LOAD BEARING CAPACITY OF TRADITIONAL ROOF STRUCTURES – MODELLING OF JOINTS

Heiko Koch, Dipl.-Ing.
Werner Seim, Prof. Dr.-Ing.
University of Kassel, Germany
Department of Structural Engineering
Kurt-Wolters-Straße 3, D-34125 Kassel

Summary

Historical timber structures are built with traditionally manufactured timber joints. The load transmission of these nodes occurs mostly by the contact of the compression-loaded areas. As timber shows an elastic-plastic behaviour under compression perpendicular to the grain, this can be considered for traditional timber joints in a structural analysis by using nonlinear spring elements. Two types of spring-elements were derived from test results, which were taken from literature. Application of the spring-elements into a nonlinear structural analysis opens up reserves of the load bearing capacity, that matters particularly with regard to the structural analysis of existing historical timber structures.

1. Introduction

The structural safety of historical timber structures has always then to be checked, when a change of use is required or when structural deficiencies are obviously. In such cases a careful modelling is necessary to check the load bearing capacity of the structure and to minimize strengthening measures. As the load bearing behaviour depends highly on the strength and the deformation of the joints, it is essential to introduce load–displacement conditions which are close to reality [1].

The nodes of traditional timber structures are normally built with craftsman manufactured joints. The load transmission occurs mainly through the contact of the compression-loaded areas parallel and perpendicular to the grain. Directly in these areas timber shows an elastic-plastic behaviour (e. g. [2]), see figure 1.

Fig 1 Stress-strain curves of timber: (a) parallel and perpendicular to the grain [3], (b) for compression perpendicular to the grain [4].
The consideration of this load bearing behaviour opens up additional potentials of the load bearing capacity which matter to the static calculation of historical timber structures. Consecutively a method will be presented, that allows to consider the elastic-plastic behaviour of traditional timber joints close to reality.

This work is a first step of a larger research project on historic roof structures.

2. Derivation of elastic-plastic spring-elements

2.1 Rectangular skew notch

The experiments of Heimeshoff and Köhler [5] form the basis of the elastic-plastic spring-elements. The authors analysed the load bearing behavior of traditional timber joints, especially of the rectangular skew notch. Multiple series of specimen with different dimensions were carried out. Results from the series 2 (see figure 2 (b)) were used for the identification of the characteristics of the spring element.

The series 2 consists of 6 pairs of specimen with the same dimensions. The dimensions are displayed in figure 2 (a).

![Fig 2 Tests of the rectangular skew notch: (a) rectangular skew notch, (b) load-displacement curves, according to [5].](image)

The typical load-deflection-attitude can be divided into 3 phases:

I. Slip-phase:
The proper manufactured specimen received shrinkage deformations. The resulting gaps are closed at the beginning of the loading. This phase shows a flat inclination of the load-displacement curve.

II. Elastic-phase
The load-deflection curve proceeds approximated linear. The force is proportional to the displacement.

III. Plastic-phase
The displacement increases highly before the fracture, with more or less increasing load.
Two types of failure can be distinguished: The compressive stresses at the front contact areas reached the plastic region. After this arised substantial deformation until several grains buckled and the testing load plunged down. In other cases the upper part of the ledger runner sheared off. This happened at specimen with branches in the ledger runner.

The load-displacement behaviour was averaged and linearised with the phases I and II summarised as one phase. It is now possible to use this curve in nonlinear computer-aided calculations as the force-deflection properties of spring elements, if accurate timber (no branches in the compressive zones) is secured by visual examination (see figure 2 (b)).

To use these curves for design calculations in practice, it is necessary to transform the ultimate load capability to the design load capability.

### 2.2 Contact joint

Eberhardsteiner [6] conducted tests over the mechanic behaviour of timber (spruce) under compression perpendicular to the grain, see figure 3.

![Fig 3 Load-displacement curves of timber under compression perpendicular to the grain, according to [6]](image)

![Fig 4 Linear strain allocation in the girder (elastic state).](image)

The characteristic point of a simplified stress-strain curve is given with:

- Proportional limit: \( f_{c,p,90} = 7 \text{ N/mm}^2 \) \( \varepsilon_{c,p,90} = 0.015 \)

Hence a load-displacement curve for a contact joint can be calculated, if a linear strain allocation (figure 4) and, for loading over this point, ideal-plastic behavior is assumed. That means, when the proportional limit strain is exceeded, the strains increase under further deformation by constant stresses.

