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

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**Abstract** Delamination at the glue lines is one 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 relative to its type and extension, a numerical study was developed.
Finite element modeling (FEM) was used to evaluate the delamination influence (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 are close to 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.

**Keywords** glued laminated timber, delamination, finite element models

## 1. INTRODUCTION

Delamination at the glue lines is one 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, but they may denote insufficient strength or durability of the bond joints regarding the service class they are exposed to.
In some cases, local separation of lamellas that are visible at the member faces may be a result from fabrication defects like adhesive starvation, variations in lamellas' thickness, lack of pressure or a too long open time leading to failure in contact or proper adhesion. These are not true delamination of the glue lines and should be the object of complementary tests to check if these glue 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 tend 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 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.

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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.
This numerical work focused the case of straight beams previously tested by the authors for strength and stiffness (Gaspar 2006), and therefore results are somehow limited 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.

## 2. MODEL

### 2.1. Geometry

A 3-D finite element model of a straight glulam beam was developed using software Abaqus/CAE Version 6.7-EFI of Dassault Systèmes Simulia Corp., Providence, RI, USA.
The modeled beam was 0.10 m wide x 0.24 m high (h) (6 x 0.04 m thick lamellas) x 4.40 m long, simply supported over a 4.32m span (equal to 18 times its height, according to EN 408), with two loads symmetrically applied relatively to the middle of the beam.
Tridimensional solid elements of 20 nodes and 3 degrees of freedom per node (displacement in x, y and z directions) were adopted.
Timber lamellas were modeled with elements of 0.04 m x 0.04 m (the lamellas' thickness) x 0.033 m, in the x, y and z directions, respectively. Smaller elements (0.02 m side) had been tried, but although increasing substantially the calculation time, no benefits were obtained.
The adhesive elements were 0.01 m x 0.01 m (in the glue line plane) x $0.1 \times 10^{-3}$ m thick (x, y and z directions, respectively). Delamination would therefore be modeled by removing some adhesive elements.
The different dimensions of timber and adhesive elements were accounted for by introducing restrictions at the corresponding interfaces.
Supports were modeled to simulate the use of steel plates (0.08 m x 0.10 m x 0.02 m, in x, y and z directions, respectively) to avoid stress concentration. Similarly, low stiffness material plates of 0.08 m x 0.10 m were modeled under the loading points. Displacements were fully restrained at one support and allowed only in the x direction at the other support.
Glued joints were numbered from 1 to 5, starting from the lower face of the beam.

### 2.2. Loading

The following limit states were considered: deformation (DLS), bending strength (BLS) and shear strength (SLS), according to EN 1995-1-1 (2004). The maximum load for each limit state was determined assuming glulam class GL24h (EN 1194, 2002). For the deformation and bending limit states maximum loads found, applied at 1.44m (6 x h) from the beam ends (the test set up proposed by EN 408 (2003)), were of 5 kN and 7.5 kN. For shear limit state, maximum loads determined were of 18.4 kN applied at a distance of 2 x h from the supports.

### 2.3. Material properties

Since that a 3-D FEM was considered, the timber was modeled as orthotropic material, to better reproduce the real performance of the beam. So, in addition to the mean modulus of elasticity in the grain direction ($E_{0,\ mean}$), bending strength (fm.k), compression and tension strengths in the grain direction and perpendicular to the grain (fc,0,k; fc,90,k; ft,0,k and ft,90,k) and shear strength (fv,k), the modulus of elasticity perpendicular to grain ($E_{90,mean}$), the Shear modulus ($G_{LR,}$, $G_{LT}$ and $G_{RT}$) and the Poisson coefficients ($\upsilon_{RL}$,$\upsilon_{TL}$, $\upsilon_{LR}$, $\upsilon_{LT}$, $\upsilon_{RT}$ and $\upsilon_{TR}$) had to be considered.

