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# FINITE ELEMENT ANALYSIS OF GLULAM BEAMS WITH TRANSVERSE AND LONGITUDINAL NOTCHES

**Sardar Malek [1], Azadeh Goodarzi [2], Roger Parra [3], Parham Khoshkbari [4]**

**ABSTRACT:** Laminated wood composites, such as glued-laminated timber (Glulam) and cross-laminated Timber (CLT), are increasingly being used in the design of mass timber buildings. In solid timber (sawn lumber) and engineered wood products (EWPs), transverse notches are generally used at connections or at supports to reduce the height of beams. Small longitudinal notches may also be cut along beams and columns for aesthetic purposes. It is known that abrupt cross-section changes create stress concentrations, which can cause the structural member to fail at lower loads compared to an unnotched member. European (Eurocode 5), Canadian (CSA O86-19), and American (NDS 2018) codes provide guidance on designing solid timber and Glulam beams with transverse notches. However, no recommendation has been provided for longitudinal notches along Glulam beams. To address this gap, a 3D Finite Element (FE) model is developed in ANSYS© software to assess the stress field of Glulam beams with the transverse end notches. The developed model is validated with experiments from the literature. The predicted load-bearing capacities are compared with those of notched beams based on the design equations provided in the codes and existing test data. The validated model is then used to comprehensively assess the effect of rounded notched corners and longitudinal notches on the stress fields of Glulam beams.

**KEYWORDS:** Glulam, Notch, CSA O86, Eurocode 5, NDS, Finite Element Analysis (FEA)

## 1 INTRODUCTION

Transverse notches are commonly used in solid timber and engineered wood products (EWPs) for various purposes. These notches are typically placed at connections like mortise and tenon or dovetail joints or at supports. In order to achieve a desired visual effect, it is also possible to create small longitudinal notches on structural members. It is well known that tension side transverse notches significantly reduce the load-bearing capacity of Glulam beams. This capacity reduction is mainly due to stress concentration near notched corners and the low tensile strength of timber perpendicular to the grain direction. The structural behavior of Glulam beams with transverse end notches has been studied experimentally and numerically in the literature [1-4].

European (Eurocode 5 [5]), Canadian (CSA O86-19 [6]), and U.S. codes (NDS 2018 [7]) provide design provisions for Glulam beams with the tension side transverse notches. However, currently, there are no guidelines or recommendations regarding longitudinal notches in Glulam beams.

In this paper, first, the design provisions for Glulam beams with transverse notches in their tension sides are reviewed and compared. A detailed review of the design equations, the considered notch geometry parameters, and limitations on maximum notch depth is provided. Then, the stress fields in a Glulam beam with the tension side transverse end notches are analyzed based on a 3D FE model developed in ANSYS software. The material and geometric parameters are selected based on the four-point bending test reported in [2]. The shear resistance of the end-notched Glulam beam based on provisions in various standards is compared with available test data [2] and the predictions of the developed FE model. The validated model is then used to numerically assess the effect of a rounded notch corner on the stress components. Finally, two longitudinal notches are added in the model, and the effects of these notches on the stress fields are investigated.

## 2 DESIGN APPROACHES FOR NOTCHED GLULAM BEAMS

A typical notched Glulam beam with a rectangular cross-section with a width of $b$ and a depth of $d$, has been shown in Figure 1. In this figure, the $d_n$ and $i$ are the notch depth and notch inclination, respectively. The notch length, $e$, is defined as the horizontal distance from the support to the notched corner. The effective depth of the notched beam, $d_{ef}$, is obtained by:

$$d_{ef} = d - d_n \quad (1)$$

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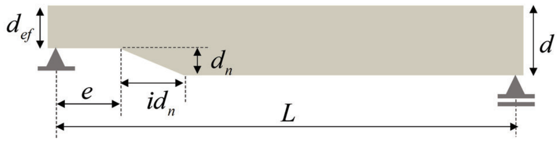


