

Application of Multi-material Topology Optimization Method for Positioning Reinforcements in Glued laminated Timber Structures

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Glued-Laminated Timber (GLULAM) is a wood-based product often used in construction in many countries such as the USA, Canada, and many countries on the European continent. Briefly, GLULAM can be defined as wood layers glued together for a structural application. This way, GLULAM becomes viable for floors, beams, and stairs. In addition to low density, GLULAM is a sustainable option for civil construction due to transportation's direct reduction of carbon dioxide emission in the atmosphere. In this sense, applying a consolidated technique to find regions where structural substitutions can be made becomes attractive for direct manufacturing cost reduction or new blended GLULAM structures such as GLULAM combined with steel to improve its performance. One of the best-known ways to change the performance of structures is through Topology Optimization. Therefore, this work proposes an adaptation of the Bi-direction evolutionary structural optimization (BESO) to position steel bars in GLULAM structures submitted to static loads. By creating the concept of the sub-design domain and applying the optimization theory. For this, ANSYS software is used to solve the finite element problem in conjunction with Matlab software, where the developed methodology is implemented to solve the topological optimization problem. Simulation results show that the addition of stiffening bars increases the structure's stiffness by up to 77%. Furthermore, the stiffness gained by adding the bars has a nonlinear behavior.

Keywords: BESO, Glued-Laminated Timber, Structural Optimization, Reinforcement Steel Bar

INTRODUCTION

Wood products with any particular manufacturing method, such as Glued Laminated Timber (GLULAM) and Cross Laminated Timber (CLT), are engineered wood products. GLULAM and CLT are products that are candidates to replace conventional products in civil manufacturing, such as concrete and steel. GLULAM is a product generally produced by stacking and gluing layers in the same direction as the selected wood fiber. While in CLT, the fiber direction relative to the neighboring layers is rotated, generally 90°. In countries like the USA, Canada, Europe, and Asia, products like GLULAM and CLT are already being used in large quantities in their civil constructions (Kremer and Symmons, 2015; Central City Association, 2019). The price per volume of engineered wood products such as GLULAM and CLT are higher than when directly compared to competitors in the construction industry such as steel and concrete. However, because it is a low-density material, there are savings in the value of transportation and foundation. Typically, engineered wood product structures are transported semi-ready for assembly, making the workspace clean and faster (Gustavsson et al., 2006).

Given the advantages of engineered wood products and the need for carbon reduction (World Green Building Council, 2019; D'Amico et al., 2021; Hart et al., 2021), studies are conducted to improve these materials' structural capacity (Franzoni et al., 2016, 2017, 2018; Peixoto et al., 2021). The combination of materials with engineered wood product structures is also an option in pursuit of the decarbonization of new buildings (D'Amico et al., 2021). This combination can be made between wood and concrete (Hassanieh et al., 2016b; Sebastian et al., 2017), wood and aluminum (Chybiński and Polus, 2019), wood and bamboo (Sun et al., 2020) and wood and steel (Soriano et al., 2016; Hassanieh et al., 2016a; Chiniforush et al., 2018). The latter combination is demonstrated in Figure 1, where Soriano et al. (2016) added 10 mm diameter steel bars through groves fabricated symmetrically along the neutral axis and the entire length of the GLULAM.

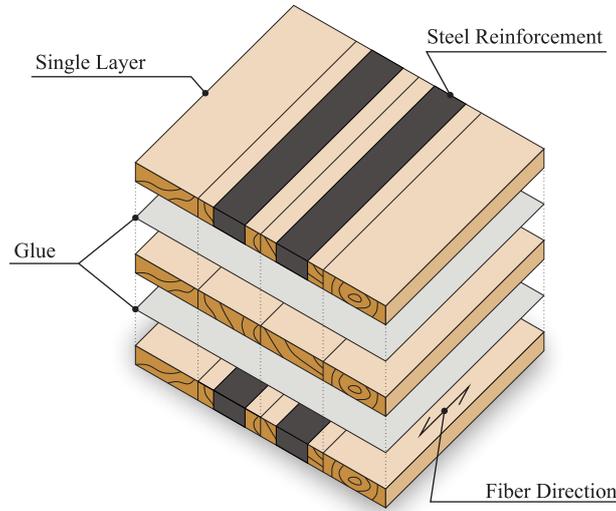


Figure 1 – Construction scheme of the reinforced GLULAM.

