Impact of Strengthening on Shear Stress Distribution in Built-Up Timber Beams

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Abstract
The growing emphasis on sustainability has led to an increased use of renewable and low-carbon materials, such as timber, in structural applications. Built-up timber elements are increasingly preferred over solid timber elements due to their superior mechanical properties and dimensional stability. However, strengthening interventions can considerably modify the internal stress distribution within built-up sections. This study presents a theoretical analysis of elastic shear stress distribution at bonding interfaces in built-up beams strengthened with steel plates applied to the tension zone. Different cross-sections, including homogeneous and non-homogeneous rectangular sections, as well as symmetric and asymmetric I-sections, are analyzed. The analysis is performed using the transformed section method, assuming linear elastic material behavior. The results indicate that increasing the steel plate thickness leads to higher interlayer shear stresses, particularly near the first and second layers of the built-up timber sections used in this analysis. Increasing the steel plate thickness from 1 mm to 2 mm resulted in approximately a 66% increase in interlayer shear stress at the flange–web interface in symmetric I-sections and about a 64% increase in asymmetric I-sections. In contrast, non-homogeneous rectangular sections exhibited more pronounced stress redistribution than homogeneous ones. In non-homogeneous and asymmetric sections, the stress increase occurs more gradually and is more evenly distributed, whereas homogeneous and symmetric sections display sharper and more concentrated increases near the steel plate. These findings underline the importance of considering not only load-bearing capacity but also interface behavior in strengthening, particularly in aged or historic timber structures where bonding layers may be vulnerable.

1. Introduction

Over the past several years, the building industry has begun to utilize more renewable, natural, and low-carbon footprint materials, as people have become increasingly aware of the environment and the importance of sustainability. In this situation, wood has once again become important, as it can store carbon and be beneficial to the environment. However, standard solid wood members may not perform well mechanically, especially when subjected to varying loading conditions. This restriction has led to the employment of built-up timber pieces, which are stronger and more stable in size. Lamination and connecting processes used during the production of built-up timber pieces can significantly reduce defects common in natural wood, such as knots and irregular grain patterns. These methods enable the redistribution of stresses from layer to layer, thereby enhancing the element's capacity (Falk & Colling, 1995; Wang et al., 2024). GLT, CLT, and LVL are examples of built-up timber products that help provide long-span structural solutions by making solid wood less uneven through their layered designs (Abed et al., 2022). However, the structural performance of built-up timber pieces may deteriorate over time due to various factors, such as dynamic forces, prolonged static loading, or deficiencies in connecting details. In these situations, employing materials such as steel plates, CFRP, or GFRP to repair and strengthen the structure can enhance its strength and prevent deterioration.

Experimental and theoretical studies aimed at enhancing the flexural strength of timber beams can generally be categorized into two main groups based on the type of reinforcement material used. In the first group, where steel plates are employed for flexural strengthening, the steel elements are typically applied to the tension zone of the beam, either by bonding with epoxy or using mechanical fasteners. Experimental studies utilizing this method have reported significant improvements in flexural capacity, along with observations of a more ductile failure mode and a notable increase in stiffness (Jasieńko & Nowak, 2024; Waseem et al., 2022; Jardim et al., 2022; Yoresta & Nogroho, 2023).

Strengthening applications using FRP composites in the tension zone of timber beams have demonstrated significant improvements in their flexural behavior. Experimental studies in the literature have shown that such reinforcements increase load-carrying capacity, enhance structural stiffness, and positively influence deformation control. It is also emphasized that bonding surface quality and application details play a critical role in performance, and that, when appropriately applied, FRP reinforcement can offer a reliable long-term solution (Donadon et al., 2020; Mansour et al., 2024; Triantafillou & Deskovic, 1992; Halicka & Ślósarz, 2021; Fiorelli & Dias, 2011; Gilfillan et al., 2003).