***Figure 1:*** *Schematic of a typical notched beam.*

Based on the design provision provided in Eurocode 5 [5], the shear force at the notched support of the beam should be verified using:

$$V \leq \frac{2}{3}\, bd_{ef}k_v f_{v,d} \tag{2}$$

where $f_{v,d}$ is the design shear strength and $k_v$ is a reduction factor calculated by the following equation for the Glulam beam:

$$k_v = \min\left\{\frac{6.5\left(1+\frac{1.1\, i^{1.5}}{\sqrt{d}}\right)}{\sqrt{d}\left(\sqrt{\alpha(1-\alpha)}+0.8\,\frac{e}{d}\sqrt{\frac{1}{\alpha}-\alpha^2}\right)}, 1\right\} \tag{3}$$

here, $\alpha$ is the notch ratio defined by $\alpha = d_{ef}/d$.
According to the design provisions in CSA O86-19 [6], the shear force at the notched support of a Glulam beam with less than 2.0 $m^3$ in volume should be verified by:

$$V \leq F_r \tag{4}$$

and

$$V \leq V_r \tag{5}$$

where $F_r$ is the factored fracture shear resistance at a notch on the tension side at support obtained by:

$$F_r = 0.9F_f dbK_N \tag{6}$$

In Equation (6), $F_f = f_f(K_D K_H K_{Sf} K_T)$. It should be noted that $f_f$ is the specified fracture shear strength at a notch and obtained by $2.5(b)^{-0.2}$ or 0.9 MPa (whichever is greater). Other factors, $K_D$, $K_H$, $K_{Sf}$, and $K_T$ are the load-duration factor, system factor, service-condition factor for fracture shear, and treatment factor, respectively. $K_N$ is the notch factor calculated as follows:

$$K_N = \left[0.006d\left(1.6\left(\frac{1}{\alpha}-1\right)+\left(\frac{e}{d}\right)^2\left(\frac{1}{\alpha^3}-1\right)\right)\right]^{\frac{-1}{2}} \tag{7}$$

In Equation (5), $V_r$ is the factored shear resistance obtained by:

$$V_r = 0.9F_v\frac{2bd}{3} \tag{8}$$

for $e < d$, and

$$V_r = 0.9F_v\frac{2bd_{ef}}{3} \tag{9}$$

for $e > d$. In the above equations $F_v = f_v(K_D K_H K_{SV} K_T)$. $f_v$ is the specified strength in shear and $K_{SV}$ is the service-condition factor for shear.
According to the design approach provided in NDS 2018 [7], the shear force at support should satisfy the following equation:

$$V \leq 0.48F_v' bd_{ef}\left(\frac{d_{ef}}{d}\right)^2 \tag{10}$$

in which, $F_v'$ is the adjusted shear design value parallel to the grain. A general comparison of the limitations stated for notched Glulam members in Canadian, European, and U.S. codes has been provided in Table 1.

***Table 1:*** *Comparison of design approaches for notched Glulam beams in Eurocode 5, CSA O86-19, and NDS 2018 Standards, considering taper notches, notch length, and allowable notch depth.*

| Standards | Taper Notch | Notch Length | Limitation on Maximum Notch Depth |
|---|---|---|---|
| CSA O86-19 | - | ✓ | $0.25\ d$ |
| Eurocode 5 | ✓ | ✓ | - |
| NDS 2018 | - | - | $0.1\ d$ or 3" |

Table 1 shows that CSA O86-19 and Eurocode 5 account for notch length, while taper notches are only considered in Eurocode 5. On the other hand, NDS 2018 and CSA O86-19 impose strict limitations on notch depth, while Eurocode 5 is comparatively more flexible.

# 3 FE MODELLING

## 3.1 TRANSVERSE NOTCH

A 3D finite element (FE) model corresponding to a notched Glulam beam with reported performance in the literature [2] is developed in ANSYS software. The Glulam beam has seven layers with uniform thickness (see Figure 2). The beam has a rectangular cross-section with a width of 100 mm, a total height of 220 mm, and an overall length of 4000 mm. The beam is notched at both ends, the depth of each notch is 110 mm (half of the depth of the beam), and the notch length is 250 mm. The beam is simply supported at two ends. Two-point loads of 5 kN (*F*=10 kN) are applied to the beam at a 1200 mm distance from the supports. Four steel plates with a width of 100 mm, length of 140 mm, and thickness of 10 mm are placed at the load application and support positions to reduce the effect of local indentations. All the above-mentioned geometric parameters of the beam are illustrated in Figure 2.
All of the geometric parameters, loads, and boundary conditions are symmetric in this problem. Therefore, the symmetric constraint is considered in the middle of the span of the beam, and just half of the beam (Figure 3) has been modelled.


