ANALYSIS OF THE LOAD-SLIP BEHAVIOUR OF DOWELLED TIMBER TO TIMBER JOINTS

PhD. Thesis

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1. INTRODUCTION

Connecting timber elements can be dated back to several thousand years. From timber to timber joints created at the ancient time to the joints of the today's modern glued laminated timber structures there are several ways to connect loaded timber members. The most-important characteristics of a connection are its resistance and stiffness. It is essential to know the deflection of the joints under loading during the global modelling of the structure, because the stiffness of the joints determines the forcedistribution in the structures. In my dissertation I analyse the stiffness of screwed timber to timber joints under shear load that is perpendicular to the axial direction.

One of the frequently used timber joints is the dowel type joint, in which the connector is a slender cylindrical steel member. Dowel type connectors can be nails and screws too. The slip stiffness of a joint is the force which relates to a unit slip between the connected timber members. Because of the non linear load-slip relationship, the slip stiffness can be referred to the start or any other part of the loading process. In my dissertation I refer the slip stiffness to the initial point of the loading, but I analyse the full load-slip behaviour of the joints as well.

2. RESEARCH BACKGROUND

The basic problem in the design of dowel-type timber joint is the consideration of the deformation of the dowels. Contrary to steel dowelled joints, dowels placed in the wooden connections are not only loaded by local compression and shear, but significant bending moment acts on the connector as well. During the calculation the deformation of the dowels cannot be neglected in general. The rotation of the dowel, the curvature of the dowel, the penetration into the wood and the local compression are in close interaction, which has to be reflected by the calculation method as well.

In the case of wooden materials the material anisotropy makes the calculation complicated, so it is necessary to pay special attention to the angle between the load direction and the grain direction. The local compression which is acting on the surface of the dowel has to be considered by the embedding strength property of the wooden material. The embedding strength is influenced by the load direction as well.

The attention to the necessity of the consideration of the large deformations in the dowels has been drawn first by Johansen [5]. The calculation method introduced by Johansen assumes uniform stress distribution considering the changing of the sign of the local stresses. This calculation method was taken by Eurocode 5 [2] as well. Johansen analyses several possible failure modes by. According to this calculation the local compressive failure due to the penetration and the bending failure of the dowel are taken into account. Johansen equations are applicable only for determining the resistances of timber to timber and timber to steel joints, but there is not any guidance for the determination of the stiffness of the joints.

Current provisions of Eurocode 5 [2] do not consider the following characteristics in the calculation method of the load-slip behaviour:

- the cross sectional geometry of the timber elements
- the connection type (under single shear or double shear)

- the load direction

Foschi [3] pointed out in 1974 that the load-slip behaviour is nonlinear. Sawata and Yasamura [4] showed that the embedding strength and the embedding stress related to a unit penetration are the functions of the grain direction.

Over the above written deficiencies, in the case of multiple dowel type joints, Eurocode 5 [2] regards the slip stiffness proportional to the product of the number of connectors and the number of shear planes. This calculation method may provide inaccurate result.

3. RESEARCH AIM, RESEARCH METHODS

During my research my primary aim was to analyze and make more accurate the neglected or inadequate considered effects – summarized in the previous chapter – of the currently applied calculation methods. (Eurocode 5 [2], MSZ15025 [1])

For the consideration of the penetration of the dowels into the wooden material, it is necessary to define the penetration stiffness characteristics, which is the base of the analysis of the connections. So my first research aim was to define the force-penetration characteristics. My main propose was to create one or more general expressions, which provide more accurate result of the initial slip stiffness than the currently used ones, considering the sizes of the timber members, the grain direction as well as the type of the connection. I also intended to create a numerical procedure, which provides not only the initial stiffness but the full load-slip behaviour. In the case of multiple connector joints I analysed the interaction of the dowels under shear force.

In order to achieve my aims four research method has been used.

3.1 Experimental analysis

To achieve my ambitions several tests were carried out at the Structural Laboratory of the Budapest University of Technology and Economics. For the determination of the load penetration characteristics of the dowels 93 experiments were carried out. The diameter of the dowel, the loading direction and the type of the wood has been analyzed.

3.2 Finite element analysis

The load-slip curve in different joint arrangements can be determined using finite element analysis. In my dissertation several finite element analyses has been carried out of joints under single shear and double shear. The presented calculations are based on 3D models built up by using solid elements. The models contain the connected timber members and the screw or screws as well. The connection between the screws and the timber members are modelled by contact elements. Contact elements have been defined at the interaction surfaces of the wooden members as well. The contact elements and the nonlinear material model of the screw required nonlinear finite element analyses. The calculations were carried out with the Ansys software [6].

