, properties for the design of mechanically-fastened timber connections have been assessed under monotonic static loading conditions and used to evaluate connection performance under seismic action. As a result, dynamic test protocol is required, and several independent test standards are being developed concurrently. It is therefore imperative that a collaborative effort is made to standardise both a test procedure and the analysis of data. In this regard, the standardisation of the following is essential: the displacement sequences, the loading frequency, the definition of yield point, and the assessment of stiffness and energy dissipation capability of the connection.

INTRODUCTION

Whether timber structures containing mechanically-fastened connections behave in a ductile manner under seismic actions depends largely on the characteristics of these connections, as timber itself has limited ductile capacity. Traditionally, properties of structural timber components including connections are characterised under monotonic static loading conditions. The demand for technical information by authorities in seismically active countries is prompting the timber engineering community to develop test protocols for characterising "dynamic" behaviour of timber connections.

The response of timber connections under through-zero cyclic loading conditions (Figure 1) generally takes the shape shown in Figure 2. Analysis of test data involves evaluating the parameters describing the envelope curve and the hysteresis loops. A standard test method must provide not only details about the loading procedure, but also how the data is analysed to extract the desired information. Furthermore, the loading procedure should not be independent of the method of analysing the data and the purpose of conducting the test. In the field of timber engineering a number of test methodologies have been proposed by scientists (e.g. Reyer and Oji, 1991) including draft standards in the USA (Dolan, 1993) and Europe (CEN, 1994). The last two are intended to become ASTM and CEN standards respectively.

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The objective of standardising a test procedure is, of course, to enable a comparison of test data from different test laboratories. In attempting to achieve this objective, quite often accuracy required for numerical modelling of structural system response is sacrificed for simplicity in extracting characteristic values for test parameters. This is the case for the proposed test methods. In applications related to the seismic resistance of structures, the prime parameters assessed are the ductility ratio (ratio of ultimate displacement to displacement at yield point), energy dissipation and strength degradation. As timber connections generally do not have a well-defined yield point, an arbitrary definition of the yield point is required in order to evaluate their ductility ratios. In the draft ASTM and CEN standards, two different methods are proposed for determining the yield point from the envelope curve of the load-deformation response (Figs. 3 and 4). The two draft standards appear to agree on the method of evaluating energy dissipation within one hysteresis loop. The loading regimes proposed by the two draft standards differ however.

The draft CEN standard also includes a "short" test method for evaluating the strength degradation at a pre-defined ductility level. This "short" method provides a means of matching a connection to the requirements of performance categories in the European seismic design standard (Becker et al, 1993). An interesting observation of this proposed "short" test method is that, of all the test methods proposed, it is the method which provides the most direct link between resulting parameters and end use applications. The other methods are essentially tools to enable a comparison of test data between different laboratories. In those cases there are no indications as to how the results will be used in achieving the ultimate objective, that is, to evaluate the seismic performance of timber structures containing mechanical connections.

This paper discusses the features of the response of nailed and bolted timber joints to reversed cyclic loads, discusses the effects of the test parameters on the response, then comments on what a standardised test protocol may contain.

EVALUATION AND EFFECT OF TEST PARAMETERS ON BOLT AND NAIL TEST RESULTS

At the University of New Brunswick, tests have been conducted employing single-nail connections and one- and two-bolt connections. In the nail tests, four loading regimes were employed: a monotonic ramp test, two steadily increasing cyclic load regimes at 1Hz and 3Hz, and an increasing repetitive load regime at 1Hz. Details of these nailed connection tests are given in Ni and Chui (1994).

