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Behaviour of Timber Dowel Type Connections under Seismic Loading

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ABSTRACT

This paper describes the modelling process to present the degrading nature of the cyclic response of timber connections when subjected to seismic loading.

The results of an experimental study on single and multiple dowel connections are compared with analytical results using a finite element based approach that simulates the behaviour of steel pins embedded in wood. The non-linear interaction between dowel and wood, including gap formation, while yielding of the steel and crushing of the wood occurs, has been incorporated in a finite element model using the analogy of a beam on a deformable foundation. Experimental hysteresis curves have successfully been matched with analytical predictions, even when subjected to a mixed sequence of increasing and decreasing amplitudes.

The connection model has subsequently been incoporated in the analysis of a prototype frame to calculate its dynamic characteristics and compare its response to thye experimentally observed response during simulated seismic loading on a shake table.

INTRODUCTION

When studying the earthquake resistance of timber post and beam structures, it is often necessary to rely on moment resisting connections between beams and columns. Very little is known about the performance of such connections, however, let alone how they behave under cyclic loading.

This paper presents the results of a study on dowel type connections, which forms part of a more extensive project on the earthquake resistance of timber building systems. The aim of this study was to establish an analytical model to represent the response of heavy timber connections when subjected to cyclic loads of the type encountered during earthquakes. The type of connection studied included metallic fasteners in combination with different types of wood members, particularly newly developed wood composites like parallel strand lumber (PSL), which is marketed under the trade name *Parallam®*. The objective was to develop a model with sufficient flexibility to make it applicable to a wide variety of connectors and connection configurations, thus avoiding the need for repetitive testing. Presently, the

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connection model is being implemented in a structural analysis package, which will permit the study of entire frames with non-rigid joints.

The development of the model is thus a step towards the expanded application of wood products in engineered buildings requiring consideration of earthquake loadings. Figure 1 shows a typical beam/column connection between PSL members. One possible connection arrangement is to utilize a steel plate, hidden within the members, and tight fitting drift-pins or dowels to connect this plate to the beams and column. An added benefit of this type of connection is the enhanced fire rating of the building by prolonging the load carrying capacity of the protected steel components under the high temperatures during a fire.

Since the metallic fasteners (in this case, the dowels) are flexible, and the wood members themselves are not rigid, the overall connection is non-rigid or non-monolithic. The local deformation of the connection contributes to the overall flexibility of the structure and must be taken into account. Generally, the non-rigid response of the connection is evaluated through testing, for example, by determining the relationship between connection relative rotation (between connected members) and the applied moment.

For timber connections these hysteresis curves are typically "pinched", which means that the connection has very little resistance around the zero rotation point, resulting in play or slack which may cause a severe whipping effect during an earthquake. This "degradation" of the connection, which reflects the developing "gaps" between the metallic fasteners and the wood around them, must be taken into account in structural calculations.

The hysteresis diagrams (or "loops") are essential for a dynamic analysis, but are not easily obtained due to the multitude of variables such as the material properties, the connection's load history and configuration. If evaluated through testing, a new test must be performed every time the connection arrangement is changed. Furthermore, a loop obtained in the laboratory under a certain deformation history may not necessarily be equal to the loop corresponding to another history or earthquake. Thus, a strong need exists for the development of analytical models which permit the evaluation of the connection's response via computer analysis based on fundamental material information.

The development of the analytical model must include its verification. This paper presents the development of the model, a description of the basic information required, experimental testing to obtain such information for PSL, the model's predictions for connections with 2 or 4 pin arrangements and a comparison of these predictions with test results.

THE MODEL

Figure 2 shows, schematically, the problem at hand. Three members are connected with a metal fastener which, under load, deforms as shown. This deformation may be sufficient to cause yielding of the fastener at certain locations, while crushing occurs in the wood under bearing. When the load reverses, the fastener may again undergo yielding while travelling through a gap region in the wood. When the gap closes, the bearing resistance is restored and the fastener moves in unison with the wood.

A generalized structural model for the problem consists of a beam on a flexible foundation as shown in Figure 3. The displacement of the beam's end, Δ, can be specified as a function of time (displacement history). There may be an axial load applied to the fastener, which represents the tension in a bolt after tightening. The stress-strain relationship for the fastener's material is shown in Figure 4, where F_y is the yield stress and E is the modulus of elasticity.