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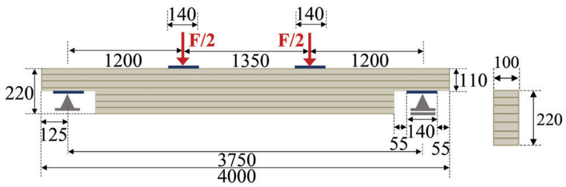


*Figure 2:* *Schematic of the notched glulam beam considered in [2] and the selected geometric parameters for model validation. All dimensions are in mm.*

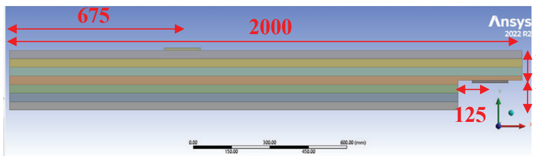


*Figure 3:* *Developed FE model corresponding to the beam in Figure 2. All dimensions are in mm. Half of the beam has been considered due to symmetry.*

### 3.2 ROUNDED NOTCH EFFECT

To investigate the effect of a rounded notch, two Glulam beams with rounded notched corners with a radius of 10 mm and 16 mm (see Figure 4) are analyzed in ANSYS Workbench. The stress fields in these models are compared with those of the Glulam beam with sharp notches in Section 4.3.

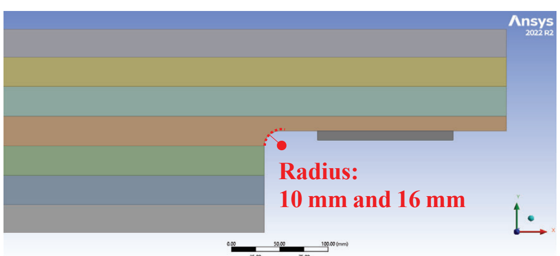


*Figure 4:* *Rounded notched corner.*

### 3.3 LONGITUDINAL AND TRANSVERSE NOTCH

In addition to the transverse end notches, two longitudinal notches are also included along the beam to investigate the effect of longitudinal notches on the stress fields (see Figure 5). The longitudinal notches have a square cross-section (20 mm × 20 mm) and are located under the sixth layer on both face sides of the Glulam beam.

## 4 RESULTS

### 4.1 VALIDATION OF THE MODEL

To validate the developed model, the predicted load-deflection curve of the selected Glulam beam with transverse notches is compared with experimental data as well as other reported models in the literature [2,3].

In experiments reported in [2], a linear elastic behaviour has been observed for the notched Glulam beam up to failure. In the FE model developed in [3], a linear elastic behaviour has also been predicted for the notched Glulam beam. Therefore, the comparisons are made based on the slope of the linear region of the load-deflection curves. The values of loads, deflections, and slopes of load-deflection lines are listed in Table 2. Preliminary results show a very good agreement between the models and experimental data (see Figure 6). The differences between the predicted slope of the load-deflection line in the current FE model and those obtained experimentally in [2] and those predicted in [3] are approximately 10% and 2%, respectively.

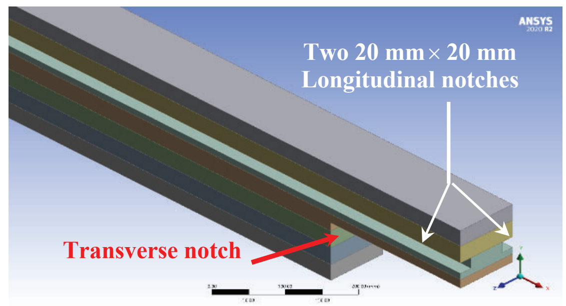


*Figure 5:* *3D FEM of the Glulam beam with the transverse and longitudinal notches.*

