The influence of nail ductility on the capacity of a glulam truss structure

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Summary

In wood structures, the way to achieve high ductility is to take advantage of the plasticity of mechanical connectors (nails, dowels, bolts etc). In this paper the influence of ductile connections on the total load-carrying capacity of a glulam truss is investigated. The connections used in the structure are slotted-in nailed joints. Experimental investigations are modelled by a finite element model of a truss to simulate how different shapes of the nail load-displacement curve affect the load-carrying capacity. The results clearly show that consideration of the true elastic-plastic load-displacement behaviour of the nails results in a higher capacity of the truss compared to using linear elastic nail properties.

Keywords: *ductility, load-carrying capacity, glulam, nail connection, timber truss*

1. Introduction

A ductile timber structure is possible when collapse is governed by failures in mechanical dowel-type joints. Since wooden structural components largely exhibit brittle failures, especially under tension and bending, most of the deformations should occur in the connections. Ductility in itself is characterized as deformation capacity and the definitions of ductility found in literature, e.g., [1, 2], are all expressed as the relationship between three key deformations; u_y (elastic displacement), u_u (displacement at maximum load) and u_f (displacement at fracture). For static loading of timber structures, ductility is traditionally not used and no verification is available of how ductility in a safe way can be employed in design.

In this paper the slotted-in connection with two steel plates and shot-through nails in glulam, Fig. 1a, presented in [3], is studied for the effect of the ductility of the connection on the load-carrying capacity of the glulam truss structure in Fig. 1b. Experimentally determined load and displacement characteristics of this connection are systematically investigated in finite element studies to investigate if and how connection ductility influences the load-carrying capacity of the structure.

2. Connection capacity

The load-carrying capacity, R , per shear plane for a joint with two slotted-in steel plates is determined by a combination of Eq. (1a) and (1b) combining EC5 [4] and [5].

a) Outer members of wood b) Inner member of wood

$$R = \min \begin{cases} 1, 1f_h t_1 d & 0, 5f_h t_2 d & \text{mode I} \\ 1, 1f_h t_1 d \left(\sqrt{2 + \frac{4M_y}{f_h d t_1^2}} - 1 \right) & & \text{mode II} \\ 1, 5\sqrt{2M_y f_h d} & 1, 1\sqrt{2M_y f_h d} & \text{mode III} \end{cases} \quad (1a, b)$$

Here t is the minimum of the timber member thickness and the embedded length of the fastener, and d is the diameter of the fastener, f_h , the embedding strength of wood and, M_y , the yield moment. Since the ultimate failure (defined by u_f) in wood is brittle, either by splitting, row or shear-plug failure, ductility is promoted using certain fastener spacing and end distances. Failure mode III yields maximum load-carrying capacity and is the most ductile of all three modes.

Fig 1. (a) Slotted-in connection with two steel plates and shot through nails in glulam (geometry of test specimen) (b) Glulam truss structure. (c) Connection design in glulam truss. (Dimensions in mm).

3. Experimental study

3.1 Full scale truss joint experiments

Fig. 2 Load-displacement curve

The joints of the glulam truss structure, Fig. 1b, were investigated in [6] by performing full-scale experiments, Fig. 1c, yielding results for tension and compression at an angle to the grain.

The load-displacement curve for one of the 16 experiments presented in [6] at pos. 1 is shown in Fig. 2. This full-scale experiment is modelled using the finite element (FE) method and the results are used to verify the validity of the FE-model.

3.2 Medium sized test in tension parallel and perpendicular to the grain

From the nail load-displacement (NLD) curves determined from 15 experiments parallel to the grain on the slotted-in, shot-through connections in [3] the three key deformations; u_y , u_u and u_f were established. These displacement values were used to construct one single, linearized, NLD curve by using a least-squares regression. The resulting mean value curve, representing the joint behaviour parallel to the grain, is shown in Fig. 3a.