The load-slip data from the nail tests may be classified into basically three different shapes: at low slip levels there is negligible pinching in the loops; at intermediate slip levels the familiar 'cigar' shape with a slight pinch is apparent; and at high slip levels, the pinching becomes more pronounced. At the lower slip levels, greater contact with the nail and bending of the nail dominates the deformation, whereas at higher slip levels, a residual deformation within the nail requires an increased load in the opposite direction to bring the nail displacement to zero. At this time, only the nail is deforming. It was found that the shapes of the hysteresis loops were similar even for different specimen groups. Each of the hysteresis loops was analysed using the following parameters: load intercept (P_0), stiffness at P_0 (K_0), residual deformation (U_0) and maximum deformation (U_m) (Dolan, 1989) (refer to Figure 5). The envelope curve was defined by the initial stiffness (K_{int}), enforcing stiffness (K_{enf}), degrading stiffness (K_{deg}) and the ultimate load (P_{max}), Figure 4.

With respect to the rate of loading, the ultimate load (P_{max}) was substantially higher in the cyclic tests than the monotonic. Under monotonic loading, there were no post-ultimate strength degradations, whereas (K_{deg}) was negative in nearly all cyclic tests. Good ductile behaviour of the joint before nail breakage was indicated since the degrading stiffness (K_{deg}) had the same range of magnitude as the enforcing stiffness (K_{enf}).

With respect to load cycling in the nail tests, it was found that load cycling leads to a higher degree of strength degradation, as indicated by higher degrading stiffness (K_{deg}) in the repetitive cyclic tests than in the steadily increasing cyclic load. This seems to support the proposition that the envelope strength degradation is a function of energy dissipation (Foliente et al, 1992). Under multi-cycle loading, the strength of the nail joint decreased progressively when loaded to the same deformation level. The largest reaction force is obtained when the wood resists the force transferred by the nail for the first time, after which the reaction force decreases exponentially at the same embedment level.

In the series of tests conducted on the 1- and 2-bolt single-shear connections, two loading regimes were employed: a monotonic ramp load (load regime 1) and a repetitive cyclic load at 0.67Hz (load regime 2) with repeated cycles at 10%, 20% and 40% of the maximum load (as determined during the monotonic tests) before being loaded to failure in tension. All specimens were 38mm by 89mm eastern spruce members and were loaded parallel to the grain. Three bolt sizes were used: 1/4-, 3/4- and 1-inch. Typical load-slip relationships for single 1/4-inch and 1-inch bolt tests can be seen in Figures 6 and 7 respectively.

A relatively high force was required at the beginning of each test to overcome initial friction between the bolted members. This was indicated by zero slip during the application of 0.5 to over 7 kN, the force increasing with bolt size and the number of bolts. Subsequently, a relatively high amount of slip occurred while the bolt "set in", as indicated by the curve prior to the point of inflection. The initial stiffness increased with increasing bolt size and number of bolts. The enforcing stiffness (K_{enf}) displayed traits similar to that of the initial stiffness (K_{int}): increasing with increasing bolt size and number of bolts.

Comparing the shape of these curves (Figs. 6 and 7) with others obtained during similar testing (Gutshall and Dolan, 1994), the degree of pinching of the hysteresis about the slip axis is less in these tests. This difference could be attributed to the restraining against joint rotation during the tests by Gutshall and Dolan (1994). Therefore, a standardised testing protocol including how the joint is to be restrained is necessary.

In each of the test joints containing 1/4-inch bolts, the bolts yielded, and at failure the bolt pulled through one of the members. All connections having a larger-sized bolt involved embedment failure of the wood prior to a brittle failure in the wood member. Some of the joints containing 1-inch bolts failed predominantly by tension failure in the wood through the plane of the bolt hole closest to the applied load.

In comparing the 1- and 2-bolt connections, the increase in ultimate load (P_{max}) was less than 43% in all cases. In comparing the ultimate loads attained during the monotonic ramp tests with those reached during the cyclic loading tests on the same connection types, it was noted that a higher load was attained under monotonic loading.