The bearing behaviour of the wood foundation can be simulated as the response of nonlinear springs distributed along the length of the beam. The relationship between the applied force *P(w)* to the displacement *w* is schematically shown in Figure 5. The model assumes that this nonlinear relationship may be represented in terms of the following equation:

$$\mathrm{P} = (Q_0 + Q_1 \bullet w)\,(1 - e^{-Kw/Q_0}) \quad \text{for } w \le D_{\max}$$

and

$$\mathrm{P} = (Q_0 + Q_1 \bullet w)\,(1 - e^{-KD_{\max}/Q_0}) - (w - D_{\max})\,Q_2 \quad \text{for} \quad w \rangle D_{\max}$$

where K is the initial stiffness (*N/mm²*), Q_1 is the slope of the asymptote line (*N/mm²*) and Q_0 is the intercept of this asymptote (*N/mm*). Beyond a displacement $w = D_{max}$, the spring softens and increasing deformation takes place under decreasing load. This is assumed to occur along a straight line with slope Q_2 (*N/mm²*).

Thus, the bearing behaviour is represented by a 5-parameter curve, and these five parameters (K, Q_0, Q_1, Q_2 and D_{max}) must be obtained from testing. Ideally, since they apply to bearing only, the experiment must avoid bending of the fastener shank through which the loads are applied. This is very difficult to do in practice, and an alternate procedure was used as described in the experimental procedures. The properties of the steel fastener (yield stress and modulus of elasticity) are easily obtained from standard tests.

The analytical model is based on a finite element discretization of the fastener shank, with each element being loaded in relation to the local bending deflection (Fig. 6). The nodes along the shank are assigned five degrees of freedom (DOF): 1) w, the bending deflection; 2) w', the bending rotation; 3) w'', the bending curvature; 4) u, the axial displacement; and 5) u', the axial strain. Between nodes, the bending deflection is assumed to follow a 5th-degree polynomial, and the axial displacement a 3rd-degree polynomial. These polynomials are uniquely determined when the DOF at the nodes are known.

Standard finite element analysis techniques were followed to assemble the system of equations, which permit the calculation of the DOF at each value of the displacement that is being enforced at the end of the beam.

EXPERIMENTAL TESTING FOR BASIC PARAMETERS

The fastener pins used in this study were made of 12.7 *mm* diameter, mild steel rod. A standard tensile coupon test provided material data that is shown on the stress-strain plot in Figure 7. A yield stress of approximately 350 *MPa*, and Young's modulus of approximately 205 000 *MPa* were observed.

The bearing parameters of the wood were obtained with a test configuration as shown in Figure 8. A slot was cut, permitting the insertion of a steel plate. A pin was then driven through a tight hole in the PSL and a reinforced clearance hole in the steel plate.

The specimen was then loaded in a universal testing machine under cyclic tension and compression, while recording the load and displacement Δ (*mm*) of the pin at midspan. The connection specimen was subjected to a cyclic displacement history of increasing amplitude, resulting in load/displacement hysteresis loops as shown in Figure 9.

The interaction of the pin and surrounding wood is shown in Figure 10. As the steel plate moves, the pin deforms locally and produces bearing pressures on the wood. Since the wood deformation is nonlinear, it does not fully recover upon unloading, and cyclic applications result in the formation of an internal gap. Provided that no secondary failure of the wood occurred (such as shear or splitting) it was found that the connection behaviour remained stable until the pin failed in shear at the plate.

The envelope of the load/deformation curve (Figure 11), which includes the contribution of both wood bearing and dowel bending deformations, was then used to calibrate the analytical model. Since the properties of the pin were known, the model was run with different values for the parameters K, Q_0, Q_1, Q_2, and $D_{\max}$ until good matching was obtained with the experimental results.

As a verification of the cyclic model, the analysis was then performed with the "optimum" bearing parameters and the same displacement history, obtaining the computed hysteresis loops of Figure 12. Comparison of Figures 9 and 12 show good agreement between the analytical and experimental results.

EXPERIMENTAL VERIFICATION FOR CYCLIC LOADING, MULTIPLE PINS

Two series of experimental tests were conducted to verify the predictions from the theoretical model. In both, the connection was installed at the end of a cantilevered beam, and the fixed end bending moment had to be transferred through multiple pins to a steel plate (Figure 13). This plate was inserted in a slot, as in the previous tests. The applied force (and thus the moment) and the rotation of the connection were measured.