Mayencourt and Mueller (2020) proposed a method where the goal is to determine the optimal density of the interlayers in CLT structures, thus reducing material consumption with a trade-off in performance. For example, applying this method to a five-layer CLT resulted in a material reduction of about 18%. Besides directly decreasing the manufacturing cost, a lighter structure, for example, a floor, decreases the size of beams and foundations.

In structure optimization, topology optimization has been used to search for the optimal material distribution in a design domain for a particular boundary condition considering a specific objective function. There are several topology optimization methods, including the Solid Isotropic Material method with Penalty (SIMP) (Zhou and Rozvany, 1991; Bendsoe and Sigmund, 2004), the Evolutionary Structural Optimization (ESO) method (Xie and Steven, 1993), the Bi-directional Evolutionary Structural Optimization (BESO) method (Huang and Xie, 2007), and the Level Set method (Sethian and Wiegmann, 2000). In past years the ESO/BESO methods have been applied to several problems, such as multi-physic, (Azevedo et al., 2018), multi-material (Huang and Xie, 2007, 2008; He et al., 2016), and multi-scale problems (Vicente et al., 2016). In this work, a particular multi-material problem will be investigated. The multi-material problems deal with design domains composed of at least two distinct materials. To the author's knowledge, the literature has not investigated the topological optimization of timber structures with reinforcement such as steel rods (Soriano et al., 2016; Mayencourt and Mueller, 2019). In this sense, this work aims to develop a methodology based on the BESO method to find the best positioning of reinforcement for GLULAM structures subjected to static loads and volume constraints.

METHODS

The method used to apply topological optimization with multiple materials in this paper is based on the consolidated methods of Huang and Xie (2007, 2008); He et al. (2016). For maximizing the stiffness of the structure composed of two materials, the mean compliance should be minimized according to the problem stated in Eq. 1.

$$\begin{aligned}
 & \text{Minimize} \quad C(x) = \frac{1}{2} \mathbf{f}^T \mathbf{u} \\
 & \text{Subject to:} \quad [\mathbf{K}] \{\mathbf{u}\} = \{\mathbf{f}\}, \\
 & \quad \sum_{i=1}^N V_i x_{ij} = \sum_{i=1}^N V_i - V_j^* \\
 & \quad x_{ij} \in (10^{-4}, 1) \quad (j = 1, 2)
 \end{aligned} \tag{1}$$

where $\{\mathbf{f}\}$ and $\{\mathbf{u}\}$ are the values of external forces and displacements applied in the structure domain. $[\mathbf{K}] \{\mathbf{u}\} = \{\mathbf{f}\}$ stands for the equilibrium equation of the system. N stands for the number of elements in design-domain, V_j^* is the

fraction of the prescribed volume for the steel beam. $\sum_{i=1}^N V_i$ stands for total design domain volume. x_{ij} stands for element density of i th element for j th material ($j = 1$ wood and $j = 2$ steel).

The case applied in this paper has a structure composed of two solid phases with Young’s modulus E_1 and E_2 . E_1 represents Young’s modulus of wood considered isotropic according to values taken from United States Department of Agriculture, Forest Service, Forest Products Laboratory (2010) for the Douglas fir species. E_2 is related to conventional steel. The parameters used in this work are presented Table 1.

Table 1 – Assumed mechanical properties.

Material	E	ν
Douglas Fir	13400 MPa	0.292
Steel	210 GPa	0.30

The sensitivity number of each element can be calculated independently of the type of loading and criteria. The procedures for obtaining the sensitivity number and its derivations are available in the literature (Vicente et al., 2016; He et al., 2016). For the case of compliance minimization, the sensitivity is given from Eq. 2

$$\alpha_i = \frac{\partial C}{\partial x_i} = -\frac{1}{2} p x_i \{u_i^e\}^T \{K_i^e\} \{u_i^e\} \tag{2}$$

where C is the mean compliance of the structure, $\{u_i^e\}$ is the element displacement, and $\{K_i^e\}$ is the element stiffness matrix. The sensitivity number has to be filtered to avoid checkerboard-like problems. There are several effective methods presented in the literature (Vicente et al., 2016; Zuo and Xie, 2015; Chen et al., 2019). In this paper, the filter applied is related to a filter size r_{min} determined by the user.

This paper uses two software programs, MATLAB and ANSYS to apply the method. ANSYS solves the finite element problem, and MATLAB for updating the parameters and solving the topology optimization problem. The sequence and indication of the software responsible for each step are shown in Figure 2.