Given the large range of values found in the literature for the modulus of elasticity perpendicular to grain (Hearmon, 1948; Bodig and Jayne, 1993; Xavier at al, 2004) and the sensitivity analysis performed that showed a small variation in predicted results due to the modulus of elasticity perpendicular to grain, the value proposed by EN 1194 (2002) was adopted ($E_{90,mean} = E_{0,mean}/30$).

Shear modulus $G_{LR}$ and $G_{LT}$ were taken equal to $E_{0,mean}$ x 6.5% (EN 1194 2002), similar to the value proposed by (Bodig and Jayne, 1993) and $G_{RT}$ was taken equal to $E_{0,mean}$ x 0.7% (the value proposed by Bodig and Jayne, 1993).

Values of 0.035 were adopted for Poisson coefficients $\upsilon_{RL}$ and $\upsilon_{TL}$, whereas $\upsilon_{LR}$, $\upsilon_{LT}$, $\upsilon_{RT}$ and $\upsilon_{TR}$ were taken equal to 0.4, based in the work done by Bodig and Jayne (1993). Sensitivity studies showed however that predictions were not much influenced by Poisson coefficients adopted.

It was found from preliminary simulations that the values adopted for the mechanical properties of glue line elements would not significantly affect the predicted stresses and deformations, coming in line with the widely accepted minute influence of glue lines quality in the elastic performance of the beams. Therefore the same mechanical properties of timber were also adopted for the glue lines.

Timber was modeled as linear elastic. Besides, plastic behavior was outside the scope of this work. However, in some computer simulations the characteristic strength values were exceeded, compromising safety. Therefore, Hill's criterion (Hill, 1950) was used, in order to compare the stress states obtained in the three limit states' verifications and to identify possible risk situations for the structural member.

The FEM was validated by comparing stresses and deformations obtained with the model and with the application of the beam theory, assuming cross sections would remain plane, for the above referred limit states. Results were satisfactory, with an expected better agreement between FEM and beam theory when timber isotropic behavior was assumed than with the orthotropic behavior.

## 3. DELAMINATION INFLUENCE ON DEFORMATIONS AND STRESSES

The above finite element model was used to evaluate the delamination influence on the mechanic performance of the beam. To do so, the finite elements of the glued joint were removed from the areas where the delamination was simulated. In such areas an interaction was inserted to simulate the contact of the lamellas and avoid overlapping.

The simulation of delamination had the objective of analyzing the performance of the beam in the presence of delamination visible on the vertical faces and ends. The delamination near the surface is a very frequent situation in structures in service and is always a reason for worries, because it shows the existence of degradation and also because it can rise some doubts about the integrity of the structural element. The delamination at the ends represents a particular risk to the glued laminated timber structures, because permeability of wood is higher in the longitudinal direction which leads to dimensional variations of the wood in transversal directions, and consequently introduces important changes in the stress state of glued joints near the ends of the structural member. No lateral restriction was introduced along the length of the beam.

Five delamination modes were simulated: A, B, C, D and E (Figure 1). Delamination influence was checked as a function of its depth, considering both symmetric delamination (modes A,s to E,s) and non-symmetric delamination (modes B,ns to D,ns). In symmetric modes, delamination varied from 10 to 40 mm deep (at each face) or up to 40 mm at one face plus 50 mm at the other face, in the case of 90 mm delamination. In non-symmetric modes, delamination was assumed on one face only, varying from 20 to 90 mm. The following delamination modes were considered:

- Modes A and B – delamination along the whole beam length: either just on the middle glued glue line (mode A) or in all glue lines (mode B);
- Modes C and D – delamination in all glue lines: either just in a central zone 3.44 m long (mode C) or near the beam ends in 0.48 m length (mode D);
- Mode E – delamination on both ends of the beam and in all glue lines. Delamination length varied from 80 to 480 mm near each end, affecting the whole beam width.

