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The Relationship between Different Proofs of Load-Bearing Capacity, Fire Resistance of the Cross-Section and the Price of Solid Softwood

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Abstract: The impact of ultimate limit state checks on the fire resistance of the cross-section (element) of softwood structural timber is analyzed in this study, which was found to depend on the cross-sectional area, strength class or material quality expressed through the actual price. The limit state method and the reduced cross-section method were used to obtain numerical results. The established practice suggests that, if the ultimate limit state is satisfied, the softwood structural timber will meet fire resistance according to the load-bearing criterion of 30 min (R30). This study shows that this is not entirely correct and is not always applicable. The main results of this study are precisely related to the above, and it will now be possible to provide much more precise answers to questions related to fire resistance according to the load-bearing criterion. Certainly, the price, which plays a significant role in achieving a certain or required fire resistance, should not be overlooked. This study provides the possibility of optimizing the choice of the cross-sectional area, fire resistance and price, depending on the state of stress to which the cross-section (element) is exposed.

Keywords: softwood; cross-sectional area; strength classes; load-bearing capacity; utilization; fire resistance; price

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1. Introduction

Fire is a self-sustaining burning process that spreads uncontrollably in space, which is calculated to be an accidental action on structures. Fire resistance is the ability of a structure, a part of a structure or an element to fulfill the required purpose for a certain level of load, which is the time of exposure to the fire [1]. Fire resistance is the ability of a part of a building to meet the required safety or mechanical resistance (R), integrity (E) and thermal insulation (I), as prescribed by the standard.

The time until the timber structure ignites, the characteristics of the combustion process and the fire resistance of the timber element depend on a number of factors: the type of the cross-section, the dimensions of the cross-section and the humidity degree. The destruction of timber elements by fire is regular and can be determined in advance. The boundary line between the burnt and healthy parts of the cross-section is clear. In the case of timber elements, it should be considered that during a fire, the cross-section of the burned part degrades, while in the remaining part of the cross-section, the element retains its mechanical properties [1]. A large number of publications on the fire resistance of timber are available. The technical guideline [2] provides the background and design methods for designing timber structures to have similar fire safety for structures of other materials [3]. The report presents design methods that will be used as input for the next revision of the Eurocode 5. Kippel et al. in [4] presented results of numerical simulations for fire-exposed timber members in tension, compression and bending. The results show that the zero-strength layer clearly depends on the time of fire exposure, state of stress and dimensions of the cross-section. König in [5] provided a review of the design rules of

EN 1995-1-2 [6]. For the determination of cross-sectional strength and stiffness properties, two alternative rules are provided in the standard, either by implicitly taking into account their reduction due to elevated temperature by reducing the residual cross-section by a zero-strength zone, or by calculating modification factors for strength and stiffness parameters. Fragiacomo et al. in [7] presented a numerical model for predicting the fire resistance of timber members. The structural analysis considers the reduction in mechanical properties (modulus of elasticity and strength) of timber with temperature. Experimental data in terms of temperature, charring depth, displacement and failure time were compared with the numerical results obtained by assuming the thermal properties and degradation of mechanical properties with temperature, as suggested by Eurocode 5, showing an overall acceptable approximation. The fire resistance of the timber member was then predicted depending on the applied tensile loads using the numerical model and analytical formulas. The proposed finite element model can be used to predict the fire resistance of timber structures as an alternative to expensive and complicated experimental tests. Pereira et al. in [8] presented a numerical model, validated with an experimental test, that uses the finite element method. The main objective of their study was to simulate the fire resistance in a standard test method using an experimental model, which allows for calibration of the developed numerical model. The results show consistency of the analysis and can be used as a good approximation to real situations.