ESSENTIAL FEATURES OF ANY STANDARDISED TEST PROTOCOL

Any standardised test protocol should consist of two components: the loading procedure and the analysis of the measured data. Since seismic excitation of structures is displacement driven, the loading regimes in characterising "dynamic" properties for seismic resistance applications should preferably be displacement controlled. For timber connections, tests have revealed that strength degradation occurs when a connection is repeatedly loaded to the same deformation level. This strength degradation can be quite significant in some cases. For instance, tests by Ni and Chui (1994) show that for nailed connections, the degradation after the first cycle can be as high as 10%. The rate of strength degradation decreases exponentially with the number of repeated cycles, and the strength degradation appears to stabilise after about 5 cycles. Thus any proposed loading should contain a series of increasing phased displacement sequences and within each phase there should be at least 5 repetitive cycles, as illustrated in Figure 8. The number of cycles proposed by the draft ASTM and CEN methods are 5 and 3 respectively. Thus the draft CEN test standard does not appear adequate in this regard. This appears to be true for both nailed and bolted connections based on tests described above.

It is well known that mechanical properties of timber depend on the rate of loading. The frequency of loading can therefore affect strength and stiffness of connections as evidenced from tests by Ni and Chui (1994). However, "high" frequency loading (greater than approximately 2Hz) can cause premature wood failure due to inertial effects from the loading head of the test machine. Experience by the authors and colleagues in Europe in numerical analyses of seismic response of timber frames shows that the frequencies at which connections in timber frames oscillate under previous seismic records are generally much lower than the dominant frequencies of those seismic records. Thus the use of a "low" loading frequency (0.25 - 0.5Hz) seems justified.

As was discussed in the previous section, there may be a need to provide guidance, if not specific details, on how test specimens may be positioned and restrained in the test apparatus to minimise unintentional deformations. Any unintentional deformation will lead to an over-estimation of the energy dissipation and possibly the ductility ratio.

The second component of any standardised test method relates to the procedure for analysing data. The envelope curve provides information on the ductile capacity and strength degradation after reaching an ultimate load, whereas the hysteresis loop governs the energy dissipation capability of the connection. As is shown by Chui and Ni (1995), that extra damping to a structural response is provided by any increase in the area contained within a hysteresis loop. Thus the calculation of the hysteresis loop area, as suggested by both draft standards, will give an indication of the damping capability of a connection in the inelastic region. The draft Eurocode 8 recommends an "elastic" viscous damping ratio of 5% for timber structures (Becker et al, 1993). Substantial increases in damping capability may be provided through the hysteretic actions of components such as connections. Availability of standardised protocols for testing and analysis of data should enable more accurate assignments of viscous damping ratios to timber structures.

With regard to the definition of yield point, there have been a number of suggestions and debates on this issue. As discussed above, an examination of load-slip responses reveals that there is no well-defined yield point for timber connections. However, the onset of plastic deformation may be detected by examining the shape of the hysteresis loops. As discussed earlier, there is a transition in the shape of the hysteresis loops from a thin cigar shape with no pinching to a pinched shape. This transition point appears to be a more appropriate definition of the yield point.

Another parameter which may provide useful information on the performance of connections under seismic actions is connection stiffness. Proposed test methods tend to use a bi-linear relationship to describe the envelope curve. The slopes of the two lines therefore represent the initial and final stiffness respectively. When a ductile structure is subjected to seismic loading, the initial displacements are controlled by the initial stiffness. As excitation levels increase, the structure softens as it enters the region governed by the "final" stiffness. Thus the slope of the load-slip curve in this region provides an indication of the structural displacement under an over-load condition. Some proposals, e.g. the draft ASTM (Dolan 1993), suggest that calculation of the bi-linear relationship be based on the balanced energy approach and an assumed zero slope (i.e. horizontal) for the bi-linear relationship after the intersection point (see Fig. 3). Other proposals, e.g. the draft CEN, suggest the stiffness be based on the tangents to the initial and final segments of the envelope curve (see Fig. 4). The problem with this approach is the subjective nature in selecting the segments for calculation. However, it is of interest to compare how the two methods of calculating stiffness might affect system responses.