The connections were subjected to a displacement history as shown in Figure 14, which contained ascending as well as descending trends in amplitude. Two- and four pin connections were tested.

Figure 15 shows the experimental hysteresis curves for the 4-pin connection, while the calculated loops are shown in Figure 16. Similar results were obtained for the other tests. Comparison of the measured and predicted hysteresis curves from all the verification tests show very good agreement as to the envelope and the pinching characteristics of the loops.

FRAME ANALYSIS

In preparation for the dynamic shake table testing of a timber frame with dowel connections (Fig. 17), a linear elastic analysis was performed to assist in determining the shake table test parameters. The connections between the beams and columns were the same as tested before, which served to provide the properties required to model the frame with the *SAP90* (Habibullah, A. 1994) finite element program. The frame test program as well as the implementation of the non-linear connection model in a dynamic frame analysis program are currently underway, which will permit comparisons between analytical and experimental studies to verify the procedure.

CONCLUSIONS

The results in this paper have shown that the hysteretic behaviour of wood/metal (non-rigid) connections can be accurately predicted with an analytical model. This model is based on fundamental material information of the metal fastener and the wood bearing characteristics and, thus, provides the flexibility required to analyze any connection configuration. The basic material information for bearing in parallel strand lumber (PSL) has been obtained. The model has been verified by testing using 12.7 *mm* mild steel pins and PSL members.

The work has served to develop a way of obtaining bearing characteristics, which may be applicable in other areas of wood engineering. The model is currently being implemented in a structural analysis program for frames.

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Habibullah, A. 1994. *SAP90 User's Manual*, Computers and Structures Inc., Berkeley, Ca.