The fire resistance of a timber element depends on the type of wood, its thickness, shape, processing and additional layers or coatings applied to improve fire resistance. Timber, as a natural material, tends to burn, but there are ways to improve these properties. For example, impregnating timber or adding fire retardants can significantly increase its resistance. Also, structural elements used in building structures, such as load-bearing columns or beams, are often coated with materials that have higher fire resistance in order to extend the time of exposure to fire in the event of a fire. In addition, thicker parts of timber tend to burn more slowly compared to thinner parts. Resistance to fire is expressed as time, in minutes, and defines the ability of the derived element to fulfill its function for a certain period of time after the occurrence of a fire. Structures must be calculated and executed so that they retain their load-bearing function during appropriate exposure to fire, and the elements that are at the boundaries of the fire compartment must retain their separation function. It must be ensured that a complete breakdown will not occur, that the insulation will not fail and that the heat-gas radiation is limited on the side not exposed to fire. Fire resistances are defined according to the functions of the elements as follows:

- Bearing capacity (criterion of mechanical resistance, R): fire resistance refers to the ability to preserve the mechanical resistance of the element during the entire time of exposure to fire;
- Separable (integrity criterion, E): fire resistance refers to the ability to contain fire, i.e., the ability of an element to prevent the spread of fire to the unexposed side;
- Insulating (criterion of thermal insulation performance, I): fire resistance refers to the element's ability to prevent or slow down the transfer of heat from the exposed to the unexposed side.

The combination of actions for analysis is determined for an accidental action situation, with modified calculated values of strength and stiffness. For the calculation of the elements, the reduced cross-section method is relevant, according to which the calculated cross-section is defined as the remaining cross-section, in accordance with the described behavior of timber in a fire. The relationship between price and the limit state of the load-bearing capacity and fire resistance is explored in this study.

2. Materials and Methods

For the purposes of this study and obtaining numerical results, solid softwood was used (spruce and fir). This timber was chosen because of its widespread growth and, particularly, its use in timber structures. In addition to softwood, hardwood is also used in construction, but its application is much less than that of softwood. The reason why the application of softwood is much greater compared to hardwood lies primarily in the significant price difference in the material itself, the faster growth of softwood, as well as its mechanical characteristics that are entirely sufficient for use in construction, especially in roof structures. Also, one should not disregard the much simpler processing of softwood compared to hardwood, which has a significant impact on the economic aspect of the production of one or the other. In timber structures according to [9], solid softwood is classified into different strength classes. The classification of various types of softwood into strength classes makes it easier for civil engineers to apply them. The most commonly used strength classes of solid softwood in timber structures are C24, C27 and C30. For further analysis, these three strength classes of solid softwood were selected, primarily due to their mechanical characteristics, which are presented in Table 1.

Table 1. Material properties [9].

Strength Classes	Characteristic Strengths [N/mm^2]				Characteristic Density [kg/m^3]
	Tension	Compression	Shear	Bending	
	$f_{t,0,k}$	$f_{c,0,k}$	$f_{v,k}$	$f_{m,k}$	ρ_k
C24	14.5	21.0	4.0	24.0	350
C27	16.5	22.0	4.0	27.0	360
C30	19.0	24.0	4.0	30.0	380

Since the material price primarily depends on the dimensions of the cross-sectional area or the ultimate limit state evidence, it was first necessary to prove each ultimate limit state depending on the internal forces, i.e., the state of stress. After proving the ultimate limit state of evidence, a proof of fire resistance was performed. Due to the sheer number of proofs conducted and the simplicity of the calculations, different common square cross-sectional areas of varying material quality were chosen for both proof cases, as shown in Table 2.

Table 2. The display of analyzed square cross-sections.

Strength Classes	The Dimensions of Cross-Sections, b/h [mm]			
C24	100/100	120/120	160/160	200/200
C27				
C30				
Cross-sectional area, A [mm^2]	10,000	14,400	25,600	40,000

For the presented material properties in Table 1 and the analyzed cross-sectional areas in Table 2, the following proofs were made depending on the internal forces:

1. Tension parallel to the grain;
2. Compression parallel to the grain;
3. Shear;
4. Bending;
5. Combined bending and axial tension parallel to the grain;
6. Combined bending and compression parallel to the grain.

