DESIGN OF REINFORCEMENT AROUND HOLES IN LAMINATED VENEER LUMBER (LVL) BEAMS*

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ABSTRACT

Many practical situations require holes in timber beams. When the hole is large relative to the depth, the failure of the beam is governed by crack initiation and propagation around the hole. Cracking of a timber beam decreases the capacity of the beam considerably. This paper presents a method for designing the reinforcement around holes in Laminated Veneer Lumber (LVL) beams so as to recover their full flexural capacity. The design procedure is complemented by two worked examples where all verifications are discussed in detail.

KEYWORDS: LVL, Screw, Plywood, hole, reinforcement, tensile stresses

1. INTRODUCTION

Many practical situations including building services installation and architectural considerations require the introduction of holes in timber beams. Introducing a hole into a timber beam can cause stress concentrations which vary from tension to compression. The inherent low tensile strength of wood perpendicular to the grain makes the beam susceptible to crack initiation and crack propagation at rather low load levels [1]. A good survey of the test methods, results and calculations for the glulam beam have previously been presented by Danielsson [2]. Riipola [3] used Linear Elastic Fracture Mechanics (LEFM) to predict the failure load of a glulam beam with a hole. The expanded formulation had a number of limitations. Johannesson [4] used the theory of elasticity for failure load prediction of glulam beams with holes.

Figure 1 shows a Laminated Veneer Lumber (LVL) beam with a hole that has cracked at the perimeter. Around the hole, the tensile stresses will most likely exceed the low tensile strength perpendicular to grain, in this way causing crack initiation. Subsequently, the crack propagation due to the coupled shear and moment in the beam section reduces the strength and stiffness of the beam significantly. Reinforcement around the hole is an effective option for improving the behaviour of the timber beam. Good reinforcement should recover the load carrying capacity of the beam completely. Plywood and screws are two alternative methods to control crack propagation and to enable the beam to be restored to its original capacity [5]. The choice of the reinforcement type is very much dependent on the stresses in the section, architectural requirements, ease of installation, and other factors.

The mechanisms developed by plywood and screws to control the stresses around the holes are different. Screws can develop local stress concentrations, whereas plywood uniformly controls the stresses around the hole due to the large contact area with the LVL. For thick members where plywood is not so effective, screws can provide a better means to reduce the stress concentrations around holes.

Figure 1. Crack propagation around a hole .

1.1. SCREW REINFORCING

Self tapping screws are drilled into the beam to block the path of the crack propagation, in this way increasing the load-carrying capacity of the beam (Figure 2). Although the screws can handle the tensile stresses and control those stresses very well, it may not effectively stop increased shear stresses in the section of the beam.

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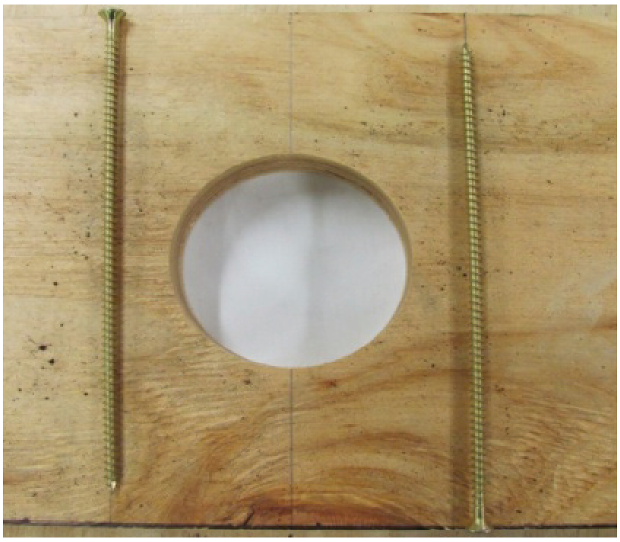

Figure 2 . Reinforcing with screws.

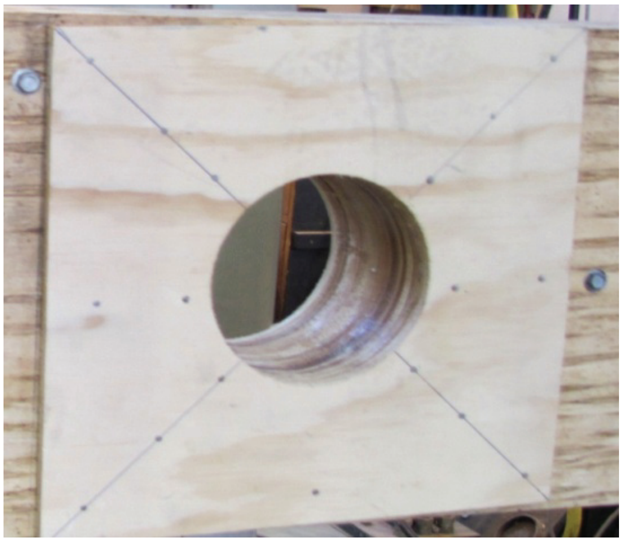

Figure 4. Reinforcing with plywood.

The design of the screws is somewhat challenging because the screws have to meet a number of design criteria. The main criteria for the design of the screws are that the screws should carry tensile loads in the section without yielding, and without exceeding the withdrawal capacity. Besides, the screw has to be inserted at sufficient distance from the opening to prevent wood splitting. Finally, stress concentrations close to the screw should not cause failure at the tensile edge of the beam. Such an edge failure in an LVL beam is shown in Figure 3.

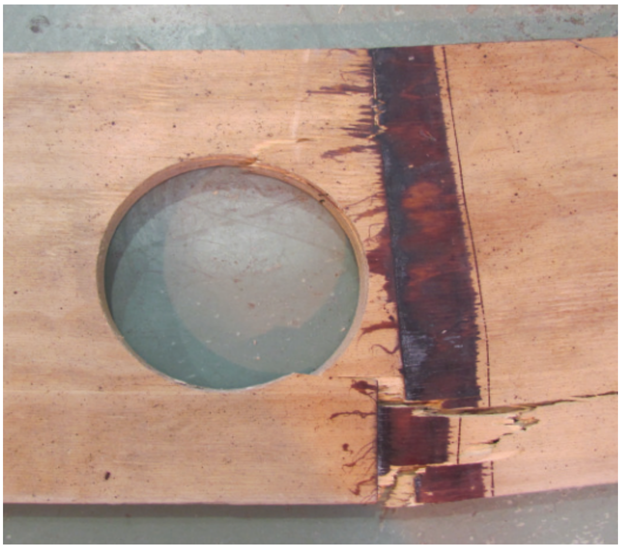

Figure 3. Edge failure in LVL beam reinforced with screws .