To this end the same timber frame structure evaluated by Chui and Ni (1995) is analysed here. The frame consists of three members: two columns and a straight beam. The column height is 5 m and the span is 10 m. The supports at the base of the columns are assumed to be pinned and the beam-column connections are semi-rigid with moment-rotation hysteresis as shown in the paper by Chui and Ni (1995). The DRAIN-2D program was used in the determination of frame response to the El-Centro earthquake excitation. Three methods of defining the envelope curves were evaluated: 1. the draft ASTM, 2. the draft CEN and 3. a tri-linear relationship which is considered to be the reference case. Analyses were conducted for the first 24 seconds of the earthquake. Figure 9 shows the horizontal displacements of the beam for the three cases. It is noted from Figure 9 that the initial responses are similar for the three cases. This is expected as the initial connection stiffnesses for the three cases are similar. In fact, cases 2 and 3 have identical initial stiffnesses. The response magnitudes differ after about 8 seconds. After that point, it is noticed that case 1 overestimates whereas case 2 underestimates the response. The reference case indicates that response starts to decay after reaching a peak at about 15 seconds. Case 2 shows a similar trend but with lower amplitudes, possibly because of the over-estimation of the final stiffness in this region by the use of a straight line. In contrast, the response in case 1 continues to increase because of the over-softening effects due to the zero stiffness assumption in this region under the draft ASTM method. Therefore, the assumption of zero final tangential stiffness appears to be inappropriate. This highlights the need to accurately represent the final tangential stiffness in any interpretation of envelope curve data.

SUMMARY

The need for a collaborative effort to standardise both a test procedure and the analysis of data is essential to effect a uniform evaluation of mechanically fastened timber connections. In this regard, the standardised determination of the following is essential: displacement sequences (increasing, phased, 5 cycles), "low" loading frequency (0.25 to 0.5Hz), energy dissipation capability of the connection (hysteresis loop area), definition of yield point, and the assessment of connection stiffness (description of envelope).

REFERENCES

Becker, K, Ceccotti, A, Charlier, H., Katsaragakis, E., Larsen, H.J. and Zeitter, H. 1993. Eurocode 8 - Part 1.3 - Chapter 5 Specific rules for timber buildings in seismic regions - A working report of the drafting panel.

Proceedings of CIB Working Commission W18 Meeting Twenty-Six, Athens, Georgia, August.

CEN. 1994. Timber structures - test methods - Cyclic testing of joints made with mechanical fasteners. (Draft), EN TC 124.117, European Committee for Standardization, Brussels.

Chui, Y.H. and Ni, C. 1995. Dynamic response of timber frames with semi-rigid moment connections. Proceedings of the Seventh Canadian Conference on Earthquake Engineering, Ecole Polytechnique, Montreal.

Dolan, J.D. 1989. The dynamic response of timber shear walls. Ph.D. thesis, Dept. of Civil Engineering, University of British Columbia, Canada.

Dolan, J.D. 1993. Proposed test method for dynamic properties of connections assembled with mechanical fasteners. Proceedings of CIB Working Commission W18 Meeting Twenty-Six, Athens, Georgia, August.

Foliente, G.C., Singh, M.P. and McLain, T.E. 1992. Response analysis of wood structures under natural hazard loadings. Technical forum for Wood Products and Engineered Structures, Las Vegas, Nevada, USA.

Gutshall, S.T. and Dolan, J.D. 1994. Monotonic and cyclic short-term performance of nailed and bolted timber connections. Report No. TE-1994-005. Department of Wood Science and Forest Products, Virginia Polytechnic Institute and State University.

Ni, C. and Chui, Y.H. 1994. Response of nailed wood joints to dynamic loads. Proceedings of 1994 Pacific Timber Engineering Conference, Queensland University of Technology, Vol.2:9-18

Reyer, E. and Oji, A.O. 1991. Timber structures - Joints made with mechanical fasteners - A proposed test procedure. Committee paper TSA/19, RILEM Technical Committee TC109 TSA Behaviour of timber structures under seismic actions, France.

