NUMERICAL ANALYSIS OF BEHAVIOUR OF CROSS LAMINATED TIMBER (CLT) IN BLAST LOADING

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Abstract. A non-linear computation model for CLT wall element that includes explicit dynamics and composite damage constitutive model was developed. The numerical model was compared with classical beam theory and it turned out that shear wood layer has significant shear deformations that must be taken into account when designing CLT. It turned out that impulse duration time has a major effect on the strength of CLT. Special attention must be payed when designing CLT wall, window and door architectural system in order to guarantee the robustness of structure. The proposed numerical modelling framework can be used when designing CLT buildings that can be affected by blast loading, whilst structural robustness must be guaranteed.

1. Introduction

Engineered timber such as plywood, glulam and cross laminated are dominant materials for load bearing timber structures. Sustainability, good strength to weight ratio, high fire resistance and low heat conductivity are the main qualities that provide reasons for using this material in low-, mid- and high-rise wood buildings. The market share of wood buildings in Europe is significantly increasing. CLT construction has a negative CO_2 footprint, therefore it allows to decrease CO_2 emissions compared to the concrete or steel industry.

The mathematical modeling and physical testing of structures depends on the strain rate (see Fig. 1). Structural loads that produce strain rates in range $10...10^6$ (s^{-1}) are classified as blast loading.
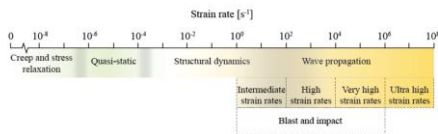

Figure 1. Structural problem classification depending on strain rate.

Physical experiments showed that wood is a strain rate sensitive material. Crushing stress and plateau stress of wood can increase up to 50 % at a high strain rate 600 (s^{-1}). Similar tendency has been experimentally observed also for other materials, such as structural steel and reinforced concrete.

Many experimental and theoretical investigations are related to structural vibration of CLT slabs. Cellulose fiber reinforced composites have been modelled using multiscale framework that includes nano, micro and macro scales.

So far, there is a gap in knowledge of structural behavior of CLT slabs and walls in blast loading. In this paper a numerical simulation methodology is proposed and preliminary numerical simulation results are presented. Unconfined and confined explosion cases are conceptually analyzed.

2. Numerical methods

Simulation of structural behavior in blast loading consists of two parts. In the first part the blast loading has to be calculated. In the second part, the mechanical response to blast loading can be estimated by various beam, shell or continuum based finite elements or an analytical approach based on the single degree of freedom system. This work is focused on the second step.

A typical pressure time profile of unconfined explosion is shown in figure 2. The pressure wave consists of a positive phase and negative phase. Typically, only the positive phase is used for structural design. In this work only the positive phase that is approximated with a linear function will be considered (see Fig. 2.).
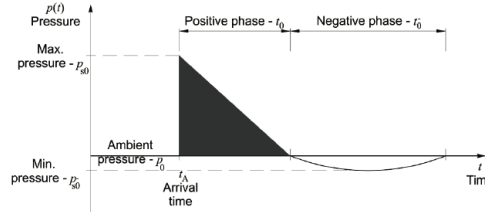

Figure 2. Pressure-time profile of the explosion wave.

Structural dynamics are numerically modelled by using the equation of motion that represents Newton's second law:

$$M\ddot{u} + C\dot{u} + R(u) = P \qquad (1)$$

where M is mass matrix, C is damping matrix, P is external load, $R(u)$ represents structural internal forces that is equal to stiffness matrix K and displacement vector multiplication $R(u) = Ku$.

In this work the damping term was not taken into account. A transversally isotropic composite damage material constitutive model was used that includes orthotropic failure criterion that is calculated using components of principal stress.

An 8- node brick finite element was used in numerical simulations. A full 8 integration was used to avoid hourglass effects. Shear locking was avoided by using at least two finite elements in a transversal direction of each wood layer.

Since no experimental data is available in the literature, a numerical model was compared with results obtained from classic beam theory. In this theory the transversal displacement of a beam is governed by the following partial differential equation:

$$EI\frac{\partial^4 w}{\partial x^4} + \rho\frac{\partial^2 w}{\partial t^2} = p(t), \qquad (2)$$

where EI is flexural stiffness, ρ is linear density, w transversal deflection, x axial coordinate, t is time and $p(t)$ is external loading.

The solution is obtained using the finite difference method. Time and space was discretized using central difference schemes. The time discretization using central difference schemes was used also in the finite element method. Therefore, an explicit finite element solver is used.

The applied load $p(t)$ was specified as a linear function with peak pressure at $t=0$ and zero value at $t > t_a$ (see Fig. 2.). Pressure dependence on spatial coordinate was not taken into account.

3. Results and discussion

CLT wall with 2.5 m height is analyzed in blast loading. CLT is made by using C24 class wood boards with 25 mm thickness. The material properties that are used in numerical and analytical simulations are shown in table 1.

Numerical simulations were done by using a 1 cm wide strip of CLT to reduce the computation time. The wall was assumed to be clamped at both ends.

Table 1. Mechanical properties of the wood that are used in simulations.