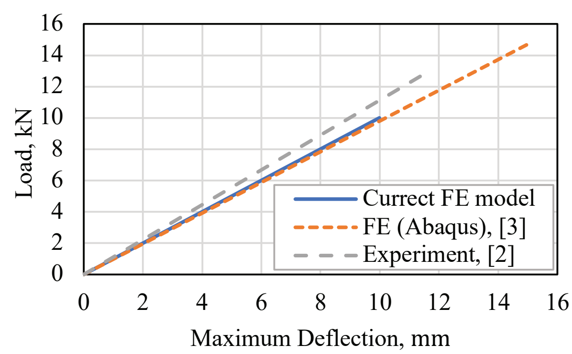


*Figure 6:* *Comparison between the elastic region of the load-deflection curves of the notched Glulam beam of the current FEM in ANSYS©, experiment [2], and FEM in ABAQUS© [3].*

*Table 2:* *Loads, deflections, and initial slopes of load-deflection curves of the notched Glulam beam of the current FE model in ANSYS©, experiment [2], and FEM in ABAQUS© [3].*

| | Load (kN) | Deflection (mm) | Slope $10^6 \frac{N}{m}$ |
|---|---|---|---|
| Experiment, [2] | 12.8 | 11.5 | 1.113 |
| FE Model in ABAQUS, [3] | 14.8 | 15.1 | 0.980 |
| Current FE Model (ANSYS) | 10.0 | 9.98 | 1.001 |

### 4.2 EFFECT OF THE TRANSVERSE NOTCH ON INDUCED STRESSES

The distribution of perpendicular to the grain stress is shown in Figure 7. It is noted that the maximum value of this normal stress, $\sigma_y$, is 3.7 MPa and occurs at the notched corner.
The stress stress distribution is shown in Figure 8. The maximum value of the shear stress, $\sigma_{xy}$, (3.0 MPa) is highlighted at the notched corner.

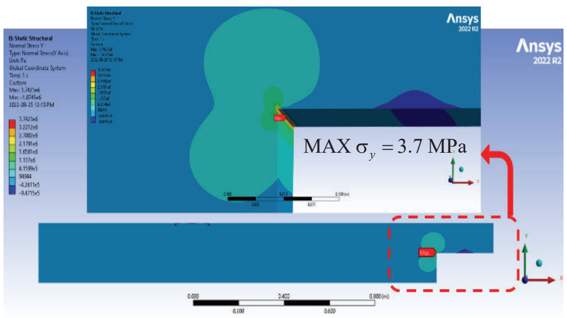


***Figure 7:*** *Distribution of normal stress* $\sigma_y$ *(Pa) under the applied load of 10 kN.*

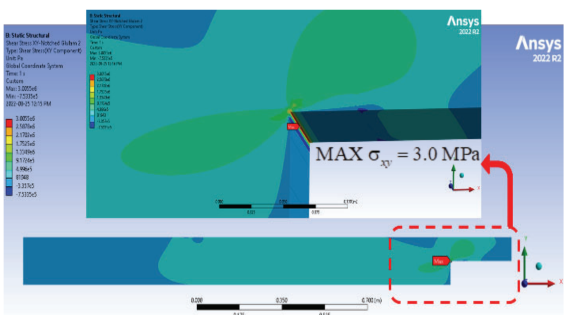


***Figure 8:*** *Distribution of shear stress* $\sigma_{xy}$ *(Pa) under the applied load of 10 kN.*

To study the state of stress at the notch vicinity, a path is defined in the model from the notched corner to the other end of the beam parallel to the beam direction. The $yy$ and $xy$ components of the stress components along this path are shown in Figures 9 and 10, respectively. An abrupt increase of the tensile stress perpendicular to the grain and shear stress at the notched corner has been noted.
It is noted that the values of shear stress and tensile stress perpendicular to the grain are increased significantly near the notch. These stress concentrations are the main cause for Mode I and II crack initiation at the notched corner and the reported brittle failure of notched Glulam beams in the literature [2].