Similarly, all proofs that were conducted were performed at the level of the cross-section. Proofs at the element level are subject to further research. It should also be noted that in many cases in timber structures when using solid softwood, the stability proof of the element is reduced to the proof of the load-bearing capacity of the cross-section. Common calculation methods used in timber structures were used for the aforementioned proofs.

2.1. The Limit States Method

The limit state evidence of load-bearing capacity, depending on the internal forces at the level of the cross-section used in this study, is found in [10–12] and takes the following forms:

$$\textbf{tension parallel to the grain} \Rightarrow \frac{\sigma_{t,0,d}}{k_h \cdot f_{t,0,d}} \leq 1.0 \quad (1)$$

where is: $\sigma_{t,0,d} = \frac{F_{t,d}}{A}$, $A = b \cdot h$, $k_h = min\left\{\begin{matrix} \left(\frac{150}{h}\right)^{0.2} \\ 1.30 \end{matrix}\right\}$, $f_{t,0,d} = k_{mod} \cdot \frac{f_{t,0,k}}{\gamma_M}$

$$\textbf{compression parallel to the grain} \Rightarrow \frac{\sigma_{c,0,d}}{f_{c,0,d}} \leq 1.0 \quad (2)$$

where is: $\sigma_{c,0,d} = \frac{F_{c,d}}{A}$, $A = b \cdot h$, $f_{c,0,d} = k_{mod} \cdot \frac{f_{c,0,k}}{\gamma_M}$

$$\textbf{shear} \Rightarrow \frac{\tau_{v,d}}{f_{v,d}} \leq 1.0 \quad (3)$$

where is: $\tau_{v,d} = \frac{1.5 \cdot F_{v,d}}{A}$, $A = (k_{cr} \cdot b) \cdot h = 0.67 \cdot A$, $f_{v,d} = k_{mod} \cdot \frac{f_{v,k}}{\gamma_M}$

$$\textbf{bending} \Rightarrow \frac{\sigma_{m,d}}{k_h \cdot f_{m,d}} \leq 1.0 \quad (4)$$

where is: $\sigma_{m,d} = \frac{M_{y,d}}{W_y}$, $W_y = \frac{b \cdot h^2}{6}$, $f_{m,d} = k_{mod} \cdot \frac{f_{m,k}}{\gamma_M}$

$$\textbf{combined bending and tension parallel to the grain} \Rightarrow \frac{\sigma_{t,0,d}}{k_h \cdot f_{t,0,d}} + \frac{\sigma_{m,d}}{k_h \cdot f_{m,d}} \leq 1.0 \quad (5)$$

$$\textbf{combined bending and compression parallel to the grain} \Rightarrow \left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,d}}{k_h \cdot f_{m,d}} \leq 1.0. \quad (6)$$

All the specified calculated values of material resistance R_d are obtained for k_{mod} = 0.9 and γ_M = 1.30 [10–12]. The modification factor was chosen for short-term loading durations and the second class of utilization (12% < u ≤ 20%). These choices are in line with the common calculations in timber structures made of solid softwood. The calculated values of internal forces or actions E_d, using the basic combination for actions [13], were obtained in a way that the cross-section of dimensions b/h = 100/100 mm and strength class C24 utilized 100% for all the shown evidence of the load-bearing capacity of the cross-section, depending on the internal forces (expressions (1)–(6)). This was conducted to obtain reference values for further comparisons conducted here. The presentation of the obtained internal forces, which all other cross-sections from other strength classes were loaded with, is provided in Table 3.

Additionally, in the proof of the load-bearing capacity of the cross-section on the interaction of bending and axial force, the same contribution of bending moment as for independent bending action was taken. This contribution for the interaction of bending and tension is 0.50, while for the interaction of bending and compression, it is taken as 0.50 for bending and 0.707 for compression, as shown in Table 3.

Table 3. The calculated values, E_d, of internal forces for a fully utilized cross-section of 100/100 mm from class C24.