Parameter name	Value	Units
Density	400	kg/m^3
Young's modulus in axial direction (wood fiber direction)	11	GPA
Young's modulus in transversal* direction	0.37	GPA
Shear modulus	0.69	GPA
Poisson's ratio v_{ar}**	0.4	-
Poisson's ratio v_{rt}**	0.01	-
Poisson's ratio v_{at}**	0.4	-
Bulk modulus	10	GPA
Shear strength	2.5	MPA
Longitudinal strength	20	MPA
Transversal strength in tension	0.5	MPA
Transversal strength in compression	2	MPA
Nonlinear shear stress	0.5	MPA

* it is assumed that tangential and radial direction of wood has the same mechanical properties. ** symbols a,r,t indicate axial, radial and tangential directions of wood, respectively.

1.1. Shear layer influence

The influence of shear layers on the maximal deflection and vibration modes is analyzed. The results for the three-layer CLT wall, where all layers are oriented in an axial direction are presented in figure 3. Classical beam theory complies with numerical results. This means that in the case when all wood layers are oriented in the same direction, the shear deformations are negligible for this case.
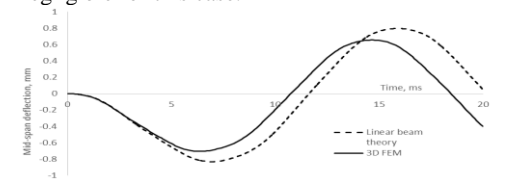

Figure 3. Deflection change in time, 3-layers, all in one direction. Applied load $p_{max}=1$ KPA, $t_0=10$ ms.

A quite different situation can be observed for a 3-layer CLT wall, when the middle layer is oriented in an orthogonal direction. This result is presented in figure 4. 3D finite element modelling shows a vibration amplitude and period that is more than 2 times higher compared to classical beam theory. It means that there is significant shear deformation that is not taken into account in classical beam theory. Therefore, it is recommended to use the theory that takes into account shear deformations when modelling CLT in blast loading. Axial and shear stress is presented in figure 5. It can be observed that axial stress on the top layer, where a blast load is applied, is in the same phase as deflection amplitude. However axial stress on the bottom side and shear stress show a significant shift of the vibration phase. This can be explained with the

stress wave movement, including interference and diffraction phenomena, which make such a difference in the structure.
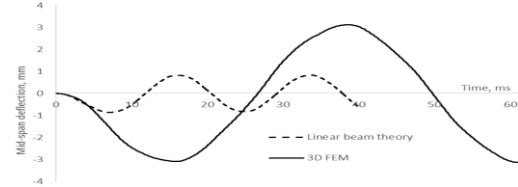

Figure 4. Deflection change in time, 3-layers, middle layer in perpendicular direction. Applied load $p_{max}=1$ KPA, $t_0=10$ ms.
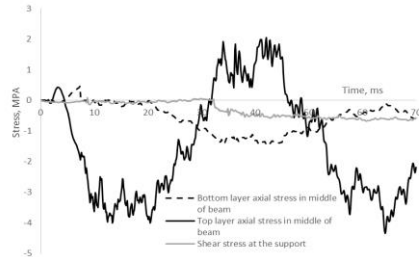

Figure 5. Axial stress change in time. Applied load $p_{max}=1$KPA, $t_0=10$ ms.

A number of layers play a crucial role in the CLT behaviour in blastload. The maximal axial stress reduces nearly linearly, by increasing the count of layers (see Fig. 6). The axial stress variation in time for the CLT layer that is subjected to blast pressure is shown in figure 7. It can be seen that the amplitude is decreasing and the vibration frequency is increasing when number of layers increase. Vibration frequency for 3 layer CLT is around 20 Hz and 7-layer CLT has around 67 Hz. It was observed that vibration amplitude is only 25% smaller for a 5-layer CLT compared to 3-layer CLT. Numerical simulations showed that mainly the first three vibration modes were excited with the blast wave.
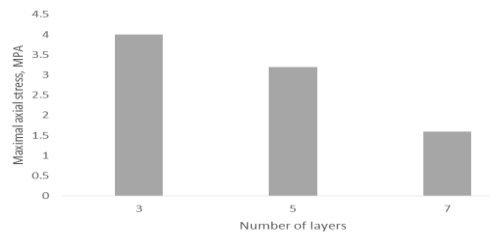

Figure 6. Stress in middle of span in layer of weave contact, depending on layer count. Applied load $p_{max}=1$ KPA, $t_0=10$ ms.
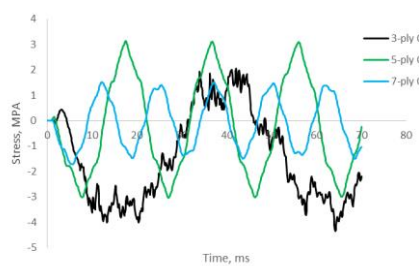

Figure 7. Stress change in time depending on number of layers. Applied load $p_{max}=1$ KPA, $t_0=10$ ms.