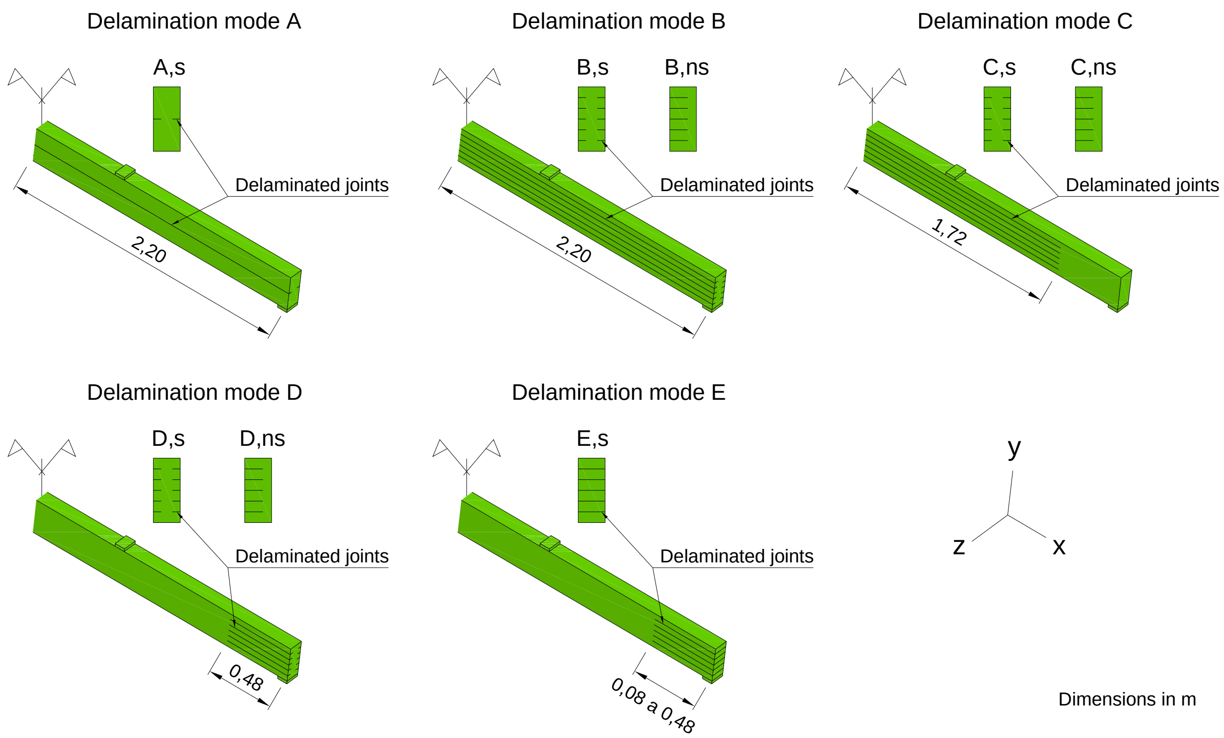


**Figure 1** – Delamination modes

The study of the delamination influence on deformations and stresses was done for the loads of the three limit states referred above: deformation (modes A,s,d to E,s,d for symmetric delamination and B,ns,d to D,ns,d for non symmetric delamination), bending strength (modes A,s,b to E,s,b for symmetric delamination and B,ns,b to D,ns,b for non symmetric delamination) and shear strength (modes A,s,s to E,s,s for symmetric delamination and B,ns,s to D,ns,s for non symmetric delamination). The following sections present the obtained results.

### 3.1. Influence of non symmetric delamination

In general, non symmetric delamination is the most unfavourable for the beam performance. Comparing to symmetric situations (B,s,d, C,s,d and D,s,d), non symmetric modes (B,ns,d, C,ns,d and D,ns,d) produces larger deformation on the y direction (Figure 2a). This effect is also shown on non-symmetric modes (A,s,d, B,s,d, C,s,d e D,s,d for 90 mm delamination depth, which correspond to non symmetric situations, where higher increase of deformation is observed. In fact, non symmetric delamination causes the lateral instability of the beam as a result of the non uniform distribution of stresses through the beam. This situation is also shown by deformations in z direction (Figure 2b). The lateral instability of the beam for non symmetric situations produces larger deformations in y direction for mode B,ns,d than for mode C,ns,d (Figure 2a), given that in the first case the delamination is also higher.