Strength Classes	Cross-Section, b/h	The Calculated Values of Internal Forces for Specific Fire Resistance Capacity Check							
		Tension, $F_{t,d}$	Compression, $F_{c,d}$	Shear, V_d	Bending, $M_{y,d}$	Bending + Tension		Bending + Compression	
						$0.50{\cdot}M_{y,d}$	$0.50{\cdot}F_{t,d}$	$0.50{\cdot}M_{y,d}$	$0.707{\cdot}F_{c,d}$
	[mm]	[kN]	[kN]	[kN]	[kNm]	[kNm]	[kN]	[kNm]	[kN]
C24	100/100 120/120 160/160 200/200								
C27	100/100 120/120 160/160 200/200	108.88	145.38	12.37	3.00	1.50	54.44	1.50	102.81
C30	100/100 120/120 160/160 200/200								

2.2. Reduced Cross-Section Method

Most of the described content below can be found in [6,14]. If mechanical resistance is required in the case of a fire, structures, or their cross-sections (elements), must be designed and constructed to maintain their primary load-bearing function during a certain period of exposure to fire. Under standardized (nominal) fire exposure [15], cross-sections (elements) must meet criteria for mechanical resistance (R), integrity (E) and insulation (I). In this study, the criterion of mechanical resistance (R) was analyzed, specifically for the load-bearing function. This criterion is common in practice and, as such, is stringent in most current regulations, depending on the building's purpose or function.

The resulting fire resistance is expressed as the time in minutes during which the cross-section (element) is capable of withstanding exposure to a standard fire before reaching any of the limit states (R, E, I). The resulting fire resistance (depending on regulatory requirements) is rounded to the nearest value: 15, 30, 45, 60, 75, 90, 105, 120, 180 or 240 min. Timber degradation at high temperatures consists of a layer of timber charring (a), a layer of pyrolysis (b) and unchanged timber (c), as shown in Figure 1.

Figure 1. Degradation of timber at high temperatures (**a**) a layer of timber charring, (**b**) a layer of pyrolysis, (**c**) unchanged timber.

The reduced cross-section method is based on calculating with a reduced cross-section area for the calculated charring depth according to the following expressions:

$$d_{ef} = d_{char,n} + k_0 \cdot d_0 \tag{7}$$

$$d_{char,n} = \beta_n \cdot t \tag{8}$$

where

$$d_0 = 7\text{ mm}, \quad k_0 = \frac{t}{20}\ for\ t < 20\text{ min}, \quad k_0 = 1.0\ for\ t \geq 20\text{ min}$$

and $\beta_n = 0.80$ [mm/min] for solid softwood with a characteristic density ≥ 290 kg/m^3.

In the above expressions, t represents the duration of the fire. Also, a simple graphical representation of the reduced cross-section method is shown in Figure 2, where the fire acts on three and four sides of the cross-section, which are analyzed in this study.

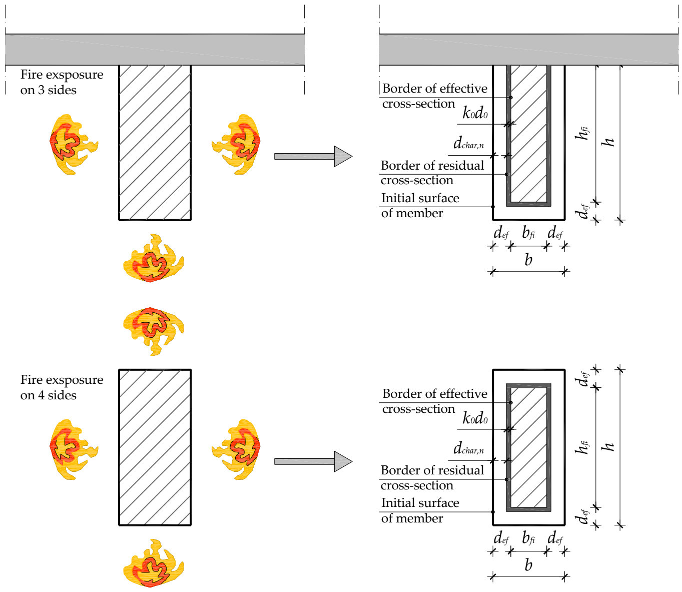


Figure 2. Reduced cross-section method.