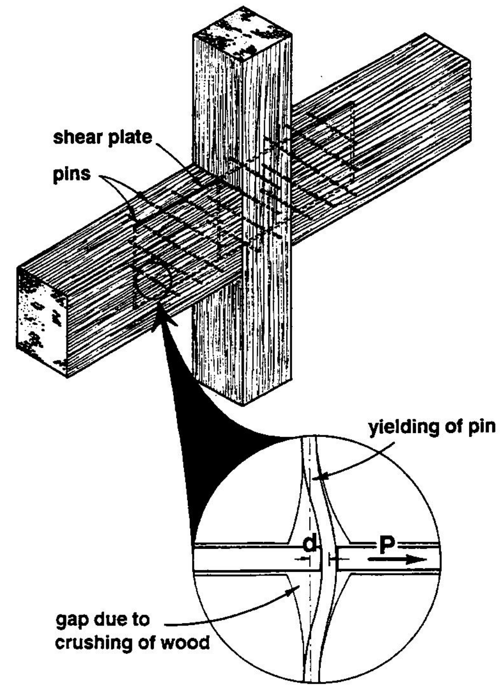

Figure 1: Dowel type connection in heavy timber construction

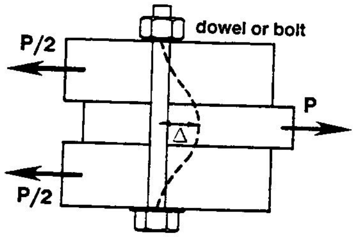

Figure 2: Fastener deformation

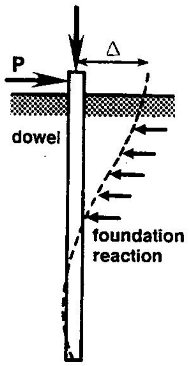

Figure 3: Beam on nonlinear deformable foundation

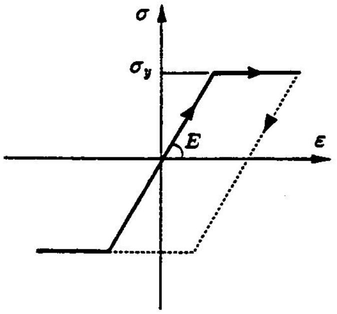

Figure 4: Stress-strain law of steel dowel

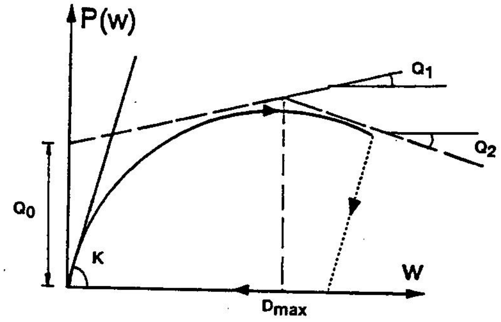

Figure 5: Load-deformation law of nonlinear foundation

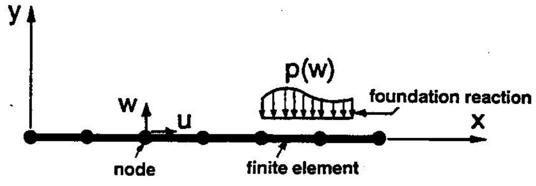

Figure 6: Finite element model

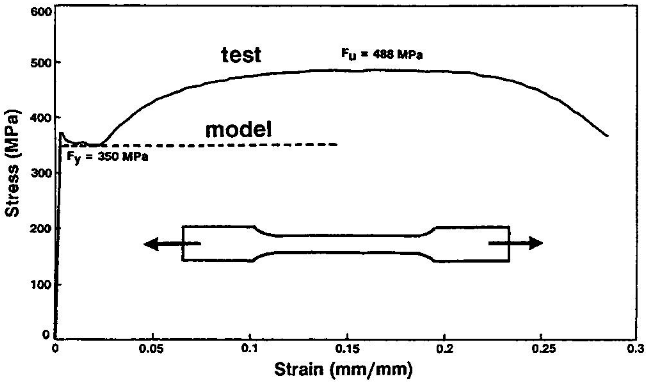

Figure 7: Steel tensile test results

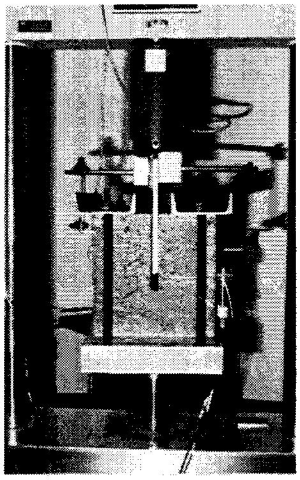

Figure 8: Bearing test on parallel strand lumber blocks

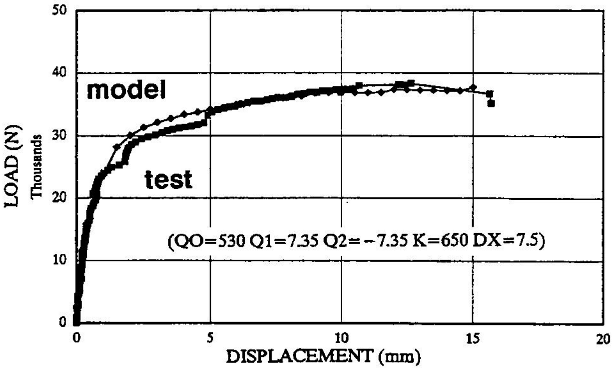

Figure 11: Envelope of load-deformation hysteresis loops of bearing tests compared to analytically fitted curve