Lateral instability, due to non symmetric delamination, causes an increase of tension stresses in x direction for modes B,ns,d and C,ns,d (Figure 2c), in particular for lower fibres, where stresses are higher. For mode B,ns,d the increase of stresses is more relevant at loaded areas, whereas for mode C,ns,d this increase is also significant at the longitudinal transition between delaminated and non delaminated areas. Compression stresses also increase for these two modes (Figure 2d) being more relevant at loaded areas. Non symmetric delamination (modes B,ns,d, C,ns,d and D,nsd) induces also the increase of shear stresses in the x-y plane relatively to symmetric modes (Figure 2g).

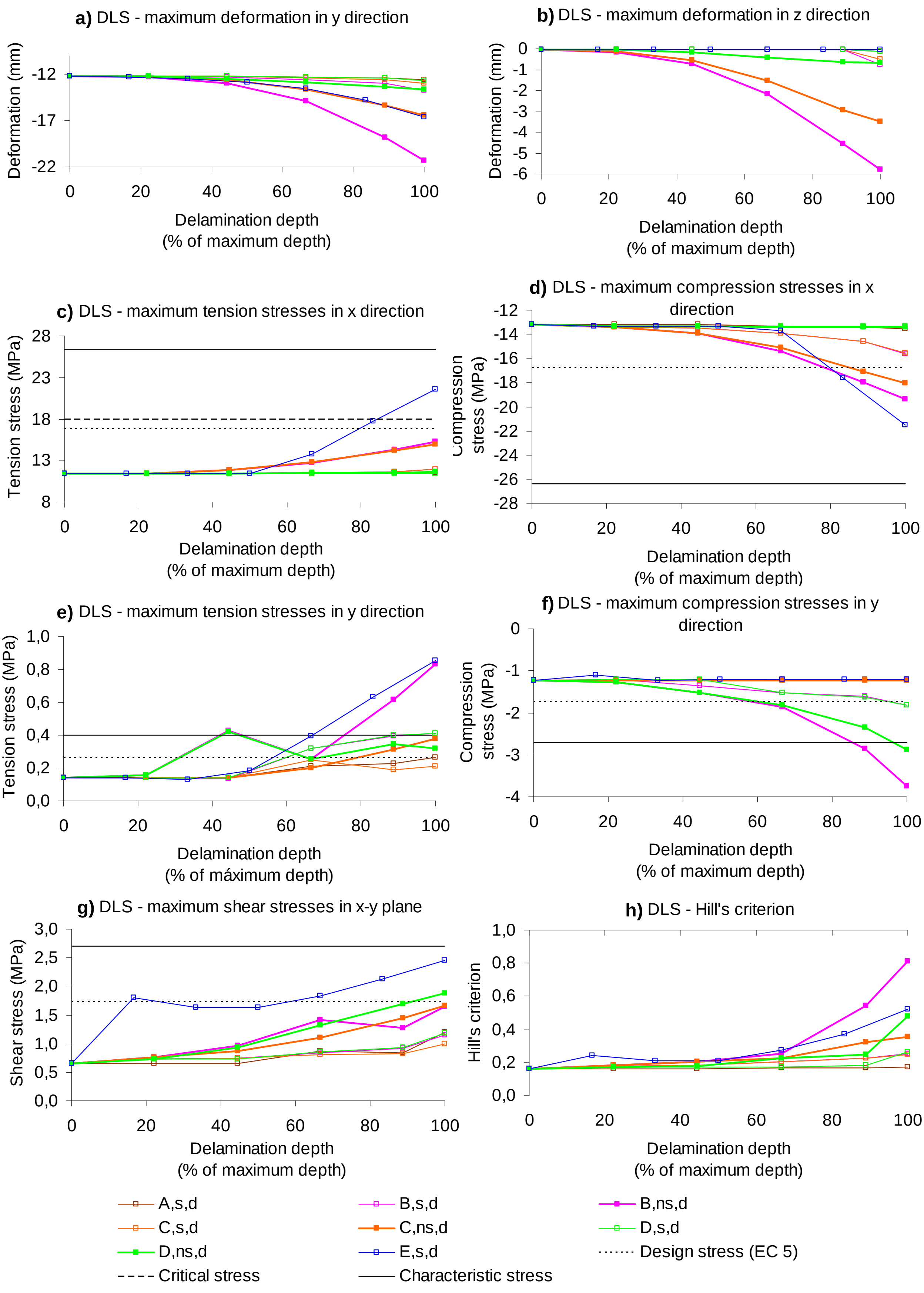


**Figure 2** – Variation of maximum deformations, stresses and Hill's criterion for the deformation limit state

The shear strength limit state differs from DLS mainly because mode C,ns,s is not significantly worsened due to delamination located out of the "transition" zone between loads and supports, causing a negligible lateral instability on this mode, as can be seen in z direction deformations (Figure 3b). This is also observed in tension and compression stresses (x and y directions – Figure 3c,d). However, for modes B,ns,s and D,ns,s, the unfavourable effect of the non symmetric delamination is also observed for this limit state (Figure 3), similarly to what happens for DLS.

### 3.2. Influence of delamination localization

The increase of stresses is related with the magnitude of bending and shear stresses at delaminated areas. For mode D,ns,d, the increase of tension and compression stresses in the x direction and deformations with the delamination depth is very low (Figure 2a,b,c,d), because the delaminated areas do not include zones with high bending moments. On the other hand, modes B,ns,d and C,ns,d, that include delamination on high bending moment zones, have higher increase of tension and compression stresses in the x direction. However, it should be noted that despite modes B,ns,d and C,ns,d are very serious situations, for the most unfavourable cases, the maximum tension stresses in the x direction are not higher than the design stress.

