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Nonlinear pre-yield modal properties of timber structures with large-diameter steel dowel connections

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ABSTRACT

In timber structures, the connections are generally flexible in comparison to the members they connect, and so contribute significantly to the dynamic properties of the structure. It is shown here that a widely-used form of connection, the dowel-type connection, exhibits nonlinear stiffness and energy dissipation, even at pre-yield loads, and that this nonlinearity affects the modal properties of structures with such connections. This study investigates that behaviour by modal analysis of a portal frame and a cantilever beam constructed from timber with steel dowel connections. The observed nonlinearity is explained qualitatively by considering the measured force–displacement response of individual connectors under cyclic load, which show a reduction in stiffness and an increase in energy dissipation with increasing amplitude of vibration. The structures were tested by modal analysis under slow sine sweep and pseudo-random excitation. Under pseudo-random excitation, a linear single degree-of-freedom curve fit was applied to estimate the equivalent linear modal properties for a given amplitude of applied force. Under slow sine sweep excitation, the frequency response function for the structures was observed to show features similar to a system with a cubic component of stiffness, and the modal properties of the structures were extracted using the equation of motion of such a system. The consequences for structural design and testing are that two key design parameters, natural frequency and damping, vary depending on the magnitude of vibration, and that parameters measured during in-situ testing of structures may be inaccurate for substantially different loads.

1. Introduction

The natural frequency and damping in a structure is often observed to vary as the amplitude of vibration varies. This variation is an important consideration in the design of structures for vibration, as it means that the stiffness and damping parameters used in design must correspond to the amplitude of vibration being considered. This has important consequences for in-situ testing of structures. The frequency and damping measured, for example, in modal tests at small amplitude may not be applicable to the larger-amplitude vibration in a severe wind event.

This study is concerned with the amplitude of vibration which a timber structure might experience as part of its everyday service life. Under such vibration, the forces in members and connections are well below their yield load, and the engineer must ensure that the vibration does not cause discomfort to occupants or users of the structure, or impede the proper use of the structure in any other way. Accurate dynamic properties are therefore required for design. It is shown that the nonlinear behaviour of connections in timber structures at these loads can lead to a variation in those dynamic properties.

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, including experimental work and modelling of light timber frames with nailed sheathing [1–3], glued-laminated timber frames with bolts [4], cross-laminated structures connected by screws [5] and a complete light timber frame residential building [6].

Under loads representative of the seismic forces on a building, the nonlinearity of the force–displacement behaviour in connections is sufficient to justify detailed curve-fitting of the hysteretic loops, and their development under repeated cycles of load, such as carried out by Zhang et al. [7], whose model includes 13 parameters to represent pre- and post-yield behaviour, pinching, stiffness degradation and energy dissipation. Based on an understanding of the limitations of timber systems under seismic loads, special devices have then been added to such structures to improve their seismic response [8–10]. Modern lightweight timber structures may be susceptible to smaller-amplitude in-service vibration

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problems, for example under wind load [11,12], and a more thorough understanding of that dynamic response is required for enhanced designs or special devices to be proposed.

Under smaller-amplitude vibration, the dynamic response of a structure can be reasonably represented by linear modal properties. A dynamic analysis of a 6-storey brick-clad timber frame building was carried out as part of the tests on the Building Research Establishment's Timber Frame 2000 project, presented by Ellis and Bougard [13]. Nonlinearity was evident even under the small-amplitude, pre-yield forces applied to this structure, and Ellis and Bougard noted the variation in natural frequency and damping in the structure with amplitude of excitation.

As modern engineered wood products are used to create more ambitious structures, the lack of knowledge of connection behaviour can make design of those structures for in-service vibration difficult, as noted by Utne [12] for the case of a multi-storey timber building, and there has already been an example of a timber bridge with unacceptable vibration attributed to movement in connections [14].

In contrast to seismic vibration, in-service vibration is often, though not exclusively, one-sided. That is to say, the mean component of the force on the structure is sufficiently large in comparison to the oscillating component that the force in the structure does not reverse, but maintains the same direction. Examples include footfall-induced vibration of a structure, in which the self-weight and imposed loads on the structure are far larger than the oscillating force imposed by footfall, and along-wind vibration, in which the mean wind load is large in comparison to the turbulent component. One-sided vibration is studied in this work.

Tests on individual dowel-type connections by Reynolds et al. [15] showed that, for cyclic loads with peak loads of 20% or 40% of the yield load, stiffness nonlinearity was evident, and stiffness was observed to reduce with an increase in amplitude of cyclic load.