The fire resistance capacity check at the level of the cross-section area (element) used in this study, which depends on internal forces, takes the following forms:

$$\textbf{tension parallel to the grain} \Rightarrow \frac{\sigma_{t,0,d,fi}}{k_h \cdot f_{t,0,d,fi}} \leq 1.0 \tag{9}$$

where is: $\sigma_{t,0,d,fi} = \frac{F_{t,d,fi}}{A_{fi}}$, $A_{fi} = b_{fi} \cdot h_{fi}$, $f_{t,0,d,fi} = k_{fi} \cdot k_{mod,fi} \cdot \frac{f_{t,0,k}}{\gamma_{M,fi}}$

$$\textbf{compression parallel to the grain} \Rightarrow \frac{\sigma_{c,0,d,fi}}{f_{c,0,d,fi}} \leq 1.0 \tag{10}$$

where is: $\sigma_{c,0,d,fi} = \frac{F_{c,d,fi}}{A_{fi}}$, $A_{fi} = b_{fi} \cdot h_{fi}$, $f_{c,0,d,fi} = k_{fi} \cdot k_{mod,fi} \cdot \frac{f_{c,0,k}}{\gamma_{M,fi}}$

$$\textbf{shear} \Rightarrow \frac{\tau_{v,d,fi}}{f_{v,d,fi}} \leq 1.0 \tag{11}$$

where is: $\tau_{v,d,fi} = \frac{1.5 \cdot F_{v,d,fi}}{A_{fi}}$, $A_{fi} = 0.67 \cdot A_{fi}$, $f_{v,d,fi} = k_{fi} \cdot k_{mod,fi} \cdot \frac{f_{v,k}}{\gamma_{M,fi}}$

$$\textbf{bending} \Rightarrow \frac{\sigma_{m,d,fi}}{k_h \cdot f_{m,d,fi}} \leq 1.0 \tag{12}$$

where is: $\sigma_{m,d,fi} = \frac{M_{y,d,fi}}{W_{y,fi}}$, $W_{y,fi} = \frac{b_{fi} \cdot h_{fi}^2}{6}$, $f_{m,d,fi} = k_{fi} \cdot k_{mod} \cdot \frac{f_{m,k}}{\gamma_{M,fi}}$

$$\textbf{combined bending and tension parallel to the grain} \Rightarrow \frac{\sigma_{t,0,d,fi}}{k_h \cdot f_{t,0,d,fi}} + \frac{\sigma_{m,d,fi}}{k_h \cdot f_{m,d,fi}} \leq 1.0 \tag{13}$$

$$\textbf{combined bending and compression parallel to the grain} \Rightarrow \left(\frac{\sigma_{c,0,d,fi}}{f_{c,0,d,fi}}\right)^2 + \frac{\sigma_{m,d,fi}}{k_h \cdot f_{m,d,fi}} \leq 1.0. \tag{14}$$

All calculated values of the mechanical resistance in the fire situation at time t $R_{d,t,fi}$, are obtained for the fire coefficient k_{fi} = 1.25, modification factor for fire $k_{mod,fi}$ = 1.0 and partial safety factor for timber in fire $\gamma_{M,fi}$ = 1.0 [6,14]. The calculated values of internal forces or actions $E_{d,fi}$, using an accidental combination for actions [13], are obtained in the manner described in the limit states method and presented in Table 4.

Table 4. The calculated values, $E_{d,fi}$, of internal forces from the fire (accidental) combination.