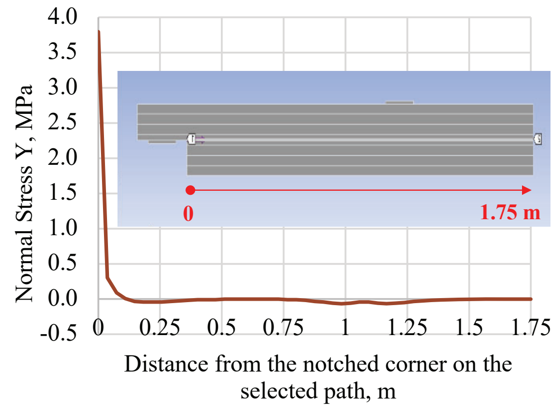


***Figure 9:*** *Normal stress* $\sigma_y$ *(MPa) along the selected path.*

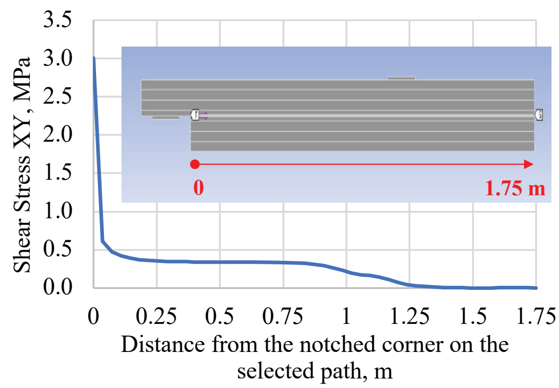


***Figure 10:*** *Shear stress* $\boldsymbol{\sigma_{xy}}$ *(MPa) along the selected path.*

To define the input material properties in ANSYS, similar to [2], we have used the mechanical properties of spruce timber that is classified under strength class C22 in accordance with EN 338 [8]. The shear strength of the material is 3.8 MPa as highlighted in [2] and [8].
For verification purposes, a comparison was made between the measured capacity of the Glulam beam with deep, transverse notches reported in the literature [2] and the expected capacity of the end-notched Glulam beam using design equations provided in Eurocode 5, CSA O86-19, and NDS 2018 (see Figure 11). It should be noted similar strength values have been considered in Equations (2), (6) and (10) for this comparison (dry condition). Considering various adjustment factors and clauses highlighted in different standards (see Section 2), slight differences are expected for the beam capacity.
Figure 11 shows that Eurocode 5 and CSA O86-19 overestimate the capacity of the notched Glulam beam, while NDS 2018 underestimates it. Considering the differences between the definitions of adjustment factors in various standards, such discrepancies may be justifiable. Also, it is noted that the predicted load-bearing capacity using the current FE model (12.66 kN) is in good agreement with the measured capacity (12.80 kN). The beam capacity (12.66 kN) has been estimated numerically assuming the material behaviour is linear followed by a brittle failure when the shear stress at the notch corner


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reaches the the shear strength of the selected spruce grade (3.8 MPa).

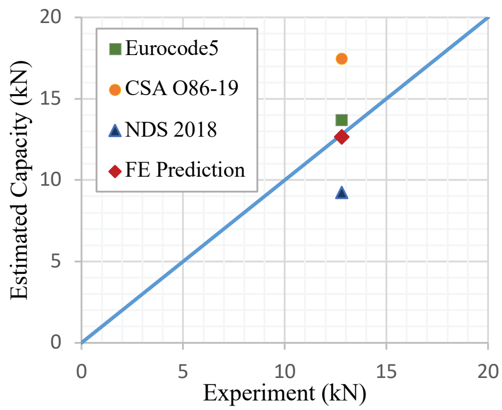


***Figure 11:*** *Comparison between the estimated capacity based on Eurocode 5 [5], CSA O86-19 [6], NDS 2018 [7], FE model prediction and the measured capacity [2].*

## 4.3 EFFECT OF THE ROUNDED NOTCHED CORNER ON THE STRESS FIELD

### 4.3.1 Rounded notched corner with a radius of 10 mm

The validated model is used to conduct a range of parametric studies on the notch geometry. The $yy$ component of the stress (perpendicular to the grain stress) in Glulam beam with a rounded notched corner with a radius of 10 mm is shown in Figure 12. The $xy$ component of the stress tensor is also shown in Figure 13.