In addition to the well-established improvements in flexural strength provided by FRP and steel plate reinforcement, several analytical and experimental studies have shown that these interventions also alter the internal shear stress distribution and interfacial behavior in strengthened timber beams. While primarily applied to enhance flexural performance, these materials introduce stiffness discontinuities that affect local shear flow, particularly at the ends of the reinforcement. In FRP-strengthened members, bond–slip relationships and interface mechanics play a crucial role in governing the transfer of shear stress. Wan et al. (2014) and Vahedian et al. (2018) conducted single-lap shear tests and developed analytical bond stress–slip models to predict shear distribution along the FRP–timber interface. Schober et al. (2015) further emphasized the need for accurate modeling of adhesive layer behavior to capture localized stress concentrations in FRP-reinforced joints. Zhao et al. (2024) investigated composite steel–timber connections and proposed analytical expressions for the shear capacity and stiffness, demonstrating that the type of connector has a significant impact on interfacial shear transfer. Complementing this, Gilbert et al. (2024) compared glued and screwed steel-to-timber joints and reported variations in shear performance based on bonding technique. In addition, Nowak et al. (2016) reviewed experimental applications of steel plate reinforcements and highlighted their effectiveness in improving load-bearing capacity while also acknowledging potential stress concentrations at the bonded interfaces that influence internal shear distributions.

Strengthening of built-up timber beams, particularly near the tension zone, can alter the internal force transfer mechanisms, leading to significant increases in interlayer shear stresses at the interfaces between timber layers. This situation necessitates a detailed evaluation of the structural behavior in composite systems. This is especially important in existing and historical structures, where built-up timber beams are common and structural safety is a major concern. This study aims to theoretically investigate the variation of shear stresses in timber layers following the strengthening of built-up timber beams. To achieve this, various thicknesses of steel plate reinforcement are used for the tension zones of timber beams with different cross-sectional configurations. After strengthening, a composite behavior is formed between the timber and the steel, resulting in the redistribution of internal forces within the cross-section. Due to the high modulus of elasticity of steel, a greater portion of the tensile force is carried by the steel element; this, in turn, may cause increased shear stresses between the timber layers. The magnitude and distribution of this increase have been theoretically evaluated based on parameters such as cross-sectional geometry and the thickness of the steel plate.

Symbols and Abbreviations

GLT	Glued Laminated Timber
CLT	Cross-Laminated Timber
LVL	Laminated Veneer Lumber
CFRP	Carbon Fiber-reinforced Polymers
GFRP	Glass Fiber-reinforced Polymers
FRP	Fiber Reinforced Polymer

E_s	Elastic Modulus of Steel
E_t	Elastic Modulus of Steel
A_i	Equivalent areas
A_t	Total Area
y_i	Distance of each area from the reference axis
τ	Shear Stress
V	Shear force acting on the cross-section
Q	First moment of area with respect to the neutral axis
I	Moment of inertia of the transformed cross-section
b	Width of the section at the location of interest
h	Height of the beam
t_l	Thickness of layers
t_s	Thickness of the steel plate
t_w	Thickness of web
hw	Height of flange
b_f	Width of flange
t_f	Thickness of flange

2. Methods

Rectangular and I-shaped cross-sections, which are commonly used in engineering applications, were selected as examples. The elastic shear stresses occurring at the bonding interfaces of built-up timber elements were calculated using the transformed section method.