The elastic deformation at the proportional limit state arises to: \( \Delta u_{el} = 0.5 \cdot \varepsilon_{c,p,90} \cdot h \)

In analogy to section 2.1 it is required to transform this load-displacement curve to the design load capability.
3. Calculation Example

The application of the elastic-plastic spring model will be illustrated with a simple example (figure 5). The connections (1) of the girder/stud with the angle-brace-ties are made with rectangular skew notches such as in figure 2 (a) and the connection (2) of the girder with the stud is made with a simple contact joint.

![Figure 5: Calculation example: Two-span-beam with angle brace ties.](image)

The strength parameters of the mechanical model are introduced as characteristic values. Maximum displacements are derived from the test results.

3.3 Model of the rectangular skew notch

The characteristic strength of the skew notch can be calculated under the terms of DIN 1052 [7]. It is required, that the areas in front of the skew notches are free from cracks and branches. The following conditions can be assumed:

- Elastic-plastic behaviour of the rectangular skew notch (see figure 2 (b))
- The timber quality is locally approved as C30
- The shearing strength \( f_{v,k}^* \) can be increased, see [8]

\[
f_{v,k}^* = \frac{f_{v,k,\text{DIN 1052}}}{0.55}
\]

Then the calculated, characteristic strength of the skew notches is \( F_{c,k} = 40.5 \text{ kN} \). The spring element in the computer-aided calculation is oriented parallel to the coordinate axis, two spring-elements are used for one joint. Therefore it is necessary to transform the load-deflection curve over 45 degrees (figure 6).

![Figure 6: Transformation of load-displacement curves.](image)
3.4 Model of the contact joint

The characteristic strength of the contact joint can also be calculated under the terms of DIN 1052 [7].

The calculated, characteristic strength of the contact joint is $F_{c,k} = 142$ kN. The simplified load-displacement curve of the contact joint is displayed in figure 7 (b).

![Fig 7 Load-displacement curves: (a) Transformed curve of the rectangular skew notch, (b) contact joint.](image)

3.5 Calculation results

The nonlinear calculation was carried out with ANSYS [9]. The load was divided into 100 steps, so that the computation was realised incremental with increasing load.

Initially the system behaves linear-elastic until a load of 16,0 kN/m (loadstep 32). When loadstep 32 is obtained, the spring elements of the rectangular skew notches (1) reach the elastic-plastic load limit. This loadstep marks the maximum load of a linear-elastic calculation (figure 8).

![Fig 8 Results from computer-aided calculation, loadstep 32 (16,0 kN/m): (a) deflection, (b) bending moment.](image)
In a nonlinear calculation the system can be loaded further. The spring elements of the angle brace ties deform without carrying any more load. The added load is taken down by the stud, until the spring element of the rectangular skew notch (1) reaches the ultimate displacement (figure 9 (a)). That happens in loadstep 52 (26.0 kN/m). The system could be loaded theoretically further until loadstep 66, when the elastic-plastic spring-element of the contact joint (2) reaches its elastic-plastic load limit. Then the system fails, the deformations increase excessively. The difference between loadstep 32 and loadstep 52 equals 10,0 kN/m and is the possible cumulation of the maximum load compared to a linear-elastic calculation. This can be denoted as "plastic-system-reserve". In that context it has to be mentioned that the failure of the structural members (f. e. the girder and the stud) is not considered. Which is not so far from the reality, because for traditional structures the nodes are mostly the weak parts.

Fig 9  Results from computer-aided calculation in loadstep 52 (26.0 kN/m): (a) deflection, (b) bending moment.

4. Conclusions

Non-linear spring-elements for two kinds of traditional timber joints, which display elastic-plastic properties, could be derived. The application of those elements in a nonlinear computer-aided calculation opens up considerable reserves of the load bearing capacity of the structure, compared to a calculation based on the linear theory of elasticity.

The transformation of the load-displacement curves to the characteristic load capability was accomplished by a displacement of the curves parallel to the displacement-axis. Here is a need for further research to backup this transformation with better probabilistic knowledge.

A comprehensive testing program on specimen of traditional timber joints is planned. More types of traditional timber joints will be examined and the influence of the concurrent stresses from compression perpendicular to the grain and bending - compression or tension parallel to the grain – will be considered.

The results of structural calculations will be approved by full scale testing.
References


[9] ANSYS, Release 10.0, ANSYS Inc., Canonsburg, PA 15317, USA