1.2. PLYWOOD REINFORCING

Another reinforcement option is the use of plywood glued to the outer faces of the beam. The plywood and the beam then form a composite entity, in this way decreasing the tensile stresses in the wood. Although plywood works very well for thin members, it is not of so much use in thick beams as plywood cannot reduce the stresses far from the beam surface. Figure 4 shows an example of plywood reinforcement to an LVL beam with a hole. Phenol resorcinol formaldehyde has been used for the gluing the plywood to the LVL. The plywood also has been nailed to the beam to provide a roughly uniform glue pressure on the surface. Design of the plywood also needs to be addressed carefully. Plywood should be designed for the tensile forces produced in the section of the beam. The plywood dimensions should be large enough to cover the stressed area.

1.3. FINITE ELEMENT MODELLING

Crack propagation is a challenge for typical elastic finite element modelling as the continuity of elements should be preserved in the elastic model used for the analysis. There are few models that can handle the crack initiation and propagation, particularly for wood structures. One of the possibilities is the use of cohesive elements in finite element modelling previously used for the connections [6]. Cohesive elements are defined at a surface or surfaces in the model where there is the probability of crack initiation and propagation. The idea of the cohesive element in crack propagation is to diminish gradually the stiffness of the elements that have reached the maximum tensile/shear strength of the material. In this way, numerical problems are reduced, and crack propagation can be effectively modelled. Figure 5 shows an example of using cohesive elements for a 2600 x 400 x 45 mm beam loaded at mid-span. The model can predict the failure load of the beam with holes accurately (within 3 to 15% accuracy) when compared with the results from an experimental programme [5].

In this paper, the design of both reinforcement methods, screws and plywood, is discussed and two worked examples are presented. The tensile forces due to the hole are calculated using an analytical formulation derived for LVL beams. The proposed design method ensures that the load-carrying capacity of the entire beam section is obtained by using the minimum amount of reinforcement calculated.

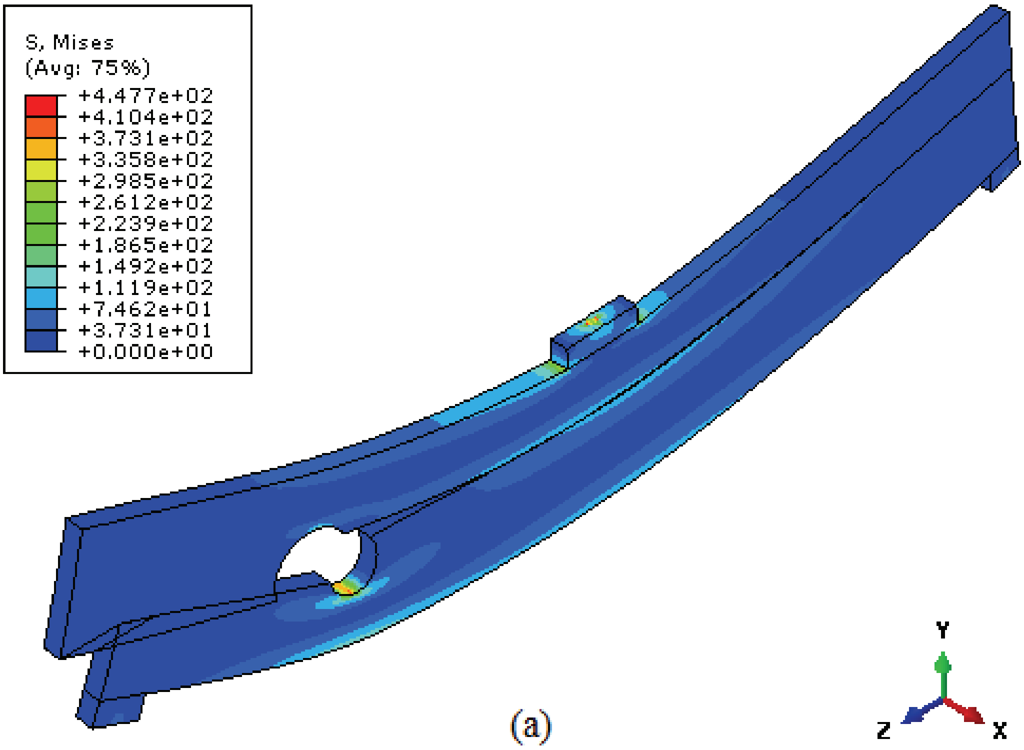

Figure 5. Use of the cohesive elements for crack modelling (units MPa).

2. BEAMS WITH HOLES AND NO REINFORCEMENT

Design of LVL beams with holes was studied through a comprehensive experimental programme [5]. The experimental programme found that for beams 200 mm, 300 mm and 400 mm deep with span length to depth ratios smaller than 10, a 50 mm hole diameter did not cause any reduction in load-carrying capacity. However, with the aim of providing a conservative design recommendation, the limitation of 50 mm diameter is proposed for beam with length to depth ratios of more than 10. Based on APA recommendations for LVL beams [7], a 25 mm diameter hole may be used for beam of length to depth ratios smaller than 10 without the need to reduce the load-carrying capacity to allow for the hole.

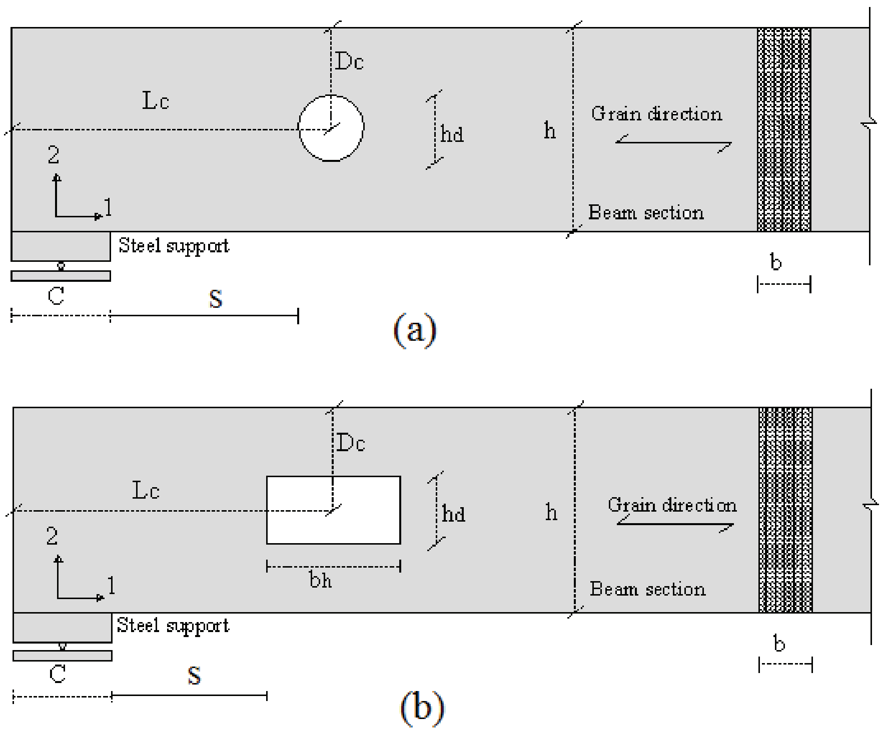

Figure 6. Drawings of beams with circular (a) and rectangular (b) holes.