2.1 Transformed section method

The analyses were conducted under the assumption that the materials exhibit linear elastic behavior (Ministry of Environment, Urbanization, and Climate Change, 2024). In composite sections composed of materials with different stiffnesses, such as wood and steel, the stress distribution varies according to the elasticity of each material. In analysis, the composite section is transformed into an equivalent timber section using a modular ratio. The transformed section method is valid only for the elastic range. The modular ratio used for transformation is given in Equation 1.

$$n = \frac{E_s}{E_t} \tag{1}$$

The width of the steel plate was multiplied by the modular ratio (n) and transformed into an equivalent timber section (Figure 1). As a result of this transformation, all analyses could be conducted based on a single material type.
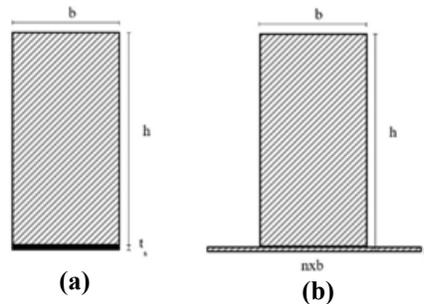

(a) **(b)**

Figure 1. Cross-section of strengthened timber beam; (b) Equivalent transformed timber cross-section

2.2 Location of the neutral axis

The new location of the neutral axis ($\bar{y}$) for the transformed section is calculated using Equation (2).

$$\bar{y} = \frac{\sum A_i y_i}{A_t} \tag{2}$$

In built-up timber beams, the average shear stress at the bonding interfaces can be calculated within the elastic range (according to the timber design code) using Equation (3).

$$\tau = \frac{VQ}{Ib} \tag{3}$$

3. Results

In this study, the distribution of shear stress at the bonding interfaces of built-up timber elements strengthened with steel plates was theoretically analyzed. Different parametric variations were systematically introduced to evaluate their influence on the interfacial shear stresses. The parameters considered in the analysis are as follows in Table 1.

Table 1. Analysis Parameters

Cross-section		Thickness of steel plate (mm)
Rectangular	Homogeneous	1~4
	Non-homogeneous	1~4
I section	Symmetric	1~4
	Asymmetric	1~4

3.1 Rectangular section

Homogeneous laminated rectangular section

For the homogeneous rectangular section analysis, a built-up timber beam composed of five equivalent layers is shown in Figure 2. A shear force of 10 kN was applied to the beam, and steel plates of varying thicknesses were placed only on the bottom surface. The variation in interfacial stresses at the timber layer joints was theoretically calculated for both the reference beam and the beams strengthened with different steel thicknesses.
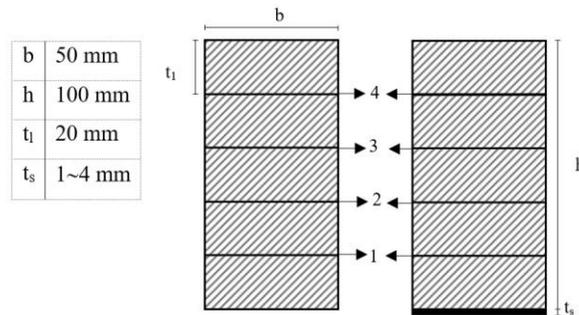

b	50 mm
h	100 mm
t_l	20 mm
t_s	1~4 mm

Figure 2. Cross-section dimensions of a homogeneous laminated rectangular beam

The distribution of shear stresses along the bonding interfaces in both the reference timber beam and the beams strengthened with steel plates is presented in Figure 3. In the unstrengthened reference section, the shear stresses were observed to be more evenly distributed across the bonding surfaces. However, with the addition of a steel plate—particularly as the plate thickness increases a significant rise in shear stress was observed at the first bonding interface (Layer 1), located immediately above the steel plate.

Figure 4 presents the shear stress values observed at the first bonding interface (Layer 1), along with the corresponding proportional increases. When the thickness of the strengthening plate is 4 mm, the shear stress at this interface increases by approximately 35% compared to the reference section. While the increase ratio is higher for 1 mm and 2 mm thick plates, it is observed to decrease for 3 mm and 4 mm thicknesses, indicating that the contribution of the steel plate to the shear stress becomes limited beyond a specific thickness.
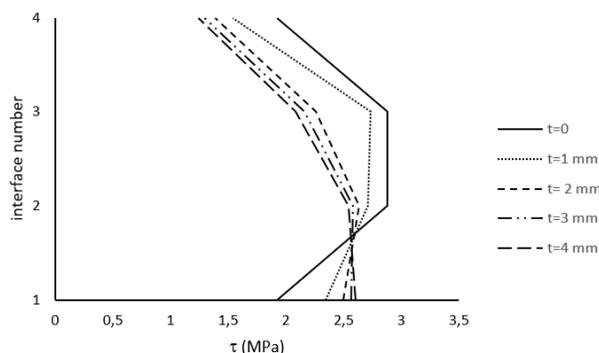

