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Modeling the influence of delamination on the mechanical performance of straight glued laminated timber beams

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HIGHLIGHTS

- Finite element modeling was used to evaluate straight glued laminated timber beams.
- Non-symmetric delamination can cause the member's lateral instability.
- Symmetric delamination on low shear stress areas is not a problem.
- High delamination can be achieved without reach the elastic limit.
- Structural integrity may be at risk for delamination depth higher than 60%.

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ABSTRACT

Delamination at the glue lines is a key factor to take into account when assessing glued laminated timber members in service. In order to gain a more objective and wide knowledge about the importance of delamination in relation to its type and extension, a numerical study was developed.

Finite element modeling (FEM) was used to evaluate the influence of delamination – near the surface, on the vertical faces and ends – on the mechanic performance of straight glued laminated timber beams. The FEM was validated by comparing stresses and deformations obtained with the model and with the application of the beam theory, showing satisfactory results. Results show that when delamination is non-symmetric regarding the member's cross section, it can cause the member's lateral instability, thus increasing its stresses and deformations. Delamination is not a problem when it occurs in members or member areas with low shear stresses, particularly when it is symmetric and does not reach the whole width of the beam. The stresses corresponding to the bending or deformation limit-states get near the elastic limit only for very important delamination. Moreover, delamination depth higher than 60% of the cross section width may be regarded as a turn point beyond which the structural integrity may be at risk.

1. Introduction

Delamination at the glue lines is a key factor to take into account when assessing glued laminated timber members in service. Not only delamination enables water intake in exterior structures fully exposed to weather and thus progressive damage due to moisture induced dimensional variations [1], but they may denote insufficient strength or durability of the glued joints regarding the service class they are exposed to.

In some cases, local separation of lamellas that are visible at the member faces may result from fabrication defects like adhesive starvation, variations in lamellas' thickness, lack of pressure or a too long open time leading to poor contact or improper adhesion. These are not true delamination of the glued lines and should be the object of complementary tests to check if these glued line openings are just local defects or, on the contrary, adhesion between lamellas may be globally deficient.

A different situation is delamination (the bondline failure in service), that tends to develop as a consequence of stresses resulting from the applied loads or moisture content variations.

Delamination influence on strength and stiffness will depend on their length, depth and exact location in the glulam member, as

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well as on the member size, shape and stress distribution. Particularly worrying is fresh fast-growing delamination, that often indicates a member failure in progress.

In order to gain a more objective and systematic insight on the importance of delamination relative to their type and extension, a numerical study was developed.

The main goal of numerical modeling performed was to assess the impact of delamination in the bearing capacity of the element, in order to make an approach to the problems that the separation of bonded lamellas in service can create in glued laminated timber structures, identifying situations that may justify a more detailed analysis of their safety and suitable remedial measures.

This numerical work focused the case of straight glued laminated timber beams previously tested by the authors for strength and stiffness [2], and therefore results are related to the chosen beam geometry. However, not only the outcome of this study helps understanding the importance of the addressed delamination problem, but it may also contribute to discussing the importance of drying fissures, both in glued laminated timber and solid timber members.

1.1. Failure of glued joints

The failure of the glued joints may occur in three distinct modes, in the direction perpendicular to the joint plane (mode I) and the others in the two perpendicular directions contained in the joint plane, mode II (in the longitudinal direction) or mode III (in the direction perpendicular to mode II).

The intensity of stresses or energy required to failure depends of the properties of wood, adhesive and stress state. The presence of small glued joint defects, such as voids, micro-cracks, areas with poor curing of the adhesive or others may generate critical discontinuities in the stress field which could also lead to failure [3]. Serrano and Gustafsson [4] showed that a single, small glueline void can have a considerable influence on reducing finger-joints' strength.

In the analysis of glued joints' failure it is necessary to consider its strength, energy required to failure and shape of the stress–strain curve of the timber. However, for sufficiently large joints it can be assumed that the failure energy is a decisive factor for strength [5]. Results obtained experimentally with common adhesives show that the shear deformation of glued joints is very low in the elastic region, subsequently verifying a high deformation until reaching the failure [6].