1.2. Pressure wave duration time

The duration time of the pressure wave has been investigated. The 3-layer CLT structure was affected by a 10 KPA peak pressure and 3 different duration times - 1ms, 10ms and 100ms. Therefore 3 different non-linear cases (see table 2.) were numerically computed.

It turned out that when $t_0 < 10ms$ the structure was not damaged. However, when duration time was 100 ms, the structure was damaged at $t = 168\ ms$. The summary of maximal stress, displacement and damage is shown in table 3.

Axial stress distribution in the CLT before and after damage occurs is shown in figure 8 and figure 9, respectively. The damage occurred when deflection exceeded 40 mm (1/63*L). The deflection change in time is shown in figure 10.

Table 2. Specification of analyzed cases.

Case No.	Peak pressure, KPA	duration time, ms
1	10	1
2	10	10
3	10	100

Table 3. Maximal stress, deflection in structure.

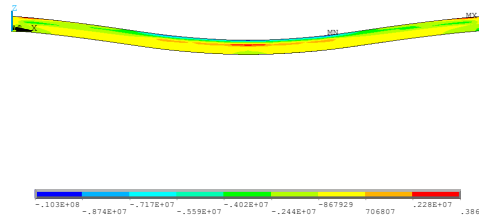| Case No.	maximal axial stress, MPA	Maximal shear stress	Maximal delfection, mm	Additional information
1	1	0.038	1,74	No damage
2	8.2	0,75	17	No damage
3	Structural failure at 168 ms			

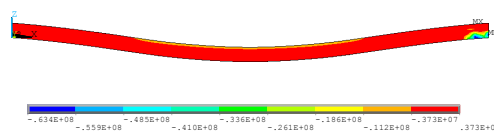**Figure 8.** Axial stress distribution before failure at $t=168\ ms$.

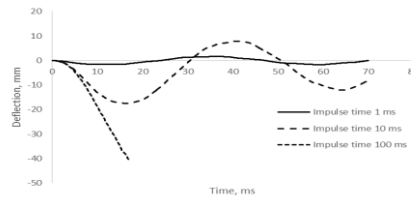**Figure 9.** Axial stress distribution after failure at $t=169\ ms$.

Figure 10. Deflection-time curves for different impulse time.

1.3. Partially confined explosion

When an explosion occurs inside the building, it is fully or partially confined. A confined explosion causes increased time duration of overpressure. The explosion load has a wave character. The initial reflected wave is followed by perhaps several reflected pulses because of reverberation from repeated wave reflections. This train of blast waves is generally of decaying amplitude. While the reverberating shock waves are decaying, the second loading phase develops because the combustion chemistry is expansive, causing a

build-up of pressure: this is called gas pressure loading. A computational fluid dynamics (CFD) approach can be used for more precise analysis of gas dynamics [6]. In this work, an empirical equation of pressure decay is used [6]:

$$p(t) = P * e^{-\frac{2.13(\alpha_e * A_s * t * a_0)}{v}} \quad (3)$$

where t is time, P peak quasi static overpressure (assumed 10KPA), α_e ratio of vented area to wall-roof-floor area, A_s total inside wall-roof-floor area, a_0 speed of sound (assumed 340 m/s).

The results obtained from the equation (3) are presented in figure 11 for three different opening sizes. The analysed room was assumed with following geometrical parameters- height 2.5 m, length 5m, width 4m. The window opening that can be easily damaged with a pressure wave had three different values- 1 m^2, 3 m^2 and 10 m^2. According to the pressure-time curve (see Fig. 11) and stress deformation state (see table 3) 3-layer CLT can withstand when the window opening is larger than 10 m^2. In this case the overpressure fully dropped to a value of nearly zero in 25 ms.
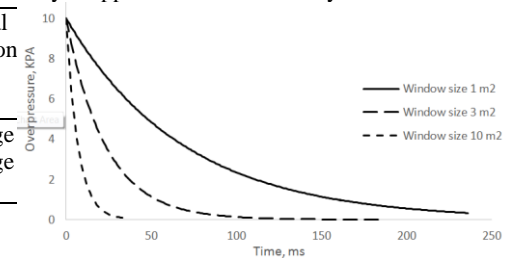

Figure 11. Pressure-time curves depending on size of openings.

4. Conclusion

The non-linear numerical simulation of a CLT wall element is performed using explicit dynamic solver and a transversally isotropic composite damage model. Blast load was applied using a triangular impulse function with an impulse duration time from 1 ms to 100 ms. It turned out that impulse duration time has a major effect on the strength of CLT. Special attention must be payed when designing a CLT wall, window and door architectural system in order to guarantee the robustness of the structure.

It was observed that overpressure impulse caused stress waves in the CLT that excited the first three vibration modes. It was shown that a significant part of vibration amplitude was caused by shear deformation of shear wood layer, therefore theories that take into account shear deformations such as Timoshenko are recommended when designing CLT.

It was shown that most of stress concentrations were located on the side where overpressure was applied. Therefore CLT can be strengthened by using higher strength materials on surface layers and inside lower strength materials can be used, even wood can be partially replaced by heat insulation without significant reduction of blast performance.