3. TENSILE LOAD

Figure 6(a) and Figure 6(b) show drawings of beams with holes including notations of geometrical parameters.

The tensile load due to the shear force and bending moment in each section of a beam was calculated using the so-called *strut and tie model*. This model assumes that the moment and shear that could not be transferred in the section of the beam due to the hole are transferred through the strut and tie action around the hole [5].

The model yielded Equation 1 for tensile load predictions of LVL beams with circular holes.

$$F_{t,d} = \frac{\sqrt{2} V h_d (3h^2 - h_d^2)}{8h^3} + \frac{3}{4} \frac{M h_d^3 (h_d + h)}{h^3 (h \,.\, h_d + h^2 + h_d^2)} \qquad (1)$$

where $F_{t,d}$ is the design tensile load, V is the shear force in the section of a beam, h_d is the hole diameter as shown in Figure 6, and M is the moment in the section of the beam. Equation 1 has two contributions: (i) the first contribution due to shear; and (ii) the second contribution due to moment.

For square holes the formulation was revised in the moment term (second term in Equation 1) because the proposed formulation was over-estimating the tensile load considerably. Equation 2 presents the tensile load due to the shear and moment in the section of a beam for a square hole.

$$F_{t,d} = \frac{\sqrt{2} V h_d (3h^2 - h_d^2)}{8h^3} + 0.7M \frac{h_d^2}{h^3} \qquad (2)$$

Finally, rectangular holes were investigated, and some formulations were derived for tensile load predictions. Equation (3) provides the tensile load produced due to a rectangular hole in a section of beam:

$$F_{t,d} = \left(\frac{\beta}{4h^3}\right) V h_d \left(3h^2 - h_d^2\right) + 0.7M \frac{h_d^2}{h^3} \qquad (3)$$

where β signifies the parameter defined as follows:

$$\beta = Max \left(\frac{b_h}{\sqrt{h_d^2 + b_h^2}} \; and \; \frac{h_d}{\sqrt{h_d^2 + b_h^2}} \right) \qquad (4)$$

It should be pointed out that only Equation 1 was derived from the Strut and Tie model, whereas Equations 2, 3 and 4 were obtained through numerical analyses on LVL beams with holes.

The aforementioned formulations were used for beams up to 400 mm deep. A series of finite element analyses on beams with circular holes showed that the predicted tensile load using Equation 1 underestimates the tensile load in the reinforcement for depths greater than 400 mm. A correction factor is required to take into account size effects. A modification factor of: $\sqrt{\frac{h}{400}}$

applied to the final tensile load predicted through Equation 1 is proposed to take into account the larger depth. The modification factor was obtained through finite element analysis of beams with holes.

Also, for a small eccentricity of the hole along the beam depth (10% of beam depth), the numerical analyses showed that the tensile load in the reinforcement increases considerably. Again numerical analyses showed that a magnifying factor of : $\left(1 + \frac{h_d}{h}\right)$

can be applied to increase the final tensile load in the screw.

4. LIMITATION OF HOLE SIZES

Experimental tests on reinforced LVL beams with holes yielded several limitations, in good agreement with the Swedish glulam handbook [8]. For circular holes reinforced with fully threaded screws:

$$h_d \leq 0.4h \qquad (5)$$

In the case of plywood reinforcement for circular holes, the limit in Equation 5 can be relaxed because plywood increases the shear capacity of the beam locally in the section, thus:

$$h_d \leq 0.45h \qquad (6)$$

The above limitations in DIN 1052 [9] for screw reinforcement is 0.3h and for plywood reinforcement is 0.4h. The limitation from Equation 5 for screw reinforcement was decreased slightly for rectangular holes due to the corners as below:

$$h_d \leq 0.35h \qquad (7)$$

Equation 7 can be adjusted when using plywood reinforcement:

$$h_d \leq 0.4h \qquad (8)$$

Finally, for rectangular holes, the dimension limitation suggested by the Swedish glulam handbook was adopted [10].

$$b_h < 3h_d \qquad (9)$$

To avoid long term crushing of the beam, a hole should have enough distance from concentrated loads and the supports. A comprehensive study showed that the distance equal to beam depth is a reasonable distance [11]. Therefore Equation 10 may be used:

$$S = \left(L_c - C - \frac{h_d}{2}\right) \geq h \qquad (10)$$

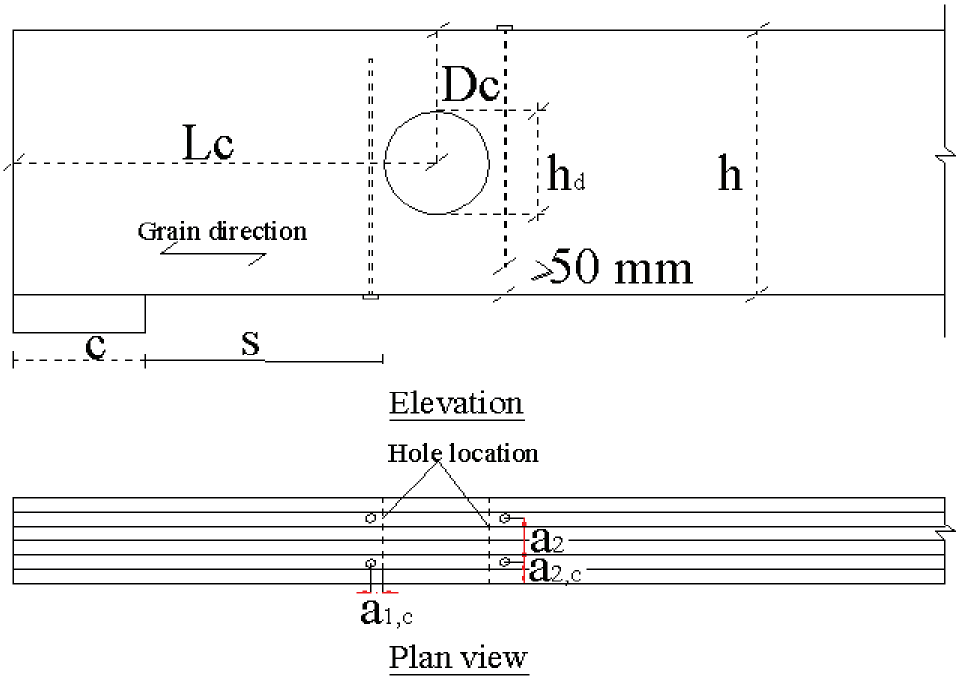

Figure 7. Reinforcement by screws.