The increase of stresses is in some cases related with delamination located at high shear stress areas. This is the reason why mode D,ns,d has a higher increase of shear stresses in the x-y plane as compared to mode C,ns,d, because in the first mode delamination is only located near the supports (high shear stress area) (Figure 2g), where the shear stress exceeds the design value. However, compression stresses in the y direction are not always higher for modes with delamination near the supports. Mode E,s,d has high delamination near the supports, although its compression stresses do not increase with delamination depth (Figure 2f). This fact is related with the uniform contact of the lamellas along the beam width, at the support areas, that leads to uniform compression stresses and without local increase of stresses. Modes C,s,d and C,ns,d do not produce an increase of compression stresses because of the absence of delamination near the supports. Mode A,s,d has only delamination on the middle joint, introducing low perturbation on stress distribution that leads to very low increase on compression stresses in the y direction. On the other hand, modes B,s,d and D,s,d, which have non uniform contact between the lamellas at the support zones, lead to an increase of the compression and tension stresses (Figure 2e,f). This fact highlights the unfavourable effect of the delamination at the supports, which in practical situations is almost always of non uniform nature.

For symmetric delamination modes (A,s,d, B,s,d, C,s,d and D,s,d) the increase of shear stresses in the x-y plane with the delamination depth is similar, because delamination covers the lateral third of the beam for all these modes (Figure 2g). In these cases the shear stresses increase mainly along the transversal transition between the glued and delaminated joint.

For the shear strength limit state, the stiffness reduction, due to delamination, in areas of higher bending and shear stresses, determined higher deformation in the y direction for mode E,s,s than for other modes (Figure 3a). Deformations in the y direction are higher for mode B,ns,s than for D,ns,s which is a consequence of the higher delamination of mode B,ns,s. However, deformation for mode C,ns,s is almost negligible whereas its delamination is higher than for mode D,ns,s, which, on the other hand, has delaminated areas near the supports, where high shear stresses occur. This evidence shows the unfavourable effect of delamination on high shear stresses areas. In addition, mode D,ns,s has higher tension stresses on the x direction than for mode B,ns,s (Figure 3c), as also happens for modes D,s,s and B,s,s, reaffirming the importance of this phenomenon.