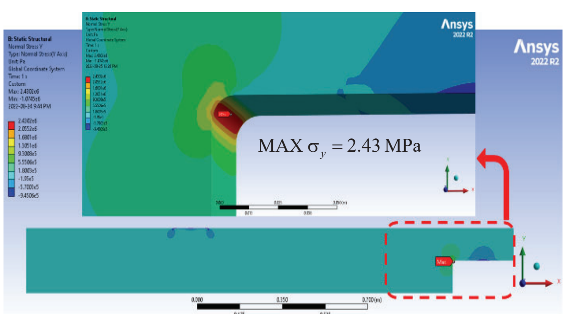


***Figure 12:*** *Distribution of normal stress $\sigma_{yy}$ (Pa) for the case of the rounded notched corner with a radius of 10 mm, under the applied load of 10 kN.*

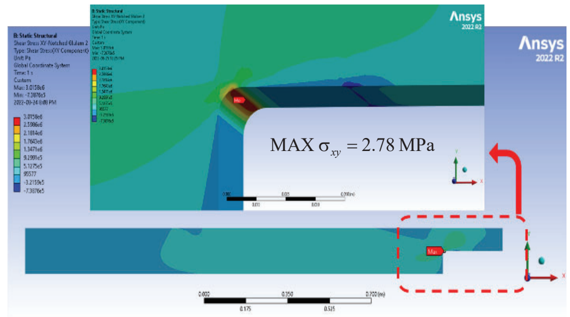


***Figure 13:*** *Distribution of shear stress $\sigma_{xy}$ (Pa) for the case of the rounded notched corner with a radius of 10 mm, under the applied load of 10 kN.*

### 4.3.2 Rounded notched corner with a radius of 16 mm

The $yy$ component of the stress tensor of the Glulam beam with a rounded notched corner with a radius of 16 mm is shown in Figure 14. It can be seen that the maximum normal stress, $\sigma_y$, occurs at the rounded notched corner, reaching a value of 1.89 MPa under the applied load of 10 kN. The $xy$ component of the stress tensor is also shown in Figure 15. Under the same applied load, the maximum shear stress, $\sigma_{xy}$, is 2.39 MPa which occurs at the notched corner.

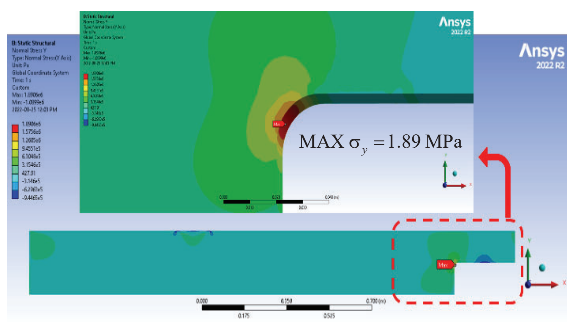


***Figure 14:*** *Distribution of normal stress $\sigma_{yy}$ (Pa) for the case of the rounded notched corner with a radius of 16 mm, under the applied load of 10 kN.*

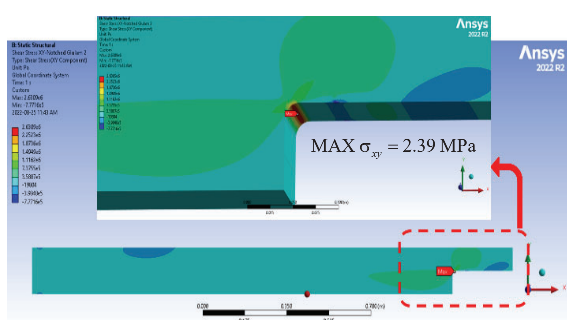


***Figure 15:*** *Distribution of normal stress $\sigma_{xy}$ (Pa) for the case of the rounded notched corner with a radius of 16 mm, under the applied load of 10 kN.*

### 4.3.3 Stress Field Comparison between Glulam Beams with Sharp Notch and Rounded Corners

A path is defined parallel to the beam axis starting from the location of the maximum stress component at the notched corner. The normal stress, $\sigma_y$, and shear stress, $\sigma_{xy}$, along the beam with the sharp notch, the beam with the rounded notched corner with a radius of 10 mm, and the beam with the rounded notched corner with a radius of 16 mm are shown in Figures 16 and 17, respectively.
According to Figure 16, it can be seen that the rounded notched corners with a radius of 10 mm and 16 mm reduce the maximum value of the normal stress, $\sigma_y$, by 34% and 49%, respectively. Based on Figure 17, using rounded notched corners with a radius of 10 mm or 16 mm can decrease the maximum shear stress, $\sigma_{xy}$, by 7% and 20%, respectively.