Parameters are defined in Figure 7.

5. REINFORCEMENT

Cracks in LVL beams with circular holes usually start at an angle of about 45 degrees relative to the horizontal axis of the beam at the edges of the hole, while cracking in the rectangular/square holes starts at the corners of the holes because of stress concentrations.

5.1. SCREW REINFORCEMENT DESIGN

Design of fully threaded countersunk SPAX screws should meet the following criteria: (i) distance of screw from edges of beam should be enough to avoid splitting of wood, (ii) screw should not yield due to the tensile stresses, and finally (iii) screw should not withdraw due to the tensile forces.

5.1.1. MINIMUM DISTANCE OF SCREW FROM EDGES OF BEAM

Figure 7 shows a drawing of a beam with a hole reinforced with two vertical screws with edge distances of $a_{1,c}$, $a_{2,c}$ and a mutual distance of a_2. The following limitations (Equations 11 – 13) were adopted from the German design code DIN 1052 [9] for the distances of the screw from edges of the beam. The distances ensure that no splitting in the LVL beam can occur.

$$2.5 d_r \leq a_{1,c} \leq 4 \mathrm{d}_r \quad (11)$$

$$a_2 \geq 3 \mathrm{d}_r \quad (12)$$

$$a_{2,c} \geq 2.5 \mathrm{d}_r \quad (13)$$

where d_r is the outer diameter of the screw.

5.1.2. YIELDING OF SCREW

Tensile stresses due to holes should not cause yielding in the screw reinforcement. Control of reinforcement stresses can be accomplished by requiring:

$$\frac{\mathrm{F}_{t,90,\ d}}{\left(\frac{\pi d}{4}^2\right)} < f_{\mathrm{y,\ d,\ screw}} \quad (14)$$

where $F_{t,90,d}$ is the design tensile force perpendicular to the grain calculated from Equations 1 to 4, d is the core diameter of the screw, and $f_{y,d,screw}$ is the design yielding strength of the screw defined as:

$$f_{\mathrm{y,\ d,\ screw}} = k_{\mathrm{mod}} \frac{f_{y,k}}{\gamma_m} \quad (15)$$

and $f_{y,k}$ is the characteristic yielding strength of screw, γ_m is a partial safety factor for screw of 1.3 according to Eurocode 5 [12]. The variable k_{mod} signifies the partial modification factor for load duration and moisture. Such a parameter should be assumed equal to 1 because screw design is not affected by the change of the moisture content in the wood or by the load duration.

5.1.3. SCREW WITHDRAWAL

Screws should not withdraw. Screw withdrawal can be prevented by using enough embedment length at both sides of the crack surface.

$$\mathrm{F}_{\mathrm{t,90,\ d}} \leq R_{ax,d} \quad (16)$$

$$\mathrm{R}_{\mathrm{ax,d}} \leq R_{ax,k} \times k_{\mathrm{mod}} / \gamma_m \quad (17)$$

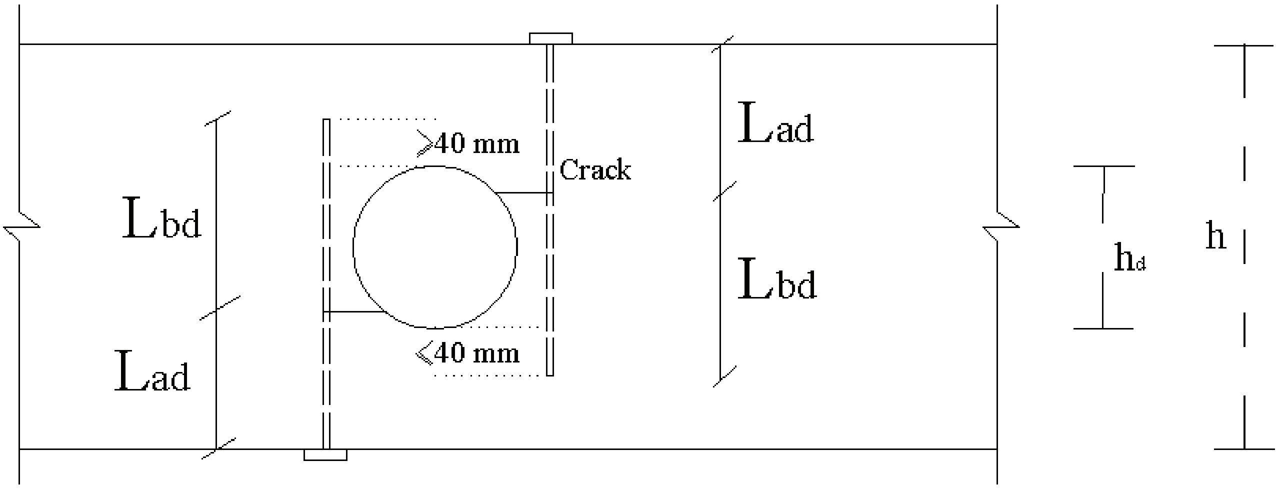

Figure 8. Withdrawal length.

where $R_{ax,d}$ signifies the design tensile strength of screw reinforcement, $R_{ax,k}$ the characteristic tensile strength of the screw, γ_m partial safety factor that for LVL is assumed equal to 1.2 and finally k_{mod} is a modification factor for LVL taking into account load duration and moisture content that for permanent loading is equal to 0.6. According to Aicher et al. [13] $k_{ax,d}$ can be calculated as:

$$R_{ax,k} = \min(R_{t,u,k}, f_{1,k} L_{bd} d_r) \quad (18)$$

Note: $R_{t,u,k}$ signifies the characteristic tensile strength of screw, $f_{1,k}$ the withdrawal strength of LVL, and L_{bd} the embedment length of screw. According to the experiments on LVL specimens [5] the characteristic withdrawal strength for screws with an outer diameter of 8 mm can be obtained through the Equation 19.

$$f_{1,k} = 81 \times 10^{-6} \rho^2 \quad (19)$$

where ρ is the density of LVL in kg/m^3. For 550 kg/m^3 density of LVL, $f_{1,k}$ is 24.5 MPa.