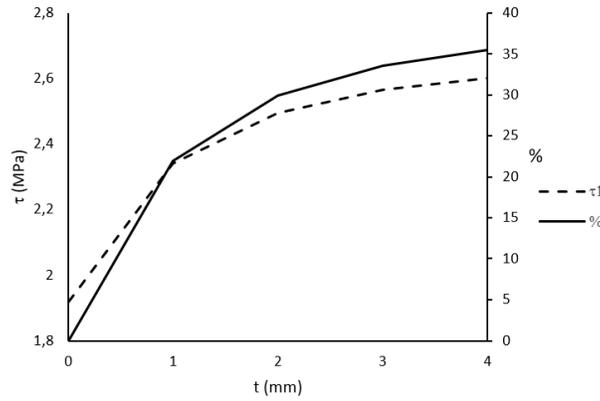**Figure 3.** Shear stress redistribution due to plate thickness

Figure 4. Effect of Steel Plate Thickness on Shear Stress and Increment Ratio at the First Bonding Interface

Non-homogeneous laminated rectangular section

For the non-homogeneous rectangular section analysis, a built-up timber beam composed of five layers was selected, with a total height of h = 100 mm and a constant width of b = 50 mm (Figure 5). The layer thicknesses were defined as follows: t_{l1} = 15 mm for the first and fifth layers, t_{l2} = 20 mm for the second and fourth layers, and t_{l3} = 30 mm for the third (central) layer. A shear force of 10 kN was applied to the beam, and steel plates of varying thicknesses were placed only on the bottom surface.
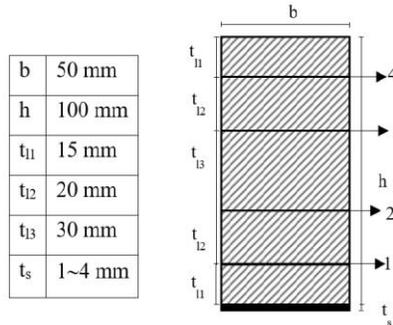

Figure 5. Cross-section dimensions of a non-homogeneous laminated rectangular beam

As illustrated in Figure 6, the distribution of shear stress across the bonding interfaces in the non-homogeneous timber beam significantly varies with the increase in steel plate thickness. In the unreinforced reference beam (t=0), shear stresses are more evenly distributed among all interfaces, reflecting a relatively balanced internal force transfer. However, with the use of a steel plate of varying thicknesses, a distinct concentration of shear stress emerges at the first bonding interface. This behavior indicates that the composite action becomes increasingly localized near the bottom surface, leading to elevated shear transfer between the layers under natural axis. The same behaviour is shown in Figure 7, where both the shear stress values and their proportional increases at the first interface are presented with respect to plate thickness. Notably, while the use of 1 mm and 2 mm thick plates results in a sharp increase in shear stress up to approximately 70% compared to the reference case, this rate of increase diminishes at 3 mm and 4 mm, revealing a limited contribution of further plate thickness to the enhancement of shear transfer.
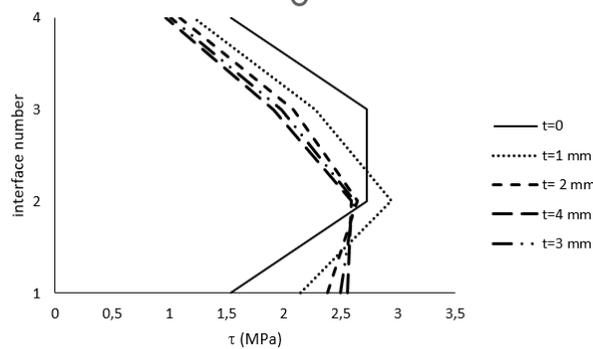