Two medium size glulam (*Picea abies*) joints, 300 mm × 450 mm, with a thickness of 29 mm were tested in tension perpendicular to the grain. Slots of 2.2 mm thickness were sawn into the specimen. The joint consisted of two 2 mm thick, 90 mm × 800 mm steel plates, with a yield strength of $f_y = 275$ MPa. Each specimen was designed with 8 nails of high strength steel, $M_y = 18.7$ Nm, of $d = 3.7$ mm and length 97 mm, driven through the wood and the steel plates into 3.5 mm pre-drilled holes. The nail pattern and end distance shown in Fig. 1a was chosen to avoid wood fracture perpendicular

to the grain. The tests were conducted according to the static ISO 6891 loading protocol using the an hydraulic testing machine and two transducers placed over the region of the joint. The transducers measure the displacement between the plates and the glulam beam at the bottom row of nails.

The elastic displacement u_y is determined according to [7] as the intersection of the lines between $0.1 \cdot F_u$ and $0.4 \cdot F_u$ and the tangent to the NLD curve, for a line with $1/6$ of the stiffness of the first curve. Here F_u is the experimentally determined nail load-carrying capacity. A curve fit to obtain a linearized single NLD curve was then calculated in the same way as for the medium sized joint tests in tension parallel to the grain. The result is shown in Fig. 3b.

Fig 3. (a) Mean value NLD- curve parallel to the grain, (b) Mean value NLD- curve perpendicular to the grain.

4. Numerical methods

4.1 FE modelling of a truss connection

The truss joint experimentally investigated above was modelled with 5000 2D solid elements, with four nodes per element, using a linear stress interpolation and plane stress state assumption. The element size varied between 400 and 2500 mm². The slotted-in, shot through joint was modelled using orthotropic parameters for the glulam, and isotropic parameters for the slotted-in steel plates, so that two sets of connected elements define the nailed joint. At wood-to-wood connections, the contact pressure was simulated by spring elements with compression stiffness only (0,22 kN/mm). In joints transferring loads at an angle to the grain, springs with varying tension stiffness taken from Fig. 3a and b simulate the non-linear wood behaviour.

Elastic material parameters, according to [8], resulted in a modelled maximum load $F_{\max} = 566,3$ kN at pos. 1 only 5.6 % larger than the experimental load. The modelled reaction force at pos. 2, Fig. 1c, is 6.4 % larger, and at pos. 3 is 0.1 % smaller than the experimental values. The results are reassuring enough, so that the same modelling method (material choice, element types, spring characteristics etc.) can be used to model the glulam truss structure.

4.2 FE modelling of the truss

Fig. 4 Glulam truss model with numbering of connections and boundary conditions. Load symmetry allows modelling of one half of the truss.

An FE-model of the truss in Fig. 1b was created using solid, orthotropic, 2D elements. The same elements, non-linear spring elements and assumptions as used for the FE-model of the full-scale truss joint, were utilized. The total number of solid, beam and spring elements in the model is 9757. The load was applied as force increments of 0.48 kN/m per incremental step.

5. Parameter studies

The finite element simulation performed examines the effect of the shape of seven different NLD curves (ductility behaviour characteristics) on the load-carrying capacity of the glulam truss structure. The load is incrementally increased until failure of one nail occurs. In these simulations, failure is defined when the displacement for one nail reaches u_f at which the nail, by definition, has zero load-carrying capacity.

As a reference case, curve 1 in Fig. 5, the result using the experimentally determined NLD-curves in Fig. 3a and b estimates a maximum load-carrying capacity for the glulam structure to $F_{\max} = 233.4$ kN, and a maximum mid-span deflection of $u_{\max} = 143.9$ mm. This state is reached when one nail fails parallel to the grain at connection 7, Fig. 4.

The NLD-curves 3-8, Fig. 5, represent an approximate increase and decrease of 20 %, compared to the experimental curve 1, of the ductility variants:

$$D_f = \frac{u_f}{u_y} ; D_{f/u} = \frac{u_f}{u_u} \quad (2)$$

Point	A	B	C	Deviation from experimental values
Load [kN]	7,9	10,4	10,4	
Curve	Displacement [mm]			
1	0,34	4,89	7,89	Experimental
3	0,28	4,89	7,89	u_y 16,7 % lower
4	0,43	4,89	7,89	u_y 25 % higher
5	0,34	4,08	7,89	u_u 16,7 % lower
6	0,34	6,11	7,89	u_u 25 % higher
7	0,34	4,89	6,31	u_f 20 % lower
8	0,34	4,89	9,47	u_f 20 % higher

Fig. 5 Schematic load-displacement curves used in parameter studies of the glulam truss and table containing values for curves 1, 3- and "code-elastic" curve 2.