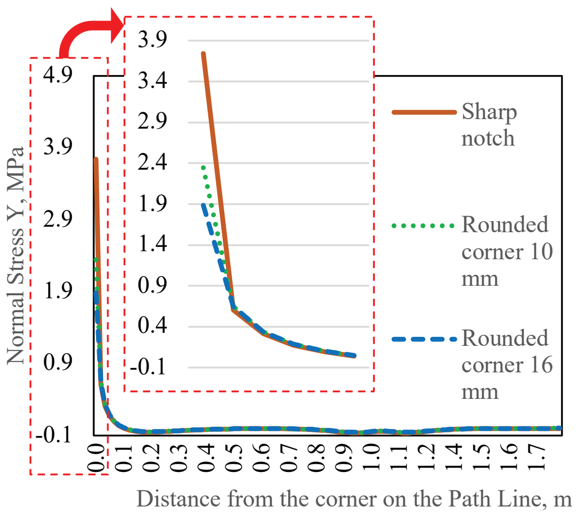


***Figure 16:*** *Normal stress, $\sigma_y$, along the selected path.*

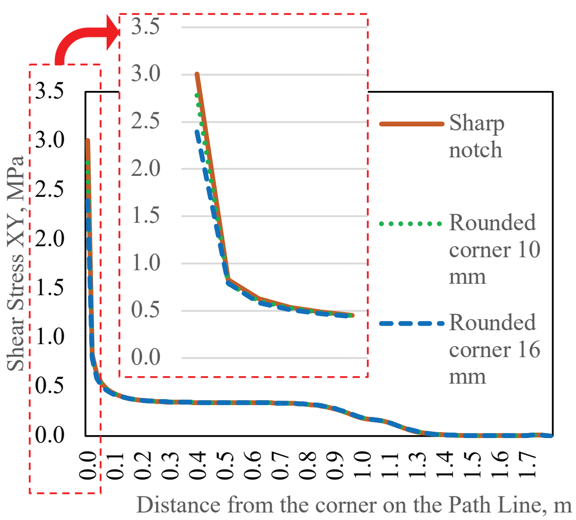


***Figure 17:*** *Shear stress, $\sigma_{xy}$, along the selected path.*

### 4.4 EFFECT OF THE LONGITUDINAL NOTCH

For the case when the Glulam beam has two longitudinal notches in addition to the transverse end notches, the distribution of normal stress, $\sigma_y$, and shear stress, $\sigma_{xy}$, are shown in Figures 18 and 19, respectively.
The maximum values of normal stress, $\sigma_y$, and shear stress, $\sigma_{xy}$, for the Glulam beam with the longitudinal notches are 4.17 MPa and 3.33 MPa, respectively, occurring at the notched corner. It can be seen that the maximum values of normal stress, $\sigma_y$, and shear stress, $\sigma_{xy}$, for this beam are increased by 13% and 11%, respectively, compared to those values in the beam without the longitudinal notch.

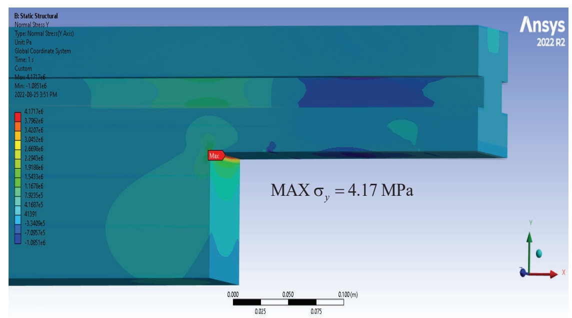


***Figure 18:*** *Normal stress $\sigma_y$ (Pa) distribution in the Glulam beam with the longitudinal and transverse notches, under the applied load of 10 kN.*

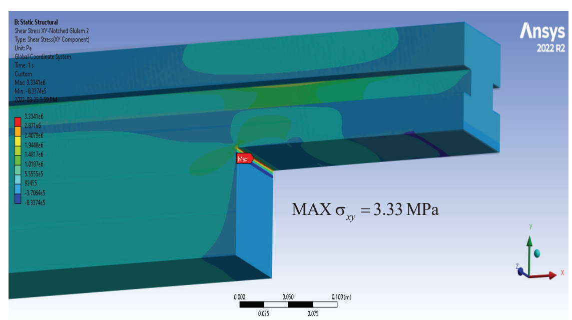


***Figure 19:*** *Shear stress $\sigma_{xy}$ distribution in the Glulam beam with the longitudinal and transverse notches, under the applied load of 10 kN.*