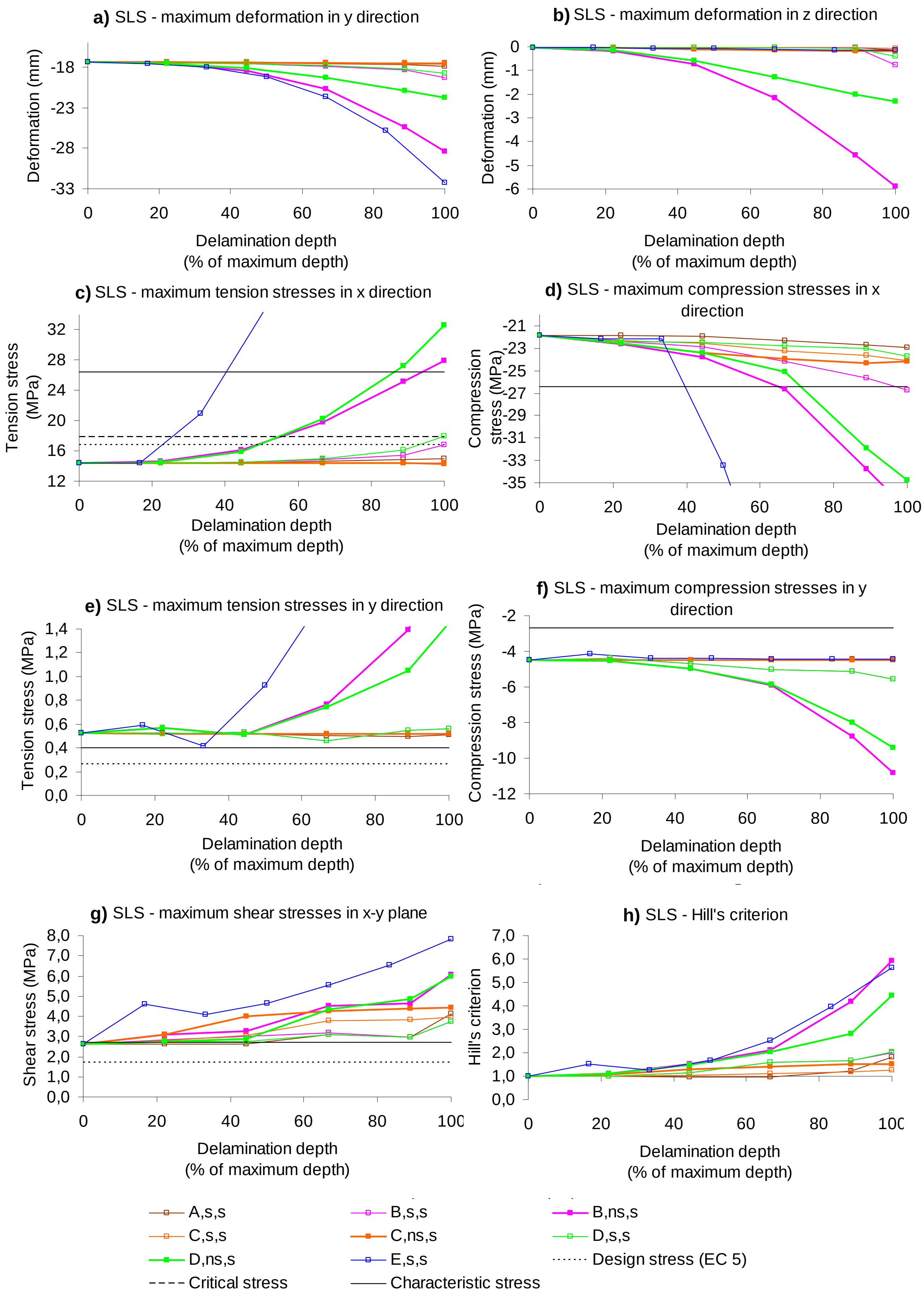


**Figure 3** – Variation of maximum deformations, stresses and Hill's criterion for the shear strength limit state

### 3.3. Influence of delamination depth

Comparing to each other the situations with symetric delamination, it is observed that for mode E,s,d the increase of deformation in the y direction with the delamination depth is higher than for the remaining symmetric modes, where the increase of delamination is very low (Figure 2a). For mode E,s,d the delamination was simulated along the whole beam width, giving a reduction of stiffness on the delaminated zone, leading to high deformations, while for the remaining modes the stiffness is not significantly changed, leading to a lower increase of deformation. In addition, for delamination mode E,s,d, the distribution of stresses in the x direction (Figure 2c,d) showed a concentration in the longitudinal transition between delaminated and non delaminated areas, leading to a significant increase of stresses with the delamination depth. The delamination of the ends affecting the whole beam width causes an individual behavior of the lamellas. Each lamella behaves similarly to a cantilever, with one fixed end in the transition zone, where maximum tension and compression stresses are obtained.

The increase of stresses with the delamination depth for mode E,s,d achieves higher values than the other delamination modes (Figure 2c,d,e,g). For the most unfavorable situation, mode E,s,d constitutes a comparable situation to modes D, since, for the maximum delamination depth, both modes have 480 mm of delamination from the ends, differing only because modes D keep 10 mm of glued joint along the 480 mm length. However, for modes D, the increase of tension stresses in the x direction (Figure 2c) is very low, indicating that delamination affecting the whole beam width is very unfavorable.

For shear strength limit state the more unfavourable effect of mode E,s,s is also observed (Figure 3) as for DLS and BLS.

### 3.4. Stress states

Hill's criterion was used to find out the most unfavorable stress states and to see in which situations they can approach to the elastic limit.

None of the modes simulated for the DLS exceeded the Hills's criterion (Figure 2h). For the BLS the unit is exceeded for mode B,ns,b to 80 and 90 mm of depth and for mode E,s,b to 480 mm depth. Note that these delamination situations are in practice very unfavorable, which would be in principle prevented by the usually recommended periodic inspection. It is also observed that the Hill's criterion increases less for delamination till 60% of beam width than for higher delamination depths, what can be an important indication for the inspection of structures in service.