Curve 2 represents the linear elastic curve in the EC5 code, where the nail load-carrying capacity, F_u , is defined at u_u . The stiffness of curve 2 is calculated according to the EC5 ultimate limit state initial stiffness, $K_u = (2\rho \cdot d^{0.8})/75$ where ρ is the timber density.

It should be noted that the experimental load values in curve 1 are kept constant in curves 3-8, since the ductility is defined as the ratios between displacement values. From the results of the simulations, the effects of seven variants of the experimental NLD-curves on the maximum load-carrying capacity of the glulam structure and the maximum mid-span deflection are calculated, Table 1.

A salient result obvious from Table 1 is the positive effect of ductility, i.e. a plastic behaviour between u_u and u_f , on the total load-carrying capacity. A comparison of $F_{\max}$ for curve 1 (experimental values) yields a 21% higher load-carrying capacity, but also 18 % higher mid-span deflection, than curve 2 (code, linear elastic behaviour).

Another interesting result is that almost no difference in $F_{\max}$ is evident when comparing curve 1 with curves 3-8, despite the relatively large differences in deformation capacity and the shapes of the NLD-curves. For example, an increase of the u_f value of 20 % only results in an increase of approximately 1 % of $F_{\max}$ and an increase of nearly 6 % of $u_{\max}$. In view of the difficulties reported in [9] when defining the displacement at fracture, this result is interesting since it indicates that an explicit measurement/definition of u_f is not crucial.

Table 1. Simulation results for maximum vertical reaction forces at connection 1 and mid-span deflections for NLD-curves 1-12. ΔR and $\Delta \delta$ shows difference between results compared with NLD-curve 1.

NLD-curve	Reaction force R (kN)	ΔR (%)	Mid span deflection δ (mm)	$\Delta \delta$ (%)
1	233,4	0	-143,9	0
2	183,5	-21	-117,7	-18
3	235,1	1	-146,1	2
4	233,4	-	-148,4	3
5	233,7	-	-142,3	-1
6	234,7	1	-152,2	6
7	230,6	-1	-138,1	-4
8	235,8	1	-152,0	6
9	133,1	-43	-150,0	4
10	219,6	-6	-150,0	4
11	270,6	16	-132,9	-8
12	27,6	-88	-226,4	57

6. Discussion, Conclusions and Acknowledgements

A salient result obvious from the experimental and numerical studies presented in this paper is the positive effect of ductility, i.e. a plastic softening behaviour between u_u and u_f , on the total load-carrying capacity. A comparison of $F_{\max}$ for curve 1 (experimental values) yields a 21 % higher load-carrying capacity, but also 18 % higher mid-span deflection, than curve 2 (code, linear elastic behaviour).

When the experimental results from medium sized joint tests performed in this study and the results of [3] were linearized, good correlation was achieved ($r^2 = 0.79$ parallel and $r^2 = 0.80$ perpendicular to the grain) for the initial stiffness, while for the plastic behaviour following the displacement u_u , very uncertain correlation was found. This clearly demonstrates the variability in wood, especially close to the final brittle failure. Taking this uncertainty in to account, the parametric study shows clearly that changing the key deformations of the experimentally determined NLD with ± 20 % did not have any significant influence on the structural load-carrying capacity. This study suggests that an accurate curve correlation or an exact determination/definition of the final failure u_f is not critical for either modelling purposes or for the task of determining the overall load-deflection behaviour of this structure.

From the modelling results in Table 1 it is clear that ductile NLD behaviour affects the load-carrying capacity in a positive way. This means that more ductile behaviour, up to a certain level, will produce a higher load-carrying capacity. This relationship between strong and ductile behaviour is also consistent with the requirements for a timber connection design with optimized load-carrying capacity and ductility, put forth by [10]. How to define the upper deformation limit or ductility level is an, as yet, unsolved question. The question can be formulated as: how close to u_f can the joint be deformed and still keep an acceptable level of safety, avoiding brittle failure and splitting? The question is pertinent to code work and ultimately to practical design applications.

6.1 Acknowledgements

The authors are grateful to Assistant Professor Milan Veljkovic, at the Division of Steel Structures at Luleå University of Technology, for all his support concerning applications of the finite element method to details and structures dealt with in this paper.

7. References

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