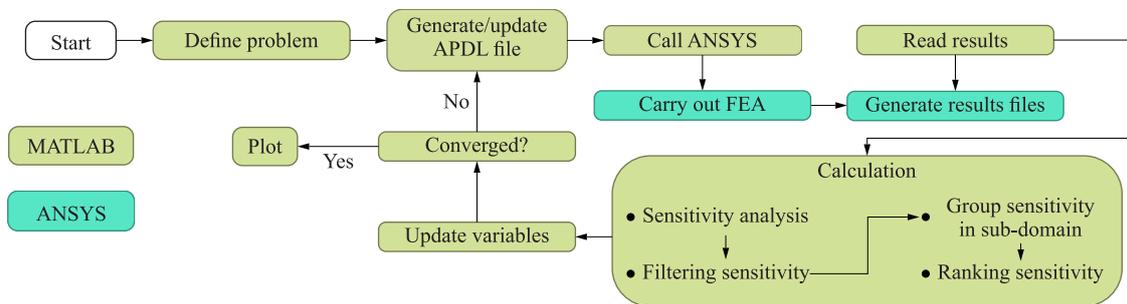


Figure 2 – Sequence adopted for solving the topological optimization problem. The colors indicate which software is responsible for which step.

To determine the location of the steel bars in a beam, first, the size of the steel beam with length L_s and height H_s is required. Then the design domain is divided into a sub-design domain, as shown in Figure 3. It is necessary to obtain the indices of the elements belonging to the sub-design domain to average the number of sensitivities of these elements. Then the elements belonging to each sub-design domain have the number of sensitivity replaced by the average of the number of sensitivity of the sub-design domain to which it belongs.

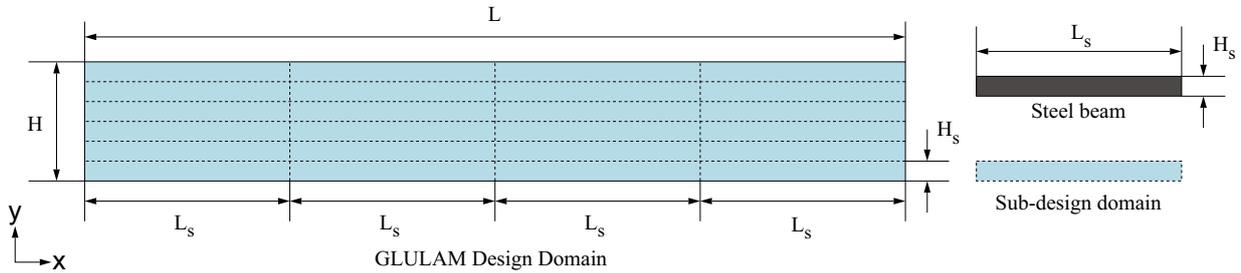


Figure 3 – An example of the design domain and sub-design domain.

NUMERICAL EXAMPLES

Example 1

In this example applying the method proposed in this paper, only half of the model is simulated to decrease computational cost. The dimensions of the GLULAM were based and adapted from Peixoto et al. (2021), being $L = 2800$ mm and $H = 150$ mm, supported at the end under a platform and subjected to a distributed load in the center of the beam, as shown in Figure 4. While the steel beam dimension are $L_s = 350$ mm and $H_s = 6$ mm. In this half of the model, 700 elements along length $L/2$ and 75 elements along H totaling 52500 elements were considered. At each iteration, a bar is added until a value of 30 bars is reached. The other parameters for the BESO method are: $r_{min} = 65$ mm, $\tau = 0.01$, $N = 4$ and $p = 3$.

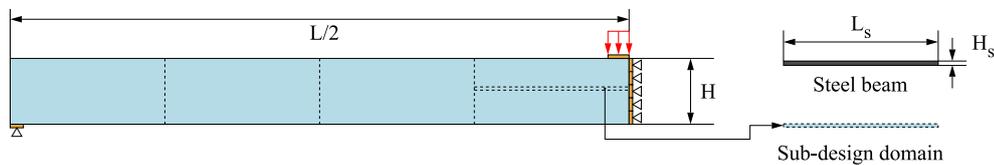


Figure 4 – An example of the design domain and sub-design domain of example 2 with indication of distributed load application region and boundary conditions.

Figure 5 presents the sensitivity number distribution from four iterations of the simulation. In the first iteration, no steel bars were added; in the 10th iteration, ten steel bars were added, distributed near to the support and the force application region; in the 20th and 34th iterations, more bars were added in the regions of interest, in addition to the region opposite the force application.