3.3 Computer iteration procedure

The determination of the load-slip characteristics of the joints by experiments or finite element analysis is time consuming and complicated. For this reason I worked out an iteration procedure, which also provides the load-slip behaviour, but its application is quick and easy.

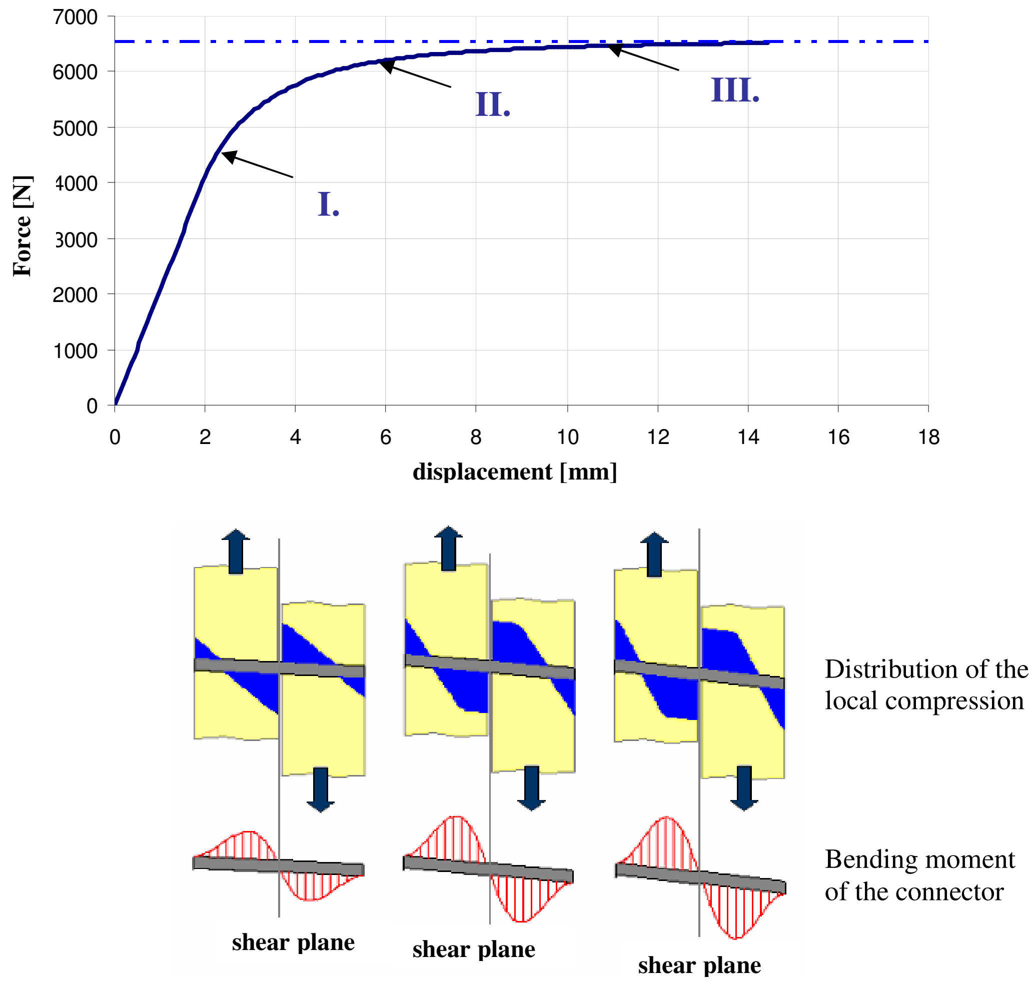

Figure 1. Iteration procedure: load-slip diagram, calculated distribution of the local compression

In the iteration method the connector is divided into unit length pieces along its axis. The calculation proceeds from one of the edges of the connector towards the other edge of the dowel, while the penetration of the connector, the local compressive stress, the curvature and the rotations are calculated in every piece. The substance of the procedure is the modulation of the penetration and rotation at the edge of the connector, starting from an initial value until both equilibrium conditions are satisfied (vertical force and moment). Increasing the loading the full load-slip relationship can be obtained.

3.4 Analytical calculation procedure

Johansen equations describing the failure of dowel type joints are based on the assumed load distributions at the failure. The simplest way of the determination of the initial slip stiffness of the joints is to assume linear local compression distributions, which are acting at the beginning period of the loading. Assuming linear local compression distribution the slip modulus of the joints can be determined analytically using the penetration stiffness behaviour.