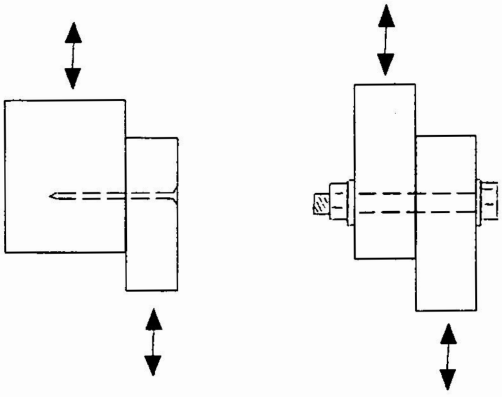

Figure 1. Schematic of typical nailed and bolted specimens loaded cyclically.

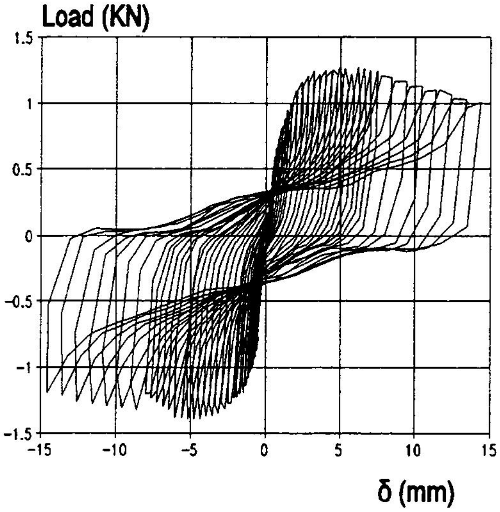

Figure 2. Hysteresis loops for nail test data.

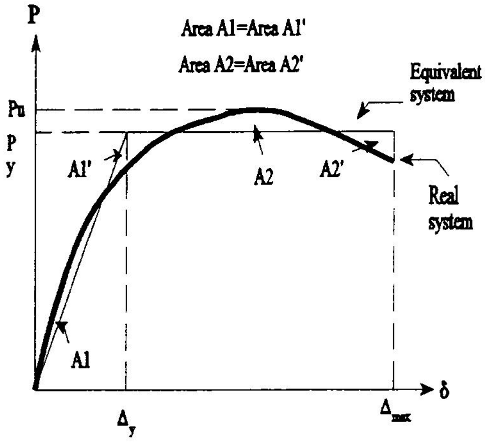

Figure 3. Definition of yield point by draft ASTM standard (Dolan, 1993).

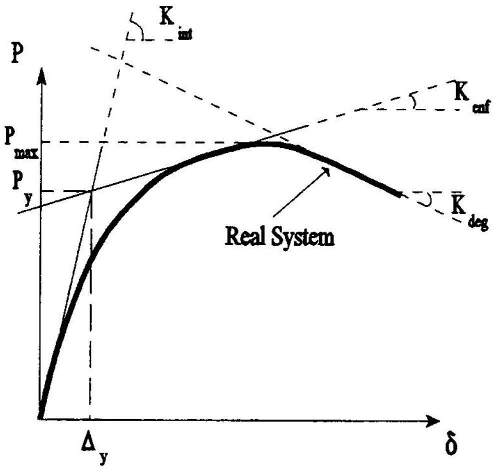

Figure 4. Definition of yield point by draft CEN standard (CEN, 1994).

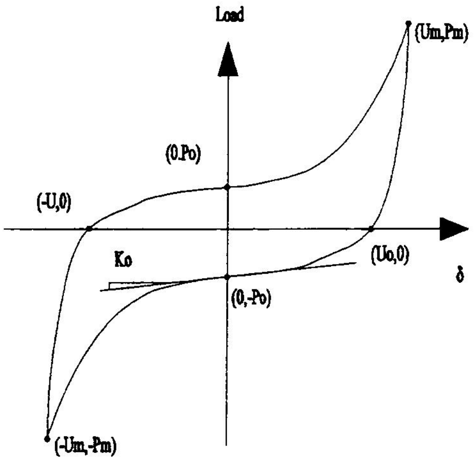

Figure 5. Parameters defining a hysteresis loop (Dolan, 1989).