Strength Classes	Cross-Section, b/h	The Calculated Values of Internal Forces for Specific Fire Resistance Capacity Check							
		Tension, $F_{t,d,fi}$	Compression, $F_{c,d,fi}$	Shear, $V_{d,fi}$	Bending, $M_{y,d,fi}$	Bending + Tension		Bending + Compression	
						$0.50 \cdot M_{y,d,fi}$	$0.50 \cdot F_{t,d,fi}$	$0.5 \cdot M_{y,d,fi}$	$0.707 \cdot F_{c,d,fi}$
	[mm]	[kN]	[kN]	[kN]	[kNm]	[kN]	[kNm]	[kN]	[kNm]
C24	100/100 120/120 160/160 200/200	80.65	107.69	9.16	2.22	1.11	40.33	1.11	76.16
C27	100/100 120/120 160/160 200/200								
C30	100/100 120/120 160/160 200/200								

3. Results

All obtained results will be presented both in tabular and graphical form, accompanied by brief explanations. Additionally, the results will be displayed according to the calculation method through which they were obtained. The material price to be displayed is obtained based on the strength class of solid softwood. It amounts to 315.00 EUR/m^3 for C24, 380.00 EUR/m^3 for C27 and 450.00 EUR/m^3 for C30. The prices are expressed as fco construction site of the company Stenavert (Croatia) and do not include timber processing, possible timber coatings for protection, transportation and timber installation.

3.1. Results of Limit States Method

By applying the limit states method, the following values were obtained, as shown in Table 5, for each mentioned limit state depending on internal forces. The displayed values represent the utilization of the analyzed cross-sections for each limit state depending on internal forces or stress state depending on the strength class of the material. Table 5 also shows the areas of the selected cross-sections, as well as the prices expressed per meter length.

From Figure 3, it can be observed how all load-carrying curves decline for each limit state depending on internal forces, and they vary with changes in the cross-sectional area or changes in material quality. In other words, we can see a decrease in the utilization of the cross-sectional area for each individual internal force action, depending on the cross-sectional area and material quality. Similarly, the effect of material quality on the load-carrying capacity of the cross-sectional area can be observed, where higher quality generally increases the load-carrying capacity. It is noteworthy that only in the case of shear force or shear stress (Figure 3c), the material quality has no effect on the load-carrying capacity of the cross-sectional area.

Table 5. The utilization of the cross-sectional area (element) depends on the limit state check and the strength class of softwood [1.0 = 100%].

Strength Classes	C24				C27				C30			
Area of the cross-section [mm^2]	10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000
Price for 1 m * [EUR]	3.15	4.54	8.06	12.60	3.80	5.47	9.73	15.20	4.50	6.48	11.52	18.00
Axial tension	1.000	0.720	0.424	0.271	0.879	0.633	0.372	0.238	0.763	0.550	0.323	0.207

Table 5. *Cont.*

Strength Classes	C24				C27				C30			
Axial compression	1.000	0.694	0.391	0.250	0.954	0.663	0.373	0.239	0.875	0.608	0.342	0.219
Shear	1.000	0.694	0.391	0.250	1.000	0.694	0.391	0.250	1.000	0.694	0.391	0.250
Bending	1.000	0.600	0.264	0.135	0.888	0.533	0.235	0.120	0.799	0.480	0.212	0.108
Combined bending and axial tension	1.000	0.660	0.344	0.203	0.883	0.583	0.304	0.179	0.781	0.515	0.267	0.158
Combined bending and axial compression	1.000	0.541	0.209	0.099	0.900	0.486	0.187	0.089	0.782	0.424	0.164	0.078

* The stated measurement unit refers to one meter in length.

