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Review

Remarks on the slip modulus of nailed connections for linear analysis of plywood timber beams

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A B S T R A C T

In mechanically jointed plywood timber beams, the deformation of the connection has an important influence on the stiffness of the beam and the distribution of internal forces. To quantify this influence, the mechanical behavior of the connection, expressed by its non-linear load–slip relationship, is required. In the linear elastic range, load and slip are related by the slip modulus. This study deals with the analytical determination of the slip modulus of nailed connections based on the theory of beam on elastic foundation, in which the wood foundation modulus was estimated through the embedment test. In general, the conclusion is that this model is adequate for the description of the behavior of the connection in the linear limit range and its main parameter is the wood foundation modulus, which needs further investigation regarding data for tropical species of wood and plywood.

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1. Introduction

The study of the stiffness of laterally loaded semi-rigid connections in wood pieces is justified by the influence that the deformation of the connection has on the overall displacements of the structure in which it is used as well as on the distribution of internal forces. Semi-rigid laterally loaded connections are characterized by the occurrence of slip between the connected wood parts. The efficiency of the interaction between the wood parts and hence the stiffness of the structure depends on the stiffness of the connectors. The basic behavior of a connection is described by its load–slip relationship. In the linear range of physical behavior, this relationship is described by a straight line, whose angular coefficient is called the slip modulus.

During the 20th century, research on the influence of the stiffness of connectors on the behavior of composite beams was very intense, and extended to several types of wood composite beams

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and composite beams of other materials such as concrete and steel. Primary investigations, in the first half of the 20th century, were probably purely experimental and led to empirical methods of calculation.

The first theories describing the deformation of the connectors and the slip between the parts of the beams were developed around the 1950́s. As reported by Girhammar and Gopu [1] in 1993, the first theories were developed independently and resulted in very similar general theories on the partial interaction in composite beams. In these theories, linear behavior was adopted for the connectors. The basis of these theories was the method of equilibrium of an infinitesimal length of the beam. After these first studies, many others were developed with the same basis, for several others types of beams and metallic connectors. The specifications of the Eurocode 5 (European Comittee for Standardization) [2] for mechanically jointed beams discussed by Kreuzinger [3] in 1995, are based on this model.

Numerical methods associated to more complex analytical models allow the description of the real non-linear behavior of the load and displacements of the beam, which is a direct consequence of the non-linear relationship of the load–slip relationship of connectors. However, for design purposes, usually the non-linear behavior is considered through two values of slip modulus, serviceability limit state and ultimate limit state. On the other hand, the connections are initially designed from the analysis with rigid connection hypothesis.

Eurocode 5 [2] provides two values of slip modulus, K_u for ultimate limit state calculations, K_{ser} for serviceability limit state calculations. Both values are based on the diameter of the fastener and density of wood, and are valid for parallel direction to the fibers.

A previous theoretical and experimental investigation on this type of beam developed by Santana and Mascia [4] in 1998, showed that the deformation of the connectors has a significant influence on the internal forces distribution, including shear forces between parts, and, remarkably, on the displacements of the structure. That influence is very sensitive to the slip modulus. Considering the limit states related to displacements often are those that govern the design of wood structures, the effect of the deformation of the connection is critical to the acceptance of the wood component. Moreover, an accurate method for the analysis of composite beams may not be effective if the slip modulus is not accurately determined.

The slip modulus depends on the stiffness properties of the wood of the parts connected, the properties of steel of the fastener, and the geometrical characteristics of the connections, which are: the fastener diameter and the sectional properties of the wooden parts, with their large variety of possibilities.

Thus, it is of practical convenience to develop a theoretical method for the characterization of the behavior of a connector, and, in fact, the researches on that behavior have been very intense too.

The theoretical modeling of connections began approximately at the same time as the theoretical modeling of composite beams. The characterization of a connection is usually based on an isolated single fastener connection. The results obtained for a single fastener are extended to the group of fasteners (considering the group effect when applicable). Some representative studies in the field of theoretical modeling were the studies of Johansen [5] in 1949, which was probably the first attempt to describe the behavior of connections; of Kuenzi [6] in 1955, who described the behavior of the connection based on the theory of beam on elastic foundation as presented by Hetenyi [7] in 1946; and of Foschi [8] in 1974, who extended the model of the beam on foundation to the non-linear range. In the subsequent decades, a vast amount of research was completed on the behavior of the connection, in two main aspects: the development and calibration of models for the determination of connection strength; the development and improvement of models for the description of connection behavior and stiffness. More recently, the research on connection behavior has advanced toward both simplified analytical models and more exact finite element models based on the real non-linear behavior and three-dimensional domain of the phenomenon. Several important studies were revised by Patton-Mallory, Pellicane and Smith [9] in 1997.

In spite of the advances in the connection characterization, technical codes for the design of timber structures remained too simple or omitted consideration on connection stiffness.

This study focuses on the determination of the slip modulus and the comparison of results with Eurocode 5 [2]. It was directed to the application of the slip modulus to the linear analysis of nailed plywood timber beams with a box section.

In Brazil, this type of beam has been increasingly investigated and used, following a trend of rationalization of wood structures; however, it can be observed that the large spread of its use is still hindered by the lack of details in the Brazilian technical code for the design of wood structures – ABNT/NBR7190 [10].

In this context, the objectives of this paper are: to review an analytical model for the determination of the slip modulus of a mechanical connection with pin-shaped fastener; to approach the determination of the geometrical and material properties involved in the model, remarkably, the wood stiffness in the phenomenon of connection deformation.

2. General theory

2.1. Remarks on the basic operation modeling for a single nail connection

In general, the typical behavior of fasteners shaped like a cylindrical rod, including dowels, bolts, nails, and screws, are similar in many aspects. The study of dowel-type connections is usually based on an isolated single connector.

When two pieces of wood are connected with a dowel and loaded laterally by a tensile or compressive force, a shear force is transmitted from one piece to another through the dowel. As a consequence, the dowel undergoes bending, and the wood pieces, when reacting to the bending of the dowel, undergo crushing. The wood pieces undergo a relative displacement (slip) resulting from a combination of wood crushing and dowel bending. Depending on the material properties – both stiffness and strength properties – the diameter of the dowel, and the sectional properties of the wood parts, the loading will lead to different deformed shapes, and the description of that phenomenon including elastic–plastic deformation of the materials is the essence of the determination of macroscopic connection's stiffness.

Mathematically, the relationship among the longitudinal force transmitted by the fastener (P) and the slip (Δ) may be expressed in the linear elastic range by:

$$P = K\Delta \tag{1}$$

where K is denominated the "slip modulus" of the connection.

The deformation of a connection is a three-dimensional problem. The stress distribution around the fastener cross section (and, clearly, variable along its axis) represents the compressive stresses distribution of the fastener over the wood part, and in the opposite direction, the reacting stresses distribution of the wood part over the fastener.

Simplified analytical models consider the two-dimensional stresses distribution around the fastener cross section as a stati-