This study uses loading representative of in-service vibration, such as might be imposed on a structure by wind or footfall, and investigates the variation in stiffness and damping resulting from nonlinearity in modes of vibration of two glulam frame structures. The nonlinearity is related qualitatively to the force–displacement behaviour observed in isolated connections. A simple single degree-of-freedom curve-fitting approach suitable for weakly non-linear modes is developed and applied to measure the variation in stiffness and damping in the structures as the amplitude of vibration is varied.

This work extends the field by relating the nonlinear vibration of timber structures under pre-yield loads to stiffness variation in their connections. It shows that, although they cannot describe it completely, Duffing's equations for a system with cubic stiffness can be used as an inverse modelling tool to extract information about that nonlinear vibration. It is also shown that, for a widely-used form of connection, modal properties, particularly damping, can vary dramatically with amplitude, and that variation is quantified for two structures in laboratory tests.

2. Behaviour of dowel-type connections

A series of tests was carried out investigating the response of a single dowel-type connector to cyclic loads, the results of which are presented by Reynolds et al. [15]. Some of the results from that paper are presented here with a different focus, to investigate how nonlinearity in the behaviour of connections may affect the dynamic response of the cantilever beams and frames tested in this study. Fig. 1 shows the force–displacement diagram for two individual cycles of force, both having approximately the same mean force, on the same single-dowel connection specimen. The amplitude of the applied force differs between the two cycles by a factor of approximately 10. The gradient lines for calculation of the secant stiffness of each cycle are shown in the figure, and show that the secant stiffness is lower for the cycle with larger amplitude.

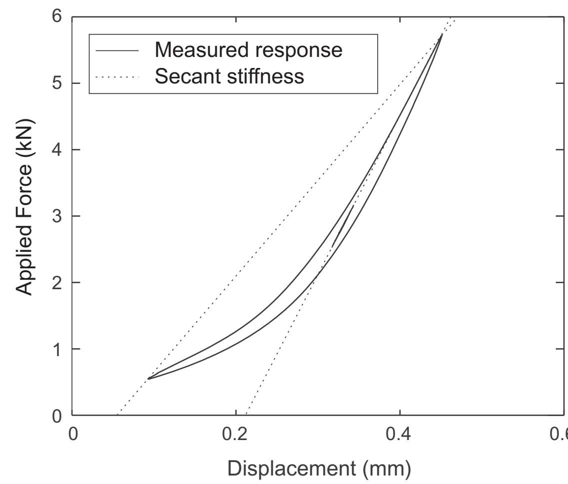

Fig. 1. Force–displacement plots for single cycles of force on a parallel-to-grain single-dowel connection specimen.

The difference in energy dissipation between the two cycles in Fig. 1 can also be seen, since the larger-amplitude cycle encloses a larger area.

The amplitude of the two cycles can be expressed as an *R*-ratio, which is the ratio of the highest to the lowest load in the cycle. Reynolds et al. [15] tested three specimens at *R*-ratios of 1.2 and 10 for specimens loaded in tension and compression, parallel and perpendicular to the grain. Here we compare the tests with a mean value of approximately 20% of the predicted yield load of the connection, to be of relevance to the frame and cantilever tests. The true mean load in the tests ranges between 16% and 22% of the predicted yield load of the connection. The variation of stiffness with amplitude is shown using the mean values for each of the three specimens tested in Fig. 2, which shows that there is a consistent reduction in stiffness as the *R*-ratio is increased from 1.2 to 10.

The following qualitative characteristics were therefore noted in the single-dowel connection tests, which were expected to influence the behaviour of the complete connection and frame:

- a variation of stiffness with amplitude of applied force due to reduced stiffness at low load;
- a variation of energy dissipation with amplitude of applied force.

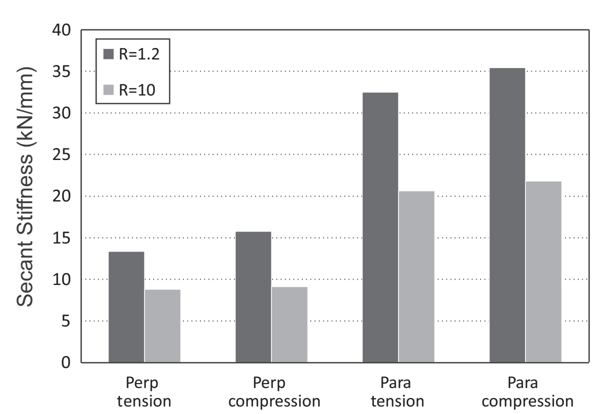

Fig. 2. Mean of secant stiffness for three specimens, varying *R*-ratio.