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Stiffness of dowel-type timber connections under pre-yield oscillating loads

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ABSTRACT

The dynamic behaviour of timber structures in service is becoming a more important consideration in design as modern engineered wood products allow longer spans and taller timber buildings, which can be sensitive to dynamic loading such as that from wind or footfall. Connections in timber structures have a pronounced effect on their structural behaviour. In dowel-type connections, the fasteners bend under load and embed into the surrounding timber and, since embedment is a nonlinear process, the stiffness of those connections varies depending on the nature of the applied load. Here, single-dowel connections are tested under cyclic loads representative of in-service vibration. One-sided and reversed cyclic loads are applied. The specimen stiffness is observed to reduce with the amplitude of one-sided cyclic load. For small-amplitude one-sided load, the specimen stiffness is seen to tend towards that predicted by an elastic model, and an analytical elastic model is presented to represent the embedment resistance of the timber and the behaviour of the connector.

1. Introduction

Dowel-type connections make a significant contribution to the stiffness of timber structures in which they are used, and most timber structures employ dowel-type connections in the form of either nails, screws, bolts or plain dowels. In recent years, engineered wood products such as glued-laminated and cross-laminated timber have allowed timber to be used in more ambitious structures, such as long-span bridge structures and multi-storey buildings, by allowing large member and panel sizes not possible in sawn timber. Such structures require thorough design for serviceability conditions, including vibration under dynamic loads such as wind and footfall.

The behaviour of dowel-type connections includes nonlinear and irreversible components, even under loads well below their nominal yield load. For example, the stiffness exhibited when a load is first applied is different to that when the load is removed and reapplied. Therefore, if the connection stiffness is to be represented by an equivalent linear elastic stiffness, as is the case in most structural engineering analysis, then that stiffness must be chosen to be appropriate to the nature of the applied load. This study investigates the stiffness of dowel-type connections under the cyclic loads resulting from in-service structural vibration, and presents an analytical model based on the elastic material properties of the timber and connector, which is shown to predict the underlying elastic response on which the nonlinear behaviour is superimposed.

The nonlinear stiffness under in-service loads differs from that under seismic loads, which have been widely studied and in which gross plastic behaviour occurs in timber and connectors. This research therefore extends the field by providing empirical evidence of the stiffness and energy dissipation in dowel-type connections under in-service dynamic loads, and the basis of a predictive model for their stiffness in those conditions.

2. Background

There has been a great deal of research into the dynamic performance of timber structures with dowel-type connections under the forces and displacements associated with seismic loading, measuring stiffness, and its variation of with the amplitude and duration of the applied cyclic load [1–6]. There has been far less research into the stiffness of connections under the pre-yield loads associated with in-service loading by dynamic forces such as wind and footfall.

Chui and Ni [7] carried out cyclic tests on connections with gradually increasing amplitude of load, and observed the development of hysteresis loops. A lower-stiffness region at low load was observed to occur as a result of local plastic behaviour around the dowel. This behaviour had been widely noted, but not thoroughly investigated until the study by Dorn et al. [8], who attributed it to

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the contact stiffness between the imperfect surface of the timber, and the relatively smooth and hard surface of the steel. Dorn et al. studied serviceability loads, but focussed primarily on monotonic, rather than cyclic loading.

This study adds to the current knowledge of the vibration behaviour of timber structures by measuring the stiffness in complete connections under one-sided and reversed loads representative of in-service vibration. An analytical model is then applied to asses the underlying elastic stiffness of the connections onto which the nonlinear behaviour, considered to be due to the interaction between dowel and timber at the contact surface, is superimposed.

The connection is modelled as a beam, representing the steel dowel, on a foundation representing the embedment resistance of the timber. The beam-on-foundation model was first applied to timber connections by Kuenzi [9], and beam on foundation models were later used to model nailed connections, using nonlinear embedment parameters for timber and connector [10–12].

The stress–strain behaviour of steel can be readily used to evaluate the behaviour of the beam in its elastic and plastic ranges. The foundation modulus, in contrast, has conventionally been empirically defined [7,13,14]. Embedment has also been modelled using the finite element method [15,16]. A model for embedment must take into account the contact behaviour and friction at the interface between dowel and timber. Finite-element models therefore must include contact elements, which adds to their computational intensity.