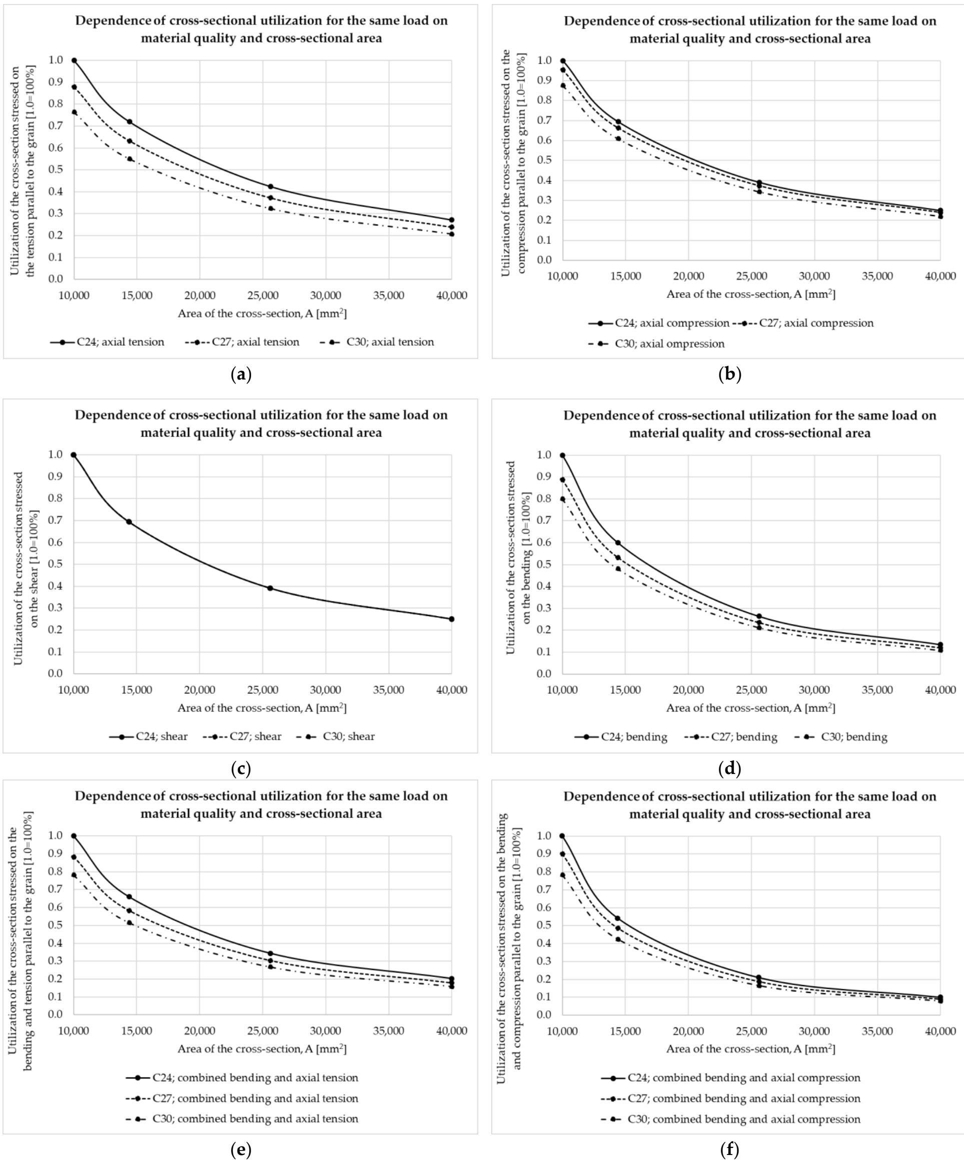


Figure 3. Graphic representation of cross-section utilization (element) depending on check of limit state and strength class: (**a**) tension parallel to the grain; (**b**) compression parallel to the grain; (**c**) shear; (**d**) bending; (**e**) bending and tension parallel to the grain; (**f**) bending and compression parallel to the grain.