For wood, energy is approximately between 200 and 400 J/m^2 for the failure mode I and reaches approximately three times this value for the failure mode II. To make a more accurate assessment, the value of energy corresponding to the mixed mode involving the two previous should be known [7]. The determination of failure energy of glued joints is difficult [8]. For resorcinol/formaldehyde adhesive, Wernersson [5] obtained 360 J/m^2 for the failure energy for mode I and values between 850 and 1000 J/m^2 for the failure energy in mode II. According to the same author, the relationship between the strength (P_{max}) and the fracture energy (G_{fII}) is as follows:

$$P_{\max} = \frac{1}{2}\sqrt{E\, G_{fII}\, b_n\, A} \tag{1}$$

where:

E is the modulus of elasticity in bending of wood.
b_n is the width of the glued joint.
A is the cross-section of the lamellae.

Petersson [9] developed an expression to determine the critical moment (M_c) where an unstable crack will develop in the glue line between the failed lamination and the rest of the beam:

$$M_c = \sqrt{\frac{2\, G_f\, b\, E_L\, I}{1/\alpha^3 - 1}} \tag{2}$$

where:

E_L is the modulus of elasticity in the direction of the fibers.
G_f is the energy needed to propagate a crack.
b is the width of the beam.
I is the moment of inertia of the beam.
α is equal to $(h - \Delta h)/h$ where h is the height of the cross section and Δh the thickness of the lamella.

In fact, the failure cracks may represent an area of lower strength located at the outermost fibers, such as a knot or a finger-joint, which can fist reach the failure. The subsequent behavior of the beam shall be governed by crack propagation along the beam. This expression leads to the conclusion that the flexural strength decreases with increasing thickness of the lamella. The applicability of this expression was confirmed by Serrano and Larsen [7] that carried out simulations using 2D finite element to model an element with 1.60 m length subject to bending where a fissure was introduced in the outermost fiber subjected to tension. Furthermore, these authors concluded that with decreasing lamella thickness the governing failure mode changes from mode I to mode II approach, meaning that thinner lamellas (around 3 mm) tend to lead to shear failure whereas the failure for ticker lamellas (around 0.05 m) tends to be mixed. The possibility of failure beginning in a knot, finger-joint or fissure located in the outermost lamella depends of the height of the beam [10], however this weak zone should always be carefully inspected because it can lead to substantial strength reducing.

1.2. Influence of delamination or drying cracks

There are relatively few known studies regarding the influence of delamination or drying cracks on the mechanical performance of glued laminated beams.

Soltis and Gerhardt [11] performed a state of the art review of shear design of wood beams. They mentioned that shear strength depend on crack depth for depth over 30% of beam width.

Khorasan [12] studied the influence of formed cracks on glulam beams load-carrying capacity. Simulations produced with ABAQUS were compared with previous available experimental results by Anderson and Oden [13]. Two groups of spruce glulam beams of 2.6 m × 0.315 m × 0.115 m were tested in 3-point bending over a 2.275 m span. The first group had no cracks and the other had natural cracks due to natural weathering. Although both groups showed similar density, there was no effect of surface cracking on the ultimate strength.

The FEM developed by these authors and calibrated with good approach for these beams was then extended to predict the performance of beams with 9 m × 0.14 m × 0.45 m that had been exposed to outdoor climate during 5 years. Calibration of the model was done for a beam with a large number of cracks (12 of which over 15% of the beam width (in this case, between 22 and 44 mm deep)), distributed along its length but on one face. Simulations were done considering the load point located at mid-span, 1/4 or 1/8 of the span, indicating that the strength of the beam is reduced of 5.9%, 11.7% and 26%, respectively.

Pousette and Ekevad [14] studied the importance of different types of cracks for the shear strength of spruce glulam beams. Five types of 2.6 m × 0.115 m × 0.315 m glulam beams, with or without lengthwise cracks of different depths and locations were tested in three-point bending. Cracks made by sawing (grooves), as well as natural cracks due to weathering, were considered. They tested the following situations: no cracks; one crack in the middle glued