Control of the length L_{bd} is necessary to avoid screw withdrawal as follows:

$$L_{bd} \geq \max(12 d_r, L_{ad}) \quad (20)$$

L_{ad} and L_{bd} are shown in Figure 8.

L_{ad} is the distance of the crack surface from the upper or lower edge of the beam. The crack surface is assumed to begin at an angle of 45 degrees relative to the horizontal surface passing through centre of the hole. L_{ad} is hence calculated as [5] :

$$L_{ad} = 0.5h - 0.345 h_d \quad (21)$$

5.2. PLYWOOD DESIGN

Design of plywood should meet the following criteria: (i) plywood should carry the tensile load due to the hole; and (ii) plywood should cover the portion of beam where tensile stresses exceed the tensile strength of LVL.

5.2.1. CONTROL OF DIMENSIONS

Plywood as reinforcement should be glued and nailed/screwed to both sides of the beam around the holes. Nailing/screwing with gluing of plywood to both sides of the hole provides full bond between LVL and plywood. Figure 9 provides a drawing of a hole reinforced with two plywood sheets with dimensions shown in the figure.

The limitations below should be used for beams with holes.

$$0.25 h_d \leq a_r \leq 0.3(h + h_d) \quad (22)$$

$$h_1 \geq 0.25 h_d \quad (23)$$

5.2.2. TENSILE STRESS CONTROL

The plywood should control the increase in stresses due to the hole. Control of the tensile stresses can be performed using the following equations:

$$\sigma_{t,90,d} \leq f_{d,ply} \quad (24)$$

$$f_{d,ply} = k_{mod} \frac{f_{t,90,k}}{\gamma_m} \quad (25)$$

$$\sigma_{t,90,d} = \frac{K F_{t,90,d}}{2 a_r t_r} \quad (26)$$

where $\sigma_{t,90,d}$ signifies the tensile design stress of plywood

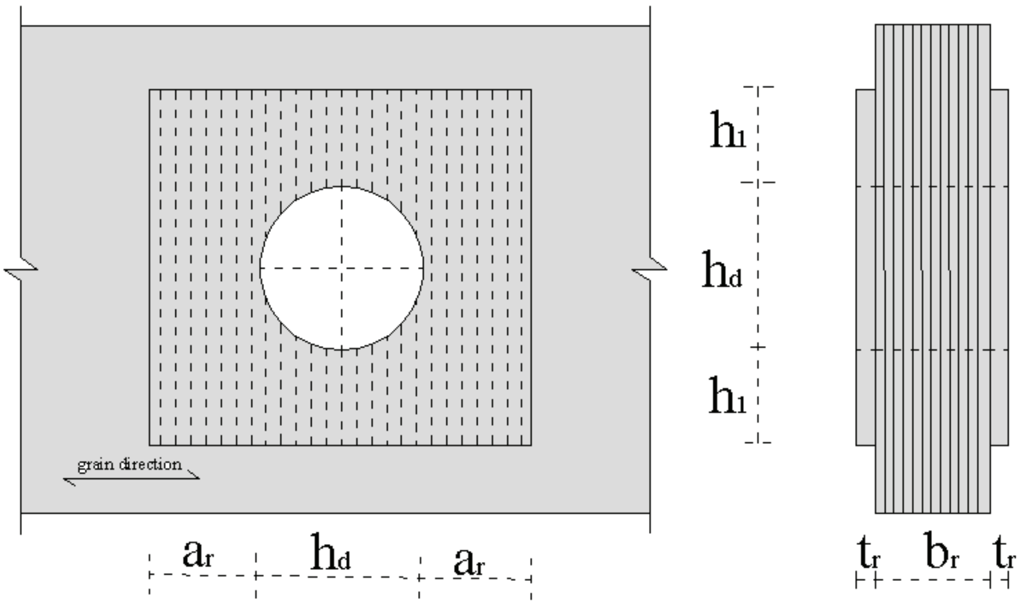

Figure 9. Plywood reinforcing on both sides of a hole in a beam.

perpendicular to face grain, $f_{d,ply}$ the design tensile strength of plywood perpendicular to face grain, and K is a factor taking into account the non-uniform stress distribution around the holes in LVL beams. K according to Aicher et al. [13] may be taken as 2. $F_{t,90,d}$ is the design tensile force in plywood due to the hole. Parameters a_r and t_r are introduced in Figure 9.

According to New Zealand Standard, NZS 3603 [14], the tensile strength of plywood for different classes of plywood are as shown in Table 1.

Table 1. Characteristic tensile strength of plywood perpendicular to face grain [15].

Class of plywood	Characteristics tensile strength of plywood (MPa)
F22	34.6
F17	30
F14	22
F11	17.3
F8	13.5

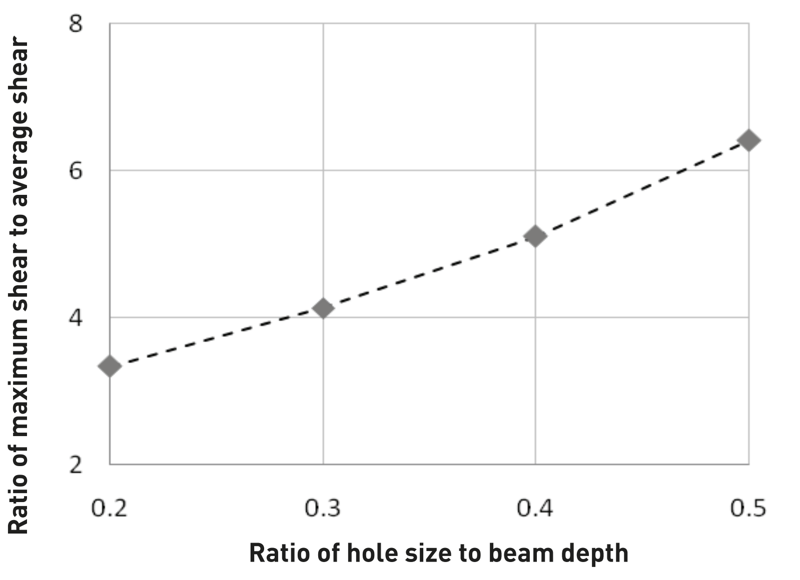

Figure 10. Ratio of the maximum shear to average shear for different hole width to beam depth ratios [5] .