4. RESEARCH RESULTS

4.1 Load-penetration relationship of metal dowels

When modelling dowel-type timber joints the main point of the calculation is the load-penetration characteristics of the dowels. Fig. 2. represents the penetration parallel and perpendicular to the grain.

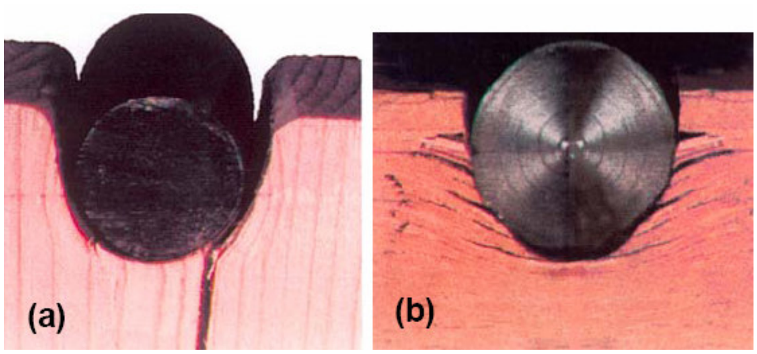

Figure 2. a, penetration parallel to the grain b, penetration perpendicular to the grain

The carried out analyses proved, that the penetration stiffness is influenced by the type of the wood, the grain direction and the diameter of the dowel as well.

New result #1.

I provided the local compression-penetration relationship of five different wood types (used in structural engineering in Hungary) relating to three different dowel diameters by experiments in the grain direction and perpendicular to the grains as well.
a, I introduced the penetration stiffness behaviour, which provides the penetration of metal dowels into the wooden material under unit force.
b, I created design functions for the simplified consideration of local compression-penetration behaviour in grain direction and perpendicular to the grains as well.
c, I pointed out, that the diameter of dowel is independent of the penetration stiffness in case of grain directional loading, but in the case of perpendicular penetration the diameter influences the penetration stiffness (to larger diameter smaller stiffness belongs) .
[S1],[S3]

4.2 Stiffness analysis of a single dowel of timber to timber joints under single shear

In my dissertation I carried out parameter analysis for the determination of the load-slip characteristics of timber to timber joints under symmetric single shear, non symmetric single shear and double shear. I analysed the effect of the size of the cross sections, the diameter of the dowel and the angle between the load direction and the grain direction on the joint slip stiffness. The adequacy and accuracy of my created calculation procedure (iteration procedure) has been proved by finite element analysis (Fig. 3.) in case of symmetric and non symmetric joint arrangement as well.

In the case of symmetric joints under single shear the results showed, that the width of the wooden members increases the slip stiffness if the dowel is not too slender, which means that the proportion of the width of the wooden member and the diameter of the dowel is less than ten. (*t/d<10*).

Analysing the effect of the angle between the load direction and the grain direction on the joint stiffness I experienced, that the more the load direction deviates from the grain direction the better the slip stiffness decreases.

In the case of non symmetric joints, the distributions of the local compression in the connected elements are not the same, thus the dowel is not free from bending moment in the shear plane.

This joint behaviour totally differs from the behaviour of symmetric joint arrangements. Despite all these, the calculation method of the slip modulus is the same according to the standards in use [2] [1] in both cases. My calculation results (that is obtained from the modified iteration procedure) show, that both of the width of the wooden members and the grain directions significantly influence the slip stiffness.

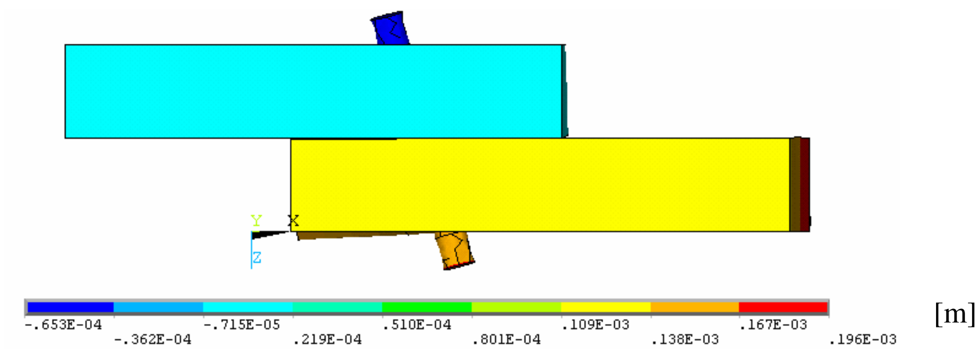

Figure 3. Displacement

I created an expression for the analytical calculation of joints under shear, which provides the initial slip stiffness for the symmetric and nonsymmetric cases too. The accuracy of the calculation has been proved by finite element analysis.