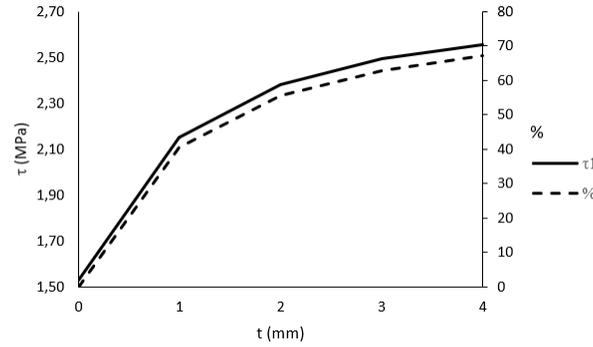**Figure 6.** Shear stress redistribution due to plate thickness

Figure 7. Effect of Steel Plate Thickness on Shear Stress and Increment Ratio at the First Bonding Interface

As presented in Table 2, the numerical results show that increasing the steel plate thickness changes the distribution of shear stresses across the bonding interfaces in all sections. In the homogeneous section, the shear stress at interface 1 increases by 35.4%, rising from 1.92 MPa to 2.60 MPa. In contrast, the non-homogeneous section exhibits a more pronounced increase of 67.3% at the same interface (1.53 to 2.56 MPa), due to the varying stiffness between layers. The upper bonding interfaces show a consistent reduction in shear stress. At interface 4, shear stress drops by 35.4% in the homogeneous section (1.92 to 1.24 MPa) and by 36.6% in the non-homogeneous section (1.53 to 0.97 MPa). This change confirms that the steel plate effectively transfers the internal shear demand from the upper layers to the strengthened layers. The redistribution is more evenly distributed in the non-homogeneous section, indicating a more gradual load transition due to differential layer stiffnesses.

Table 2. Comparison of Interfacial Shear Stress (τ) and % Changes Across Layers in Homogeneous and Non-Homogeneous Timber Sections with Varying Steel Plate Thickness

	layer number	Homogeneous section τ (MPa)& % change								Non-homogeneous section τ (MPa)& % change							
		1		2		3		4		1		2		3		4	
t (mm)	0	1,92	-	2,88	-	2,88	-	1,92	-	1,53	-	2,73	-	2,73	-	1,53	-
	1	2,34	21,9	2,71	-6,3	2,73	-5,2	1,54	-19,8	2,15	40,5	2,94	7,7	2,28	-16,5	1,21	-20,9
	2	2,49	29,7	2,63	-8,7	2,26	-21,5	1,38	-28,1	2,38	55,6	2,64	-3,3	2,09	-23,4	1,09	-28,8
	3	2,57	33,9	2,58	-10,4	2,16	-25	1,30	-32,3	2,49	62,7	2,62	-4,2	1,98	-27,5	1,01	-34
	4	2,60	35,4	2,54	-11,8	2,09	-27,4	1,24	-35,4	2,56	67,3	2,59	-5,1	1,91	-30	0,97	-36,6