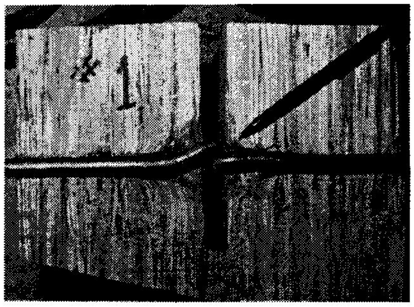

Figure 10: Deformation pattern in bearing test

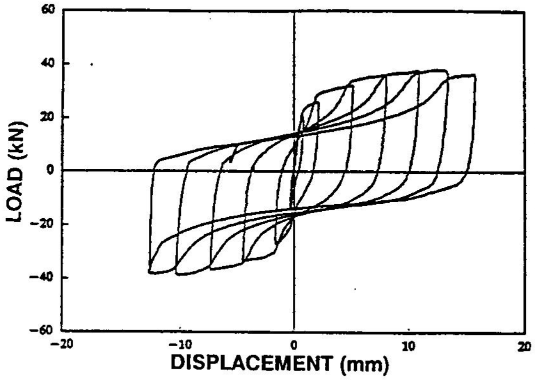

Figure 9: Typical hysteresis loops for bearing tests

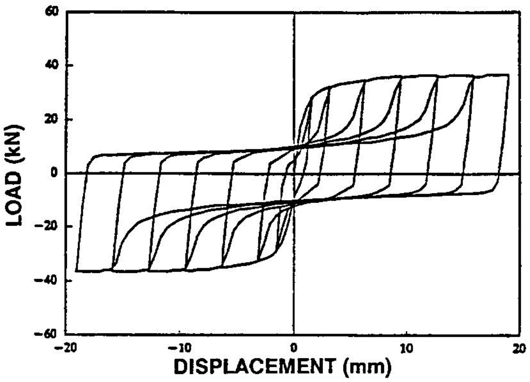

Figure 12: Computed hysteresis loops

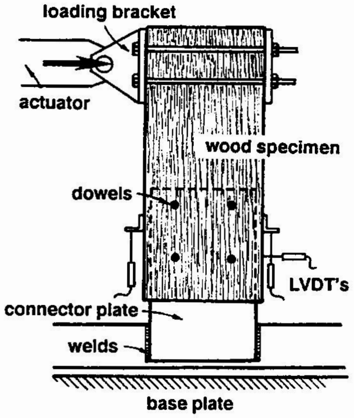

Figure 13: Multiple pin test arrangement

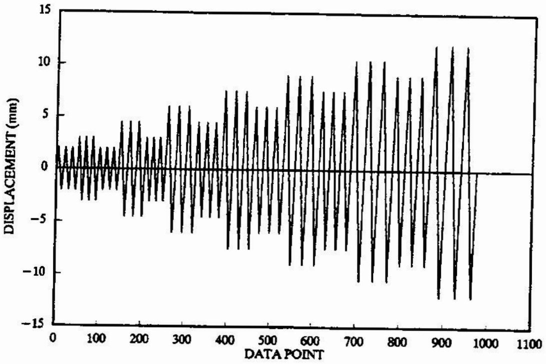

Figure 14: Displacement history of multiple pin tests

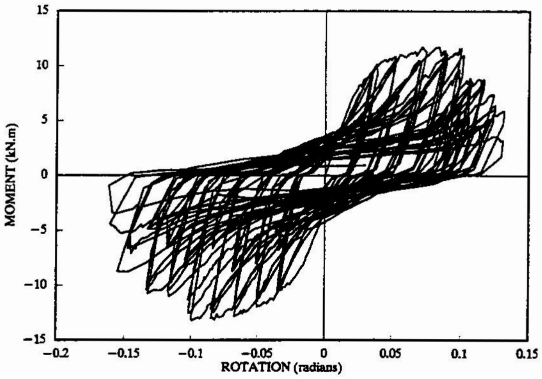

Figure 15: Experimental hysteresis loops for four-pin connection

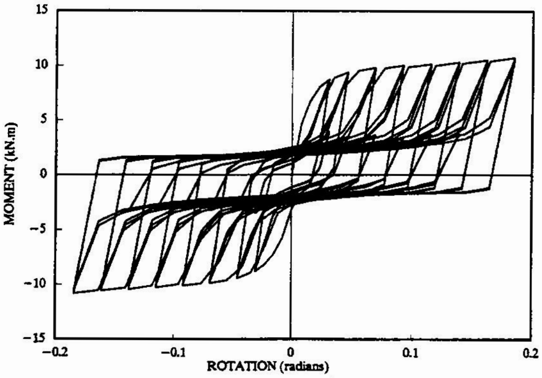

Figure 16: Calculated hysteresis loops for four-pin connection

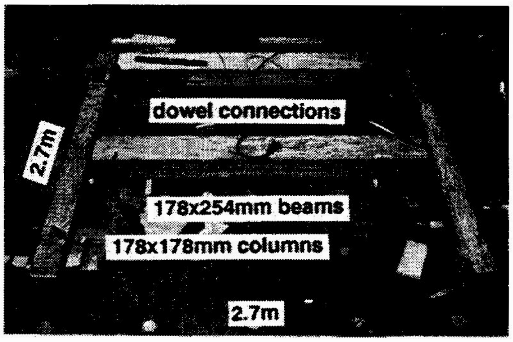

Figure 17: Timber frame