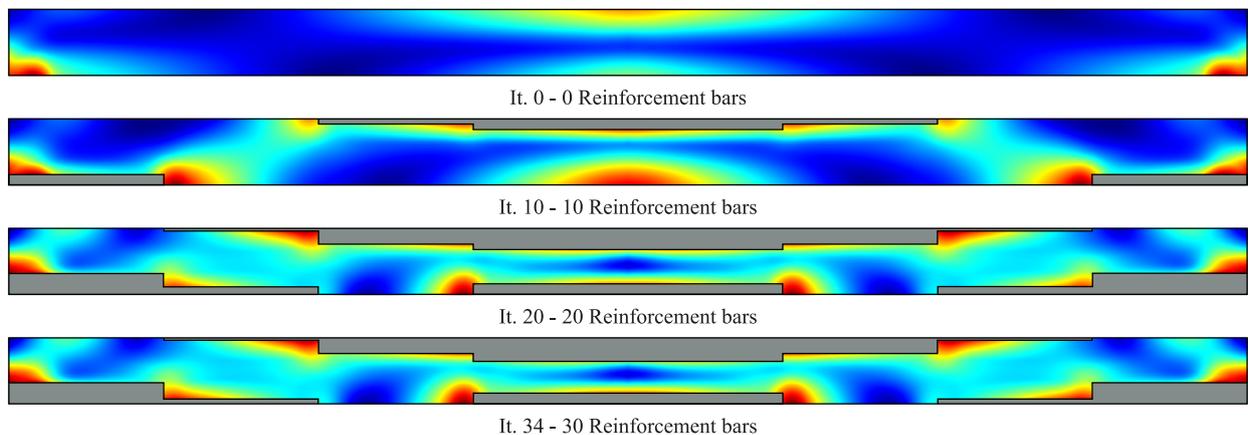


Figure 5 – Four iterations with indication of the filtered sensitivity number and positioning of the steel bars from example 1.

Figure 6 shows the evolution of the objective function and the number of reinforcement bars as a function of iterations. In this graph, it can be observed that between iteration number 15 and the number 25, the addition of 10 bars did not contribute proportionally to the objective function as between iterations 0 and 10. That is, considering the assumptions of this model, it can be stated that to improve the stiffness by approximately 77%, i.e., reduce compliance from 2.25×10^{-4} Nm (iteration 0) to 0.6×10^{-4} Nm (iteration 10), 10 steel bars of dimensions H_s and L_s are required. While to improve the stiffness from 0.6×10^{-4} Nm to 0.27×10^{-4} , 20 more bars are needed.

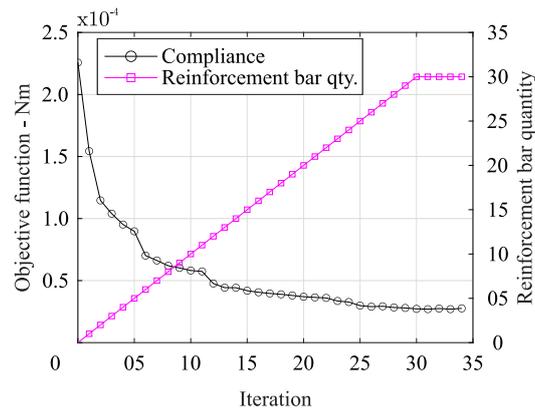


Figure 6 – Optimization histories of the objective function and the evolution histories of the reinforcement bar quantity for example 1.

Example 2

In this example applying the method proposed in this paper, only half of the model is simulated to decrease computational cost. The dimensions of the GLULAM were based and adapted from Peixoto et al. (2021), being $L = 2800$ mm and $H = 150$ mm, supported at the end under a platform and subjected to a distributed load in spaced $L_F = 470$ mm from center, as shown in Figure 7. While the steel beam dimension are $L_s = 200$ mm and $H_s = 10$ mm. In this half of the model, 700 elements along length $L/2$ and 75 elements along H totaling 52500 elements were considered. Fourteen bars of dimensions L_s and H_s are present in the initial design domain positioned at a distance $H_y = 20$ mm, as shown in Figure 7. In this example, the reorganization of the 14 bars already added is sought so that no bars will be added, and at each iteration, only one bar can be changed. The other parameters for the BESO method are: $r_{min} = 50$ mm, $\tau = 0.001$, $N = 4$ and $p = 3$.