The stress distributions of $\sigma_y$ and $\sigma_{xy}$ for the layer of the Glulam beam in which the longitudinal notches are located are shown in Figures 20 and 21.
It is noted that at the longitudinal notch above the notched corner, the normal stress perpendicular to the grain, $\sigma_y$, has a maximum value of 1 MPa (see Figure 20). The maximum shear stress, $\sigma_{xy}$, also reaches 1.78 MPa (occurring at a location between the support and the notched corner) which is significant for the longitudinal notch (see Figure 21).


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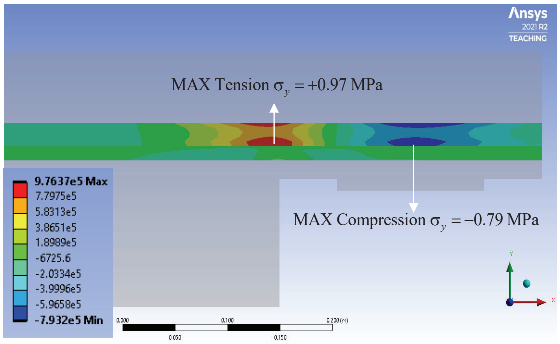


***Figure 20:*** *Normal stress $\sigma_y(Pa)$ distribution in the layer of the Glulam beam in which the longitudinal notches are cut.*

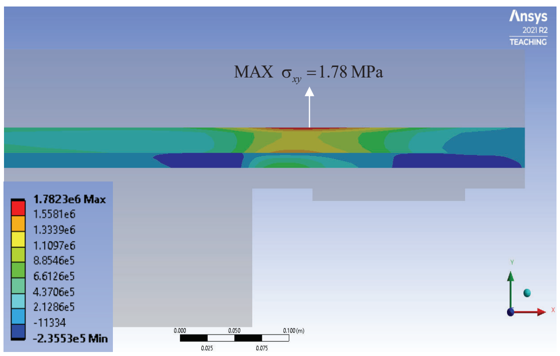


***Figure 21:*** *Shear stress $\sigma_{xy}$ (Pa) distribution in the layer of the Glulam beam in which the longitudinal notches are cut.*

## 5 CONCLUSIONS

A comprehensive review of design equations given in different standards for calculating the capacity of Glulam beams with transverse notches was conducted. Slight discrepancies were noted, which was expected due to various adjustment and safety factors. It was found that the Canadian standard (CSA O86-19) and Eurocode 5 consider the length of notches, while only Eurocode 5 accounts for taper notches. The maximum allowable notch depth is restricted by NDS 2018 and CSA O86-19, whereas Eurocode 5 is comparatively more flexible. There is currently a lack of provisions for notched columns subjected to combined axial and bending loads, which necessitates further investigation in the future.

To understand the effect of notch geometry and the interaction of notches cut in different directions, a FE model was developed and validated using experimental data. It was shown that the model predictions and experimental data in the literature are in agreement in terms of stiffness and strength. The difference between the predicted slope of the load-deflection line in the current FE model and the experimental value in the literature was approximately 10%. The current FE model also predicted a load-bearing capacity that is approximately 1.1% less from the test data reported in the literature [2].

The developed model in this paper was used to assess the notch effect on the stress distribution (normal and shear) in the tested Glulam beam for various notches and notched corners. It was shown that the longitudinal notches could interact with transverse notches and increase the stress levels. In the beam with both longitudinal and transverse notches, the maximum normal stress, $\sigma_{yy}$, and shear stress, $\sigma_{xy}$, at the notched corner were increased by 13% and 11%, respectively, compared to the values in the notched beam without a longitudinal notch. An increase in shear stress and normal stress perpendicular to the grain was also noted at the longitudinal notch near the transverse notch. It was shown that rounded notched corners with a radius of 10 mm or 16 mm could reduce the maximum normal stress, $\sigma_{yy}$, by 34% and 49%, respectively, and decrease the maximum shear stress, $\sigma_{xy}$, by 7% and 20%, respectively.

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