For the shear strength limit state, the stress states are in general more unfavourable than for the above two limit states (Figure 3h). For the reference situation, the Hill's criterion is close to the unit at the support zones, being critical for modes B,s,s, B,ns,s, D,s,s e D,ns,s. However, for mode A,s,s there is no increase of Hill's criterion at the support zones, being more relevant at the middle joint. For modes C,s,s and C,ns,s the critical zone is at the load areas without relevant increase at the support zones. For mode E,s,s the zone where the Hill's criterion assumes higher values is at the longitudinal transition between glued and delaminated joints. The most unfavourable modes are non symmetric situations or those which simulate all beam width delamination at the support zones and on all joints (B,ns,c, E,ns,c e D,s,c).

## 4. CONCLUSIONS

When inspecting glued laminated timber structures in service attention should be payed to the presence of timber defects or finger joints in the lower lamellas of bent members (the ones with the highest tensile stresses), where fissures may significantly decrease their bending strength.

When delamination is non-symmetric regarding the member's cross section, it can cause the member's lateral instability, thus increasing its stresses and deformation. Additionally, delamination around supports or under loading application points may rise highly unfavourable stress states in the structure, especially under high shear stresses where the glulam failure is more likely to occur. Delamination is particularly severe when it goes from one face to the opposite face.

On the contrary, 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 go through the whole width of the beam. The stresses corresponding to the bending or deformation limit-state are close to the elastic limit only for very important delamination. Nevertheless, 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.

## ACKNOWLEDGMENTS

The authors wish to thank *Fundação para a Ciência e a Tecnologia* (Portuguese Foundation for Science and Technology), for the PhD grant (number SFRH/BD/30310/2006) given to Florindo Gaspar.

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