New result #2.

I created an iteration procedure for the determination of the load-slip behaviour of dowelled timber to timber joints under single shear, which considers the density and the geometry of the wood, the diameter and material model of the dowel, the loading direction and the type of the failure. The accuracy of the proceudre is proved by finite element analysis.
a, I showed that in the case of not too slender dowel (t/d<10) the initial joint slip stiffness is influenced by the width of the wooden memebers (the larger the width of the wooden member the higher stiffness is obtained).

b, Based on the grain direction dependency of the load-penetration relationships I showed that the slip behaviour including the initial stiffness of joints under single shear is significantly influenced by the load direction: the grain directional stiffness is approximately three times as high as the perpendicular stiffness.
c, Based on the approximate consideration of the initial deformation of the dowel I created an expression, which can be used to determine the initial slip stiffness of timber to timber joints simply. The accuracy of the expression is proved by the iteration procedure and finite element calculations as well.
[S1]

4.3 Stiffness analysis of a single dowel of timber to timber joints under double shear

According to Eurocode 5 [2] timber to timber joints under double shear have four failure modes. Similary to joints under single shear the local compression or the yielding of the dowel can be the reason of the failure. In all four cases the failure is symmetric, thus the deformation of the dowels is symmetric too.

In the case of joints under single shear my results showed, that the diameter of the screw is linearly propotional to the slip stiffness, but in the case of joints under double shear this proportionity is not true.

The highest slip stiffness is in the grain direction, similarly to the single shear joints. In the case of perpendicular loading the joint slip stiffness may result three times less value than in the case of paralell loading.

Correspondingly to the joints under single shear, during the analysis of the slip behaviour of joints under double shear I proved my research conclusions by my selfmade numerical iteration procedure and finite element analysis as well.

New result #3.

I created an iteration procedure for the determination of the load-slip behaviour of dowelled timber to timber joints under double shear. The procedure considers the density and the geometry of the wood, the diameter and material model of the dowel, the loading direction and the type of the failure. The accuracy of the proceudre is proved by finite element analysis.
a, I showed that the slip stiffness related to one shear plane of the joint under double shear can be four-five times as big as the stiffness of the joint under single shear with the same geometrical characteristics. (the sizes of the wooden members, the grain directions, and the diameter of the dowels are the same).
b, I proved, that the slip stiffness of the joints under double shear is not the linear function of the diameter of the connector, contrary to calculation expression of Eurocode 5 [2]. According to my analyes the relationship between the joint slip stiffness and the diameter of the connector is the fuction of the joint geometry, averagely the stiffness is proportional to the diameter raised to the one and half power.
c, Based on the grain direction dependency of the load-penetration relationships I showed that the slip behaviour including the initial stiffness of joints under double shear is

significantly influenced by the direction of the loading: the grain directional stiffness is approximately three times as high as the perpendicular stiffness.
d, Based on the approximate consideration of the initial deformation of the dowel I created an expression, which can be used to determine the initial slip stiffness of timber to timber joints under double shear simply, if the widths of the wooden members related to one shear plane are approximatelly the same.
[S2],[S4].

4.4 Slip analysis of multiple connector joints

Eurocode 5 [2] and MSZ 15025 calculate the load-carrying capacity and the slip stiffness of the joint as a product of the base value, the number of connectors and the number of shear planes. Using the previously presented load-slip diagrams I analysed the changing of the slip stiffness with finite element analysis and the Lantos-modell [7] applying different connector numbers.

I showed by finite element analysis that the deformations in the dowels are nearly the same, thus the forces acting on the connectors are the same. The stiffness of the joints changes nearly linearly by the number of the connectors, one to two percent of decreasing can be experienced comparing to the linear product of the single stiffness multiplied by the connector number and shear plane number.
Considering the calculated load-slip behaviours the force distribution between the bolts can be determined by taking the different penetrations (obviously only a little difference) into account. Since the beggining part of the load-slip curve is linear in the case of any joint type and arrangement, the average force in a bolt is equal to the force that is acting on the single connector joint.

New result #4.

I analysed the effect of the number of the bolts on the full load-slip behaviour of the joints based on the load-slip relationship determined for induvidual dowels. Using the Lantos-modell and finite element analysis I proved that the force distribution between the bolts are not uniform, but inspite of this, the initial slip stiffness of the full joint can be calculated by the product of the initial stiffness for one bolt and the number of bolts. I proved that this calculation procedure results more accurate value for the slip modulus in the case of joint arrangements, where the bolts are under double shear.
[S2],[S4].

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