5.3. STRESS CONCENTRATIONS

In square and rectangular holes, corner stress concentrations occur and shear stresses increase considerably. According to Bejtka and Blass [16], for rectangular holes with sharp corners the ratio of maximum shear stress to average shear stress varies significantly with increasing hole diameter to beam depth, as shown in Figure 10 for square holes.

Figure 10 shows that for $h_d/h = 0.2$ the maximum shear stress produced is 3.3 times the average value and for $h_d/h = 0.5$ the ratio is 6.4.

Control of the shear stresses at the edges of a rectangular opening is necessary and the following formulations may be used for calculation of the maximum shear stress [17]:

$$\tau_2 = \kappa_2 \times 1.5 \frac{V_d}{b(h - h_d)} \quad (27)$$

$$\kappa_2 = 1.84\left(1 + \frac{b_h}{h}\right) \times \left(\frac{h_d}{h}\right)^{0.2} \quad (28)$$

where τ_2 is the maximum shear produced due to the hole and applies for $0.1 \le b_h/h \le 1$ and , $\frac{0.1 \le h_d}{h} \le 0.4$ subject to:

$$\tau_2 \le f_{v,d} \quad (29)$$

where $f_{v,d}$ is the design shear stress capacity of the LVL defined as:

$$f_{v,d} = k_{mod} \frac{f_{v,k}}{\gamma_m} \quad (30)$$

where $f_{v,k}$ is the characteristic shear force capacity of the LVL.

5.4. INTERACTION OF HOLES

Interaction of two or more holes (Figure 11) considerably decreases the capacity of a beam. Cracks around the holes joining each other can govern the failure mechanism. Interaction of the holes was investigated through a set of numerical analyses on reinforced beams.

Numerical analyses showed that for distances between screws greater than 1.5h the screws have no interaction to each other. This distance is recommended as a minimum clear distance between the screws that should always be ensured.

6. WORKED EXAMPLES

The following examples illustrate how the two reinforcement methods can be used to restore the beam to its original capacity.

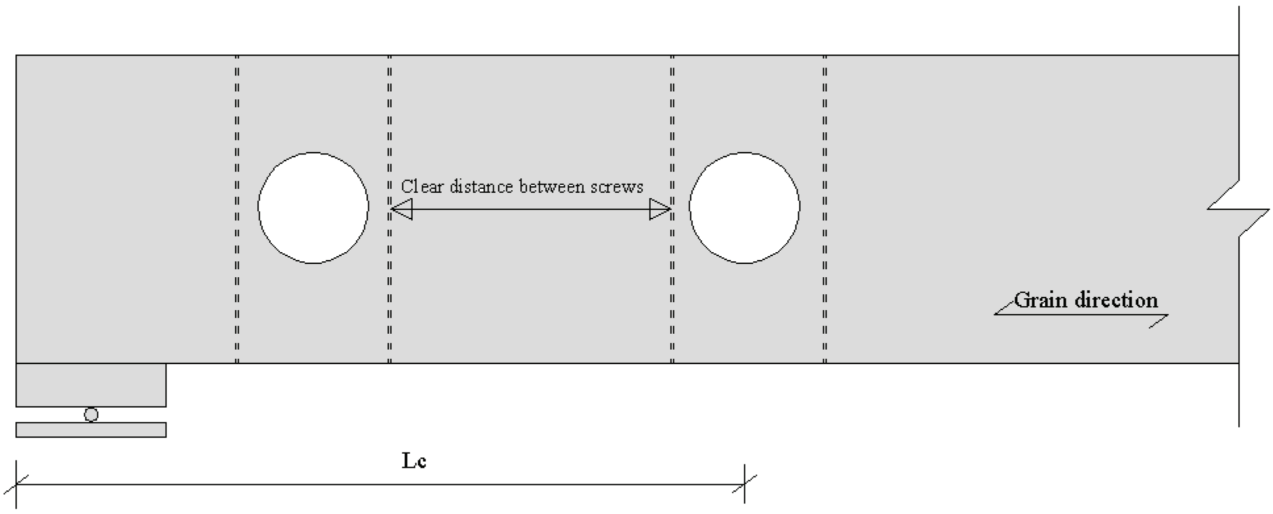

Figure 11. Interaction of the holes.

SCREW REINFORCEMENT DESIGN

A beam of dimensions 3000 x 300 x 45 mm has been loaded at mid-span. A hole of diameter 90 mm is introduced into the beam at a distance of 650 mm from the end support. The beam is used within the roof of a house subjected to permanent loads. The design of the reinforcement using fully threaded SPAX screws of 8 mm outer diameter (see Figure 12) is required. Assume 2 mm thread for the screw.

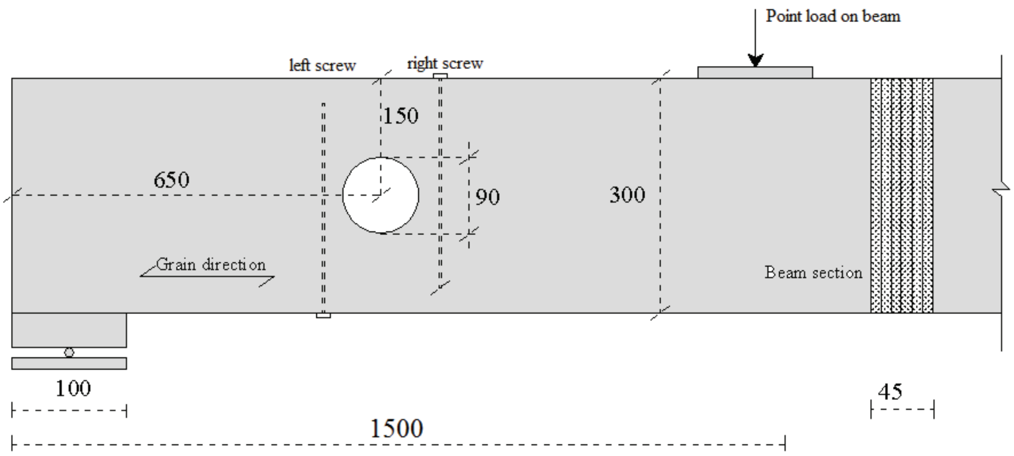

Figure 12. Beam with hole reinforced with screws (dimensions in mm).