3.2. I-Section

Symmetric I-section

The effect of a steel plate bonded to the bottom flange of a symmetric I-section timber beam (Figure 8) on the elastic shear stress at the web–flange junction was investigated. The cross-section consists of top and bottom flanges measuring 100 mm in width and 20 mm in thickness, and a web measuring 200 mm in height and 20 mm in thickness. The steel plate was applied to the bottom surface of the bottom flange. In the analysis, the thickness of the steel plate was varied between t=1-4 mm, and the shear stress at the interface between the web and the bottom flange (denoted as Interface 1) was calculated. The shear stress values and their proportional increases at the junction under different reinforcement scenarios are presented in Figure 8.
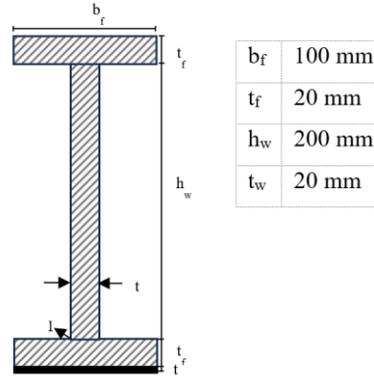
b_f	100 mm
t_f	20 mm
h_w	200 mm
t_w	20 mm

Figure 8. Cross-section dimensions of a symmetric I-section beam

Figure 9 illustrates the effect of steel plate thickness on the shear stress at the web–bottom flange interface in a symmetric I-section timber beam. As the thickness of the steel plate increases from 1 mm to 4 mm, both the shear stress values and their proportional increases (%) are observed to rise accordingly. Specifically, the shear stress at this junction increases consistently with plate thickness. While the shear stress in the reference (unstrengthened) beam is approximately 1.78 MPa, it rises to 2.96 MPa when a 4 mm thick steel plate is applied. This corresponds to an approximately 66% increase in the interface shear stress.
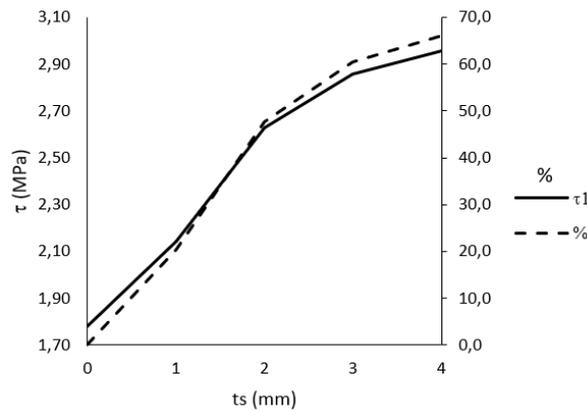

Figure 9. Effect of Steel Plate Thickness on Shear Stress and Increment Ratio at the First Bonding Interface

Asymmetric I-section

In this section, an asymmetric glued I-section timber beam, characterized by a wider bottom flange in the tension zone, is examined. This geometry is intended to reflect design cases where the tensile region is structurally emphasized. The cross-sectional geometry and dimensions of the beam are illustrated in Figure 10.
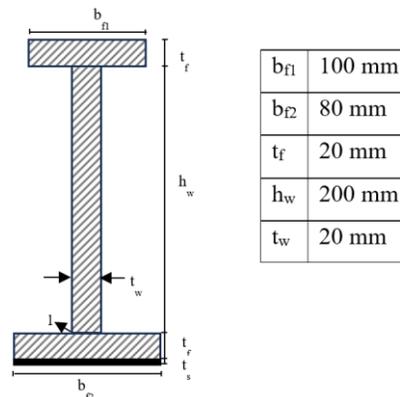

b_{f1}	100 mm
b_{f2}	80 mm
t_f	20 mm
h_w	200 mm
t_w	20 mm

Figure 10. Cross-section dimensions of an asymmetric I-section beam

Figure 11 presents the shear stresses obtained at the web–bottom flange interface of the asymmetric I-section beam following the application of steel plates with varying thicknesses (t=1–4mm) in the tension zone. As shown in Figure 11, the shear stress at the web–bottom flange junction increases significantly with the thickness of the steel plate. In the reference beam, the shear stress is 1.84 MPa,