This study sought to define and test an analytical model for embedment and connection stiffness. Such a model must represent the behaviour of an orthotropic elastic material, the timber, around a hole loaded by frictional contact with a rigid circular section, the dowel. This situation is generally referred to as a pin-loaded plate, and is common to timber and fibre-reinforced composite structures. A general analytical solution was defined by Lekhnitskii [17], and was developed by other researchers for analysis of the stress distribution around the hole [18–21]. Reynolds et al. [22] extended the application of the method to prediction of displacements, and applied the solution by Zhang and Ueng [21] to estimate the stiffness measured in cyclic embedment tests on half-hole embedment specimens according to ASTM D5764 [23].

In this study, the analytical stress function defined by Hyer and Klang [20] is used and extended to predict the stiffness of complete connections. The model is compared with experimental results for cyclic loads representative of in-service vibration.

3. Materials and methods

The experimental work in this study used Norway spruce (Picea abies) glued-laminated timber (glulam), delivered with a cross-section of 190 mm by 200 mm, made up of five 40 mm laminates. The glulam was strength-graded as GL28h according to EN 1194 [24]. After delivery, its moisture content was measured by electrical resistance to be 11.3%. The specimens were cut from the glulam and stored in a controlled environment at 18–22 °C and 60–65% relative humidity for a period of 7 months, which was assumed to be sufficient for equilibrium moisture content to be achieved. After testing, seven specimens were cut from the single-dowel connection test specimens for evaluation of this equilibrium moisture content according to EN 13183 [25]. The moisture content had a mean of 11.9% with a coefficient of variation of 0.05. The density of the glulam was measured as 458 kg/m^3, which could be corrected to give 461 kg/m^3 at 12% moisture content. This is 12% higher than the 410 kg/m^3 for standard GL28h.

The nominally 12 mm dowels were specified by the supplier as C16 bright steel according to EN 10277 Part 2 [26]. The dowels were measured as having a diameter of 11.8 mm, and the holes in the timber were predrilled using a 12 mm auger drill bit. The steel plates were 6 mm thick, and inserted into a 7 mm slot in the timber piece.

Specimens were rejected if they contained a substantial visible defect in the surface of the timber within 25 mm of the holes for the connectors. Otherwise, the specimens were used as delivered, incorporating defects elsewhere in the timber.

3.1. Single-dowel connection test

The single-dowel connection test was intended to investigate the processes which contribute to stiffness in a connection in which the dowel transmits force from the timber to a steel plate in a central slot. Loads in tension and compression were applied to each specimen to investigate the effect of the different stress distributions in the timber on stiffness. The specimen was made symmetrical, with a connection at each end, which removed the need to anchor the specimen, since a stiff anchorage could not be readily achieved in tension. Only the movement of the loading head was measured, so the measured deformation represented the sum of the deformations in the two connections. The movement of the loading head was measured using a ±1 mm LVDT on an adjustable steel mounting. The moving rod of the LVDT was attached to the loading head adjacent to the jaws in which the steel plates were clamped, and the fixed part of the LVDT was attached to a steel mounting attached to the test bed. In the tests with fully reversed loading, the displacements were out of the range of the LVDT, and so the internal displacement sensor in the loading machine was used. The LVDT which was used had no connection between the moving rod and the fixed body, the rod moved freely through the coil, and was attached by a magnet to the loading head. This ensured that no force was transferred to the mounting of the LVDT, so that there would be no movement of the LVDT body during the test. This was crucial given the small differential movements, of the order of microns, which were to be measured. It was assumed that the steel plates did not slip in the jaws of the loading machine, and that their deformation was negligible in comparison with the deformation in the connections.

BS EN 383 [27] gives recommended dimensions for a symmetrical static embedment test specimen parallel-to-grain, and so these dimensions were used to aid comparisons with work by other researchers. No guidance is given in EN 383 [27] for tests in tension perpendicular-to-grain, so the specimen dimensions were determined to match the compression tests in that standard, with the distance between the dowels specified to be double that between the dowel and the test bed in the standard. The thickness of the specimens was chosen as 190 mm, so that the failure loads for one and three plastic hinges were close for both parallel and perpendicular to grain, according to Eurocode 5 [28]. Although the loads applied were well below those necessary for any plastic hinges to form, this was considered to represent a common situation, since it is recommended that connections are designed to form one or three plastic hinges to ensure ductility. The specimens are shown schematically in Fig. 1.

The embedment strength of the timber was calculated based on the density of 461 kg/m^3, according to Eurocode 5 [28]. This gave an embedment strength of 33 N/mm^2 parallel to grain and 22 N/mm^2 perpendicular. These embedment strengths were used to calculate the expected connection strengths of 14.2 kN parallel, and 11.7 kN perpendicular.

3.2. Loading

The magnitude and form of oscillating load was chosen to be a simplified representation of the different forms of load which could result from in-service vibration. Since problematic vibration