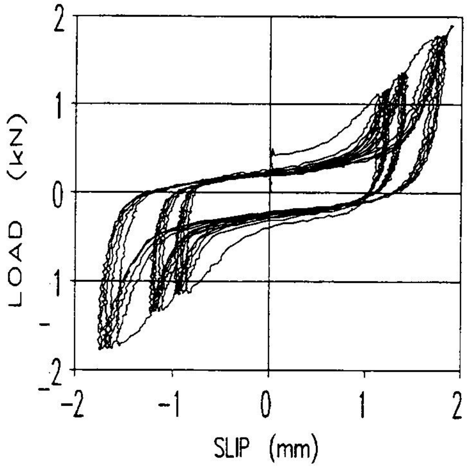

Figure 6. Hysteresis for one 1/4-inch bolt.

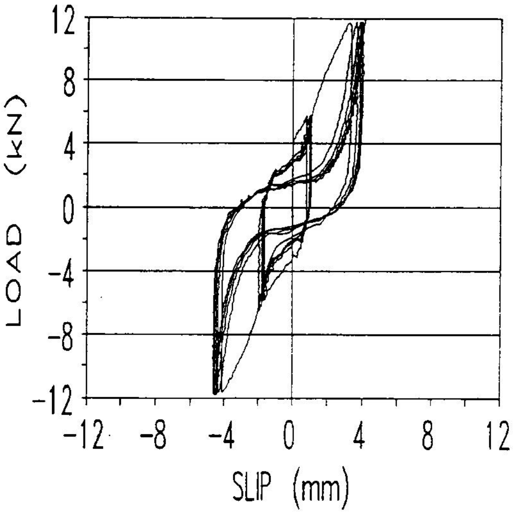

Figure 7. Hysteresis for one 1-inch bolt.

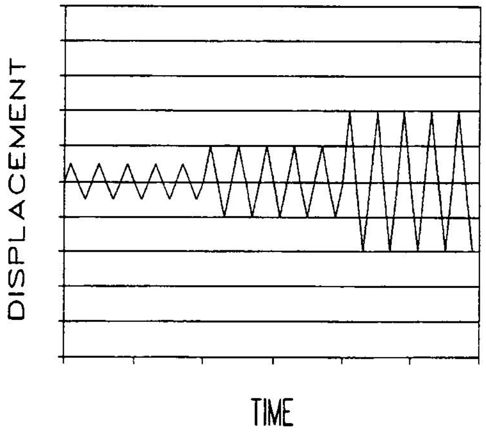

Figure 8. Load regime with 5 cycles at each displacement step.

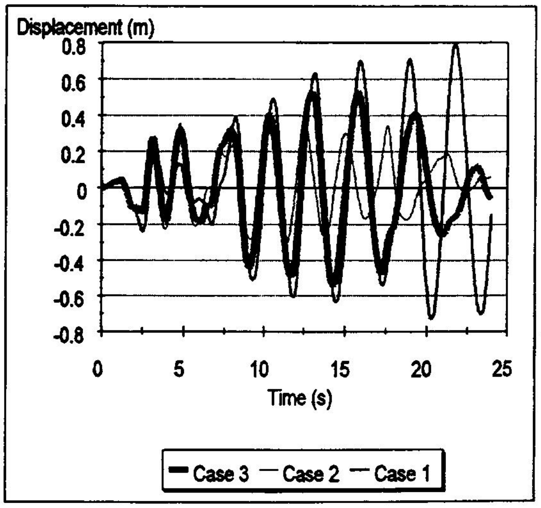

Figure 9. Displacement vs time curves.