Controlling hole diameter:

The ratio of the hole diameter (h_d) to beam dept (h) is 0.3, which is smaller than the limitation for fully threaded SPAX screw of 0.40. The reinforcement by screw needs therefore to be designed.

Tensile load perpendicular to grain in screw:

The design here is being performed for maximum shear force in the section of the beam.

The characteristic shear capacity of LVL in the grain direction is [18]:

$$f_{v,k} = 6.0\,MPa$$

Design shear capacity of the section:

$$f_{v,d} = \frac{6.0 \times 0.6}{1.2} = 3.0\,MPa$$

The maximum shear force capacity of the beam section according to Eurocode 5 [19] could be calculated as below:

$$V_d = \frac{2}{3} f_{v,k}\,bd = \frac{2}{3} \times 3.0 \times 45 \times 300 = 27\,kN$$

$$M_d = V_d \times L_c = 27000 \times (650 - 50) = 16.2\,kNm$$

Hence the tensile force in the screw can be evaluated using Equation 1 as:

$$F_{t,90,d} = F_{t,V,d} + F_{t,M,d} = \frac{\sqrt{2}}{8h^3} V_d h_d \left(3h^2 - h_d^{\,2}\right) + \frac{3}{4} \frac{M h_d^{\,3}(h + h_d)}{h^3(h.h_d + h^2 + h_d^{\,2})}$$

$$F_{t,90,d} = \frac{\sqrt{2}}{8 \times 300^3} \times 27000 \times 90 \times \left(3 \times 300^2 - 90^2\right) + \frac{3}{4} \times \frac{16200000 \times 90^3 \times (300 + 90)}{300^3(300 \times 90 + 300^2 + 90^2)} = 5.2kN$$

Design of screw reinforcement:

With the assumption of using fully threaded SPAX screws for the reinforcement, the withdrawal strength could be calculated as below using Equation 19:

$$f_{1,k} = 81 \times 10^{-6} \times \rho^2 = 81 \times 10^{-6} \times 550^2 = 24.5 \frac{N}{mm^2}$$

The embedment length of the screw could be calculated using Equation 21:

$$L_{ad} = 0.5h - 0.345\,h_d = 0.5 \times 300 - 0.354 \times 90 = 118\,mm$$

$$L_{bd} = Max\,(L_{ad}, 12\,d_r) = Max\,(118, 12 \times 8) = 118\,mm$$

The aforementioned embedment length can carry the following load:

$$R_{ax,k} = 118 \times (81 \times 10^{-6}) \times 550^2 \times 8 = 23.2kN$$

$$R_{ax,d} = \frac{R_{ax,k} K_{mod}}{\gamma_m} = \frac{23208 \times 0.6}{1.2} = 11.6kN$$

The embedment length of 118 mm provides 11.6 kN resistance to withdrawal. The above force is higher than the design force of 5.2 kN in the screw. So that embedment length will be sufficient.

The screw also should not yield. Assuming the yielding strength of the SPAX screw is 400 MPa, the yielding force of the screw is:

$$f = \frac{400 \times \pi \times 6^2}{4} = 8.7kN$$

So the force of 8.7 kN is bigger than the design axial force of 5.2 kN in the screw. The tensile force due to the hole is smaller than the resisting tensile force in the screw.

Controlling of distance of screw from edges:

Distance of screw from the edges of the beam from Equation 11 is:

$$2.5d_r \leq a_{1,c} \leq 4d_r$$

$$20 \leq 30 \leq 32 \quad \textbf{OK}$$

The distance of the screw from the other surface of the beam from Equation 13 is:

$$a_{2,c} \geq 2.5\,d_r$$

Hence the distance of the screw from the edge of the beam should be:

$$a_{2,c} = \frac{45}{2} = 22.5mm \geq 2.5d_r = 2.5 \times 8 = 20\,mm \quad \textbf{OK}$$

The distance of the hole from the support is checked through the Equation 10:

$$S = \left(L_c - C - \frac{h_d}{2}\right) \geq h$$

$$S = \left(650 - 100 - \frac{90}{2}\right) = 505 \geq 300\,mm$$

The design is now complete for reinforcement with self tapping screws. Control of other critical actions also should be performed but this is not included in the worked example.

PLYWOOD REINFORCEMENT DESIGN

A beam of dimension 3000 x 300 x 45 mm has been loaded at mid-span. A 90 mm diameter hole is introduced into the beam at a distance of 650 mm from the end section. The beam is used in the roof of a house and is subjected to permanent loads (see Figure 13).

Controlling hole diameter:

The ratio of the hole diameter to beam depth is 0.3, which is smaller than the limitation of 0.45 for plywood reinforcement. Reinforcing by plywood can therefore be used.

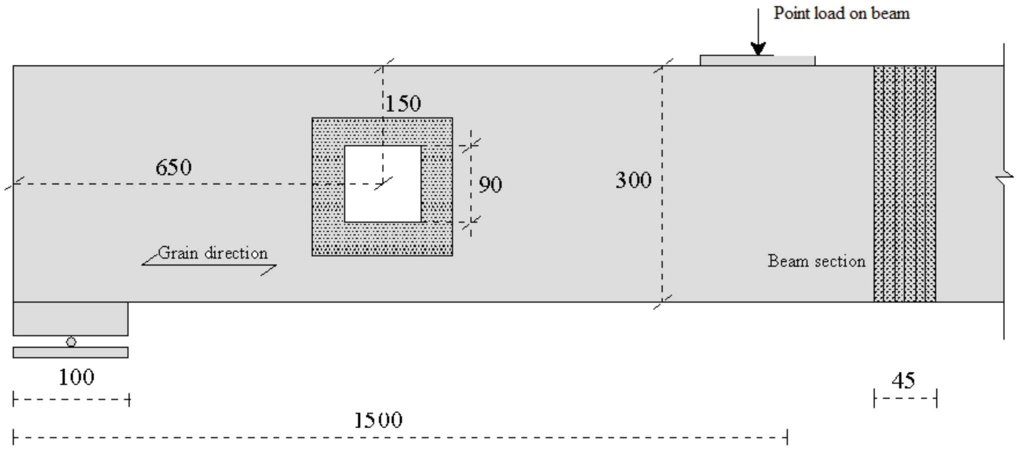

Figure 13. Beam with hole reinforced with plywood (dimensions in mm).