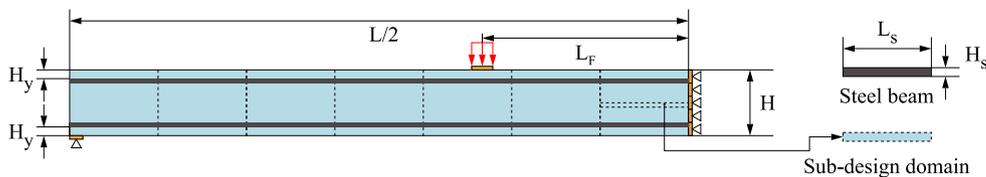


Figure 7 – An example of the design domain and sub-design domain of example 2 with indication of distributed load application region and boundary conditions.

Figure 8 presents the color plot of the sensitivity number distribution from four iterations of the simulation. In the first iteration, 14 bars were already in the design domain; in the sixth iteration the bars were rearranged closer to the center and the support region; throughout the simulation the bars continued to be concentrated in the region near the application of force and support.

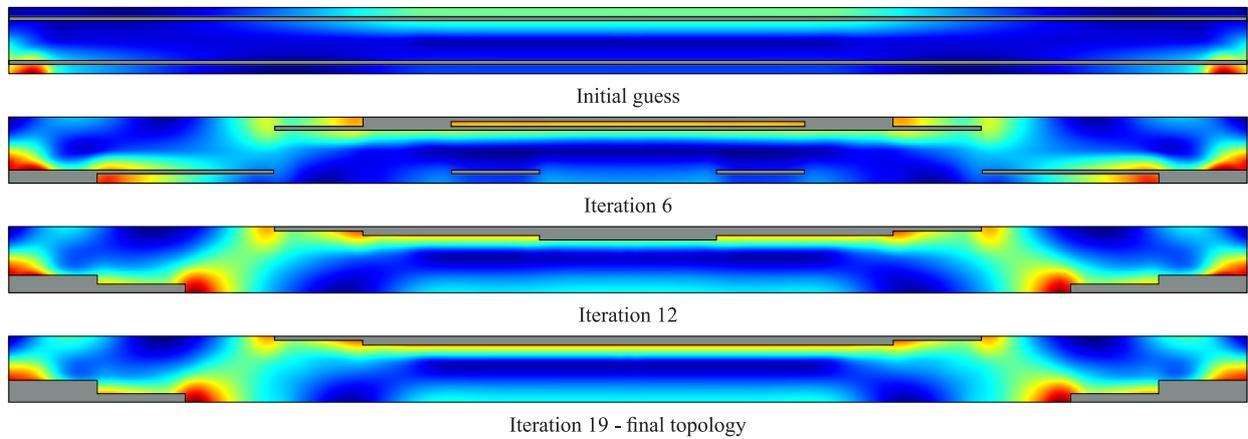


Figure 8 – Four iterations with indication of the filtered sensitivity number and positioning of the steel bars from example 2.

Figure 9 shows the evolution of the objective function and the number of reinforcement bars as a function of iterations. This graph shows that even with the existing 14 bars in the initial condition, there are better placements. Assuming the approximations and conditions presented in this simulation, it was possible to make the structure approximately 48% stiffer by rearranging the positioning of the bars.

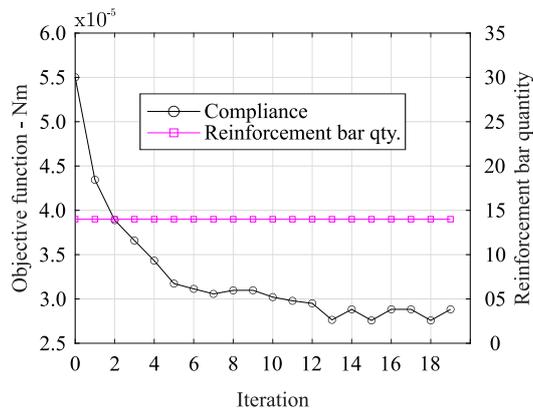


Figure 9 – Optimization histories of the objective function and the evolution histories of the reinforcement bar quantity for example 2.

CONCLUSIONS

This paper proposed adapting the BESO method to position steel bars in GLULAM structures. By creating the concept of sub-design domain and applying the optimization theory, this work proposed to find the optimum areas in the GLULAM structures where the steel reinforcing bars can be located. Besides proving the efficiency of the applied methodology, the examples studied demonstrates that although placing reinforcement bars in the wooden structure improves the stiffness, after a certain amount, the increase in stiffness is low compared to the first ones added. While considering a fixed number of reinforcement bars available for the optimization, the examples showed that it is possible to significantly increase the global stiffness of the structure considering the analyzed boundary conditions. This work has considered several simplifying assumptions, explicitly considering the practical aspect of the GLULAM fabrication. The authors intend to explore the manufacturing aspects of these optimized structures in future works.

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