whereas it reaches 3.01 MPa when a 4 mm plate is used, corresponding to an increase of approximately 64%. Unlike the case of the symmetric section, where the increase in stress was more abrupt, the stress increment here follows a smoother and more uniform trend, indicating a more gradual redistribution of internal forces in the asymmetric geometry.
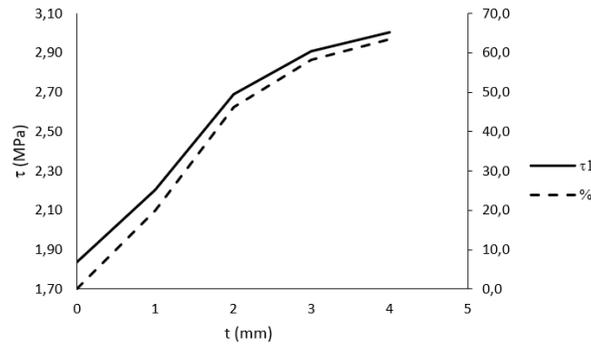

Figure 11. Effect of Steel Plate Thickness on Shear Stress and Increment Ratio at the First Bonding Interface Asymmetric I-Section

As shown in Table 3, the interfacial shear stress at the first bonding layer increases with the thickness of the steel plate in both section types. The most pronounced increase occurs within the 0–2 mm thickness range. The percentage increases in symmetric and asymmetric sections are similar, reaching 66.1% and 63.6%, respectively, at t= 4 mm.

Table 3. Comparison of Interfacial Shear Stress (τ) and % Changes at the First Bonding Interface in Symmetric and Asymmetric I-Sections with Varying Steel Plate Thickness

Symmetric I-Section			Asymmetric I-Section		
t (mm)	t_1 (MPa)	% changes	t (mm)	t_1 (MPa)	% changes
0	1,78	0,0	0	1,84	0,0
1	2,14	20,4	1	2,21	20,0
2	2,63	47,7	2	2,69	46,3
3	2,86	60,5	3	2,91	58,4
4	2,96	66,1	4	3,01	63,6

4. Conclusion

In this study, the effect of strengthening with steel plates applied to the bottom surfaces of built-up timber beams with varying cross-sectional geometries on the elastic shear stresses at bonding interfaces was investigated theoretically. Based on the analytical results, the following conclusions have been drawn:

- Interlayer shear stresses significantly increased as steel plate thickness increased, particularly below the neutral axis. With plate thicknesses of 3 mm and 4 mm, the rate of rise decreased, suggesting a slower rate of improvement rather than complete saturation. This tendency was constant across all cross-section types.
- In rectangular sections, the non-homogeneous configuration, which had a larger middle layer, had a somewhat more noticeable redistribution of shear stresses, while the impact of the steel plate was somewhat less noticeable in homogeneous configurations (with equal layer thicknesses).
- The symmetric I-section showed a progressive saturation after a sharper increase between 1 mm and 2 mm plate thickness. The shear stress of the surface between flange and web increased from 1.78 MPa to 2.96 MPa (66%).
- The asymmetric I-section showed a smoother transition between different plate thicknesses; the shear stress between the flange and web increased from 1.84 MPa to 3.01 MPa (64%) in a more linear manner.

The findings indicate that strengthening only the tension zone in built-up timber members may unexpectedly increase interlayer shear stresses, particularly at bonding interfaces close to the steel plate. This may lead to localized failure mechanisms, especially in aged or historic timber structures where adhesive bonds may have weakened due to overloading, environmental effects, or chemical degradation. Strengthening techniques must therefore be developed completely, taking into account not only the increase in load-bearing capacity but also the redistribution of internal forces and the mechanical integrity of bonding contacts.

Acknowledgements

Author Contributions

The author contributed to all stages of the study.

Compliance with Ethical Standards

Data Availability Statement: The data supporting the findings of this study are contained within the article.

Conflict of Interest: The author declares no conflict of interest.

Ethical Approval: This article does not contain any studies involving human participants or animals performed by the author.

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