Tensile load perpendicular to grain in plywood:

The maximum shear force capacity of the section according to Eurocode 5 [19] is:

$$f_{v,d} = \frac{f_{v,k} k_{\text{mod}}}{\gamma_m} = \frac{6 \times 0.6}{1.2} = 3.0\,MPa$$

$$V_d = \frac{2}{3} f_{v,d} bd = \frac{2}{3} \times 3.0 \times 45 \times 300 = 27.0\,kN$$

$$M_d = V_d \times L_c = 27000 \times 600 = 17.2\,kNm$$

The tensile force due to the hole is calculated using Equation 1 as:

$$F_{t,90,d} = F_{t,V,d} + F_{t,M,d} = \frac{\sqrt{2}}{8h^3} V_d h_d \left(3h^2 - h_d^{\ 2}\right) + \frac{3}{4} \frac{M h_d^{\ 3} (h + h_d)}{h^3 (h.h_d + h^2 + h_d^{\ 2})}$$

$$F_{t,90,d} = \frac{\sqrt{2}}{8 \times 300^3} \times 27000 \times 90 \times \left(3 \times 300^2 - 90^2\right) + \frac{3}{4} \times \frac{16200000 \times 90^3 \times (300 + 90)}{300^3 \times (300 \times 90 + 300^2 + 90^2)} = 5.2\,kN$$

Plywood Dimensions:

The horizontal dimension of the plywood should be limited by Equation 22:

$$0.25 h_d \le a_r \le 0.3(h + h_d)$$

$$22.5 \le a_r \le 117$$

The plywood should carry tensile forces due to the hole in the section of the beam according to Equations 24 and 25.

$$\sigma_{t,90,d} \le R_d$$

$$f_{d,ply} = k_{\text{mod}} \times \frac{f_{t,k}}{\gamma_m} = 0.6 \times \frac{15}{1.2} = 7.5\,MPa$$

Assuming the use of 9 mm thick plywood, the length of the coverage area is defined by Equation 26:

$$\sigma_{t,90,d} = \frac{K\ F_{t,90,d}}{2\,a_r t} = \frac{2 \times 5200}{2 \times a_r \times 9} = \frac{577}{a_r}$$

$\alpha_r \ge 77$ mm then the value $\alpha_r = 100$ mm is chosen.

Using Equation 23, h_1 should be:

$$h_1 \ge 0.25\,h_d = 0.25 \times 90 = 22.5\,mm \qquad \text{assuming } h_1 = 50 \text{ mm}$$

The actual dimensions of the plywood sheets will be 290 x 190 x 9 mm. Control of the other critical sections, such as the corners for stress concentrations in the case of square/rectangular holes, should be carried out. In a comparison of both methods of reinforcement, the use of plywood is more desirable because it avoids stress concentrations that occur around the screws while increasing the local shear capacity of the beam around the hole locally. Plywood provides alternative routes for transferring the shear stresses around the hole.

CONCLUSIONS

The paper presents a design method for LVL beams with holes based on controlling tensile stresses at the edges of the hole in order to regain its original capacity. Experiments on LVL beams show that screws and plywood can be used for reinforcement around holes. Worked examples are presented for designs using screws and plywood as hole reinforcement. Screws and plywood can be used for the reinforcement of beams with holes. Plywood plates glued and nailed on both sides of the beam are the preferable reinforcement method for LVL beams with holes; however, screws can be used for a limited range of hole diameter to beam depth ratios.

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REFERENCES

[1] Ardalany, M., et al., *Tension perpendicular to grain strength of wood, Laminated Veneer Lumber (LVL) and Cross banded LVL (LVL-C)*, in *21st Australasian conference on the mechanics of Structures and materials*, S. Fragomeni , et al., Editors. 2010: Melbourne, Victoria, Australia. p. 891- 896.

[2] Danielsson, H., *The strength of glulam beams with holes: A survey of tests and calculation methods*, 2007, LUND University: Sweden. p. 1-91.

[3] Riipola, K., *Timber beams with holes: fracture mechanics approach.* Journal of Structural Engineering, ASCE, 1995. 121(2): p. 225-240.

[4] Johannesson, B., *Design problems for glulam beams with holes*, in *Division of Steel and Timber structures*1983, Chalmers University of Technology: Göteborg, Sweden. p. 1-74.

[5] Ardalany, M., *Analysis and design of Laminated Veneer Lumber beams with holes*, in *Civil and Natural Resources Engineering*2012, University of Canterbury: Christchurch, New Zealand. p. 299.

[6] Franke, B. and P. Quenneville, *Numerical Modeling of the Failure Behavior of Dowel Connections in Wood.* Journal of Engineering Mechanics, ASCE, 2011. 137(3): p. 186-195.

[7] APA, *Allowable holes in LVL Report number T2009L-30*, 2009, The Enigineered Wood Association (EWA).

[8] Carling, O., *Swedish glulam handbook* 2001, Stockholm: Svenskt Limträ.

[9] DIN 1052, *Design of timber structures - General rules and rules for buildings (In German)*, 2008, Construction Standards Committee (NABau) at DIN: Berlin, Germany. p. 239.

[10] Aicher, S. and L. Hofflin, *A contribution to the analysis of glulam beams with round holes.* Journal of Otto-Graf, 2000. 11: p. 21.

[11] Ardalany, M., et al., *Experimental and numerical analysis of hole placement in depth of Laminated Veneer Lumber (LVL) beams (Accepted).* Australian Journal of Structural Engineering (AJSE), 2012: p. 1-11.

[12] Eurocode-5, *Eurpoean Committee for Standardization CEN, EN 1995-1-1. Design of timber structures-part 1-1: General-common rules for buildings* 2004: Bruxelles, Belgium.

[13] Aicher, S., *Glulam beams with internally and externally reinforced holes- tests, detailing and design*, in *CIB-W18/42-12-1*2011: Alghero, Italy. p. 1-13.

[14] NZS 3603, *Timber Structures Standard*, 1993, Standards New Zealand, Wellington: New Zealand.

[15] NZS3603, *Timber structures standard*, 1993, Standard New Zeland, Wellington: New Zealand.

[16] Bejtka, I. and H.J. Blass, *Self-tapping screws as reinforcements in beam supports*, in *International council for research and innovation in building and construction working commission w18 - timber structures*2006: Florence. p. 1-12.

[17] Blass, H. and B. Ireneusz, *Reinforcements perpendicular to the grain using self-tapping screws*, in *Proceedings of the 8th World Conference on Timber Engineering*2004: Lahti, Finland.

[18] Buchanan, A., *Timber design guide*. 3 ed. 2007, Wellington, New Zealand: Timber Industry Federation. 332

[19] Eurocode 5, *European Committee for Standardization CEN, EN 1995-1-1. Design of timber structures-part 1-1: General-common rules for buildings.*, 2004: Bruxelles, Belgium.