3.2. Results of the Reduced Cross-Section Method

By applying the reduced cross-section method, the fire resistance values obtained are shown in Tables 6–11 for each stress state, depending on internal forces. In the same tables, the percentage of cross-sectional area utilization is also shown for the limit states method for each mentioned stress state, depending on internal forces. It has been shown that the utilization of the cross-sectional area during the proof of load-bearing capacity has a significant impact on the proof of fire resistance, regardless of which internal forces the cross-section (element) is subjected to. The material quality is associated with the material price, as depicted in Figure 4, as well as in Tables 5–10. A graphical representation of part of the results from Tables 6–11 is shown in Figures 5–10.

Table 6. Display of fire resistance of the cross-sectional area when the fire acts on three or four sides of the section subjected to tensile stress parallel to the grain [1.0 = 100%].

Strength Classes		**C24**				**C27**				**C30**			
Area of the cross-section [mm^2]		10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000
Price for 1 m * [EUR]		3.15	4.54	8.06	12.60	3.80	5.47	9.73	15.20	4.50	6.48	11.52	18.00
Axial tension-ULS [1.0 = 100%]		1.000	0.720	0.424	0.271	0.879	0.633	0.372	0.238	0.763	0.550	0.323	0.207
Fire resistance (fire exposure on 3 sides), R [min]	0	0.41	0.30	0.17	0.11	0.36	0.26	0.15	0.10	0.31	0.23	0.13	0.08
	10	0.60	0.40	0.22	0.13	0.53	0.36	0.19	0.12	0.46	0.31	0.17	0.10
	15	0.76	0.48	0.25	0.15	0.67	0.43	0.22	0.13	0.58	0.37	0.19	0.11
	30	1.56	0.82	0.35	0.19	1.38	0.72	0.31	0.17	1.19	0.63	0.27	0.15
	45		1.63	0.51	0.25		1.43	0.45	0.22		1.24	0.39	0.19
	60			0.85	0.34			0.74	0.30			0.65	0.26
	75			1.84	0.51			1.62	0.45			1.40	0.39
	90				0.88				0.77				0.67
	105				2.27				1.99				1.73
Fire resistance (fire exposure on 4 sides), R [min]	0	0.41	0.30	0.17	0.11	0.36	0.26	0.15	0.10	0.31	0.23	0.13	0.08
	10	0.69	0.45	0.24	0.14	0.61	0.40	0.21	0.12	0.53	0.35	0.18	0.11
	15	0.96	0.58	0.28	0.16	0.84	0.51	0.25	0.14	0.73	0.44	0.22	0.12
	30	2.84	1.27	0.46	0.23	2.50	1.11	0.41	0.21	2.17	0.97	0.35	0.18
	45			0.81	0.34			0.71	0.30		2.81	0.62	0.26
	60			1.78	0.55			1.56	0.48			1.36	0.42
	75				1.02				0.90				0.78
	90								2.22				1.93
	105												

* The stated measurement unit refers to one meter in length.

Table 7. Display of fire resistance of the cross-sectional area when the fire acts on three or four sides of the section subjected to compression parallel to the grain [1.0 = 100%].

Strength Classes		**C24**				**C27**				**C30**			
Area of the cross-section [mm^2]		10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000
Price for 1 m * [EUR]		3.15	4.54	8.06	12.60	3.80	5.47	9.73	15.20	4.50	6.48	11.52	18.00
Axial compression-ULS [1.0 = 100%]		1.000	0.694	0.391	0.250	0.954	0.663	0.373	0.239	0.875	0.608	0.342	0.219
Fire resistance (fire exposure on 3 sides), R [min]	0	0.41	0.28	0.16	0.10	0.39	0.27	0.15	0.10	0.36	0.25	0.14	0.09
	10	0.60	0.39	0.20	0.12	0.57	0.37	0.19	0.12	0.53	0.34	0.18	0.11
	15	0.76	0.47	0.23	0.14	0.72	0.45	0.22	0.13	0.66	0.41	0.20	0.12
	30	1.56	0.79	0.32	0.18	1.49	0.76	0.31	0.17	1.37	0.70	0.28	0.15
	45		1.57	0.47	0.23		1.50	0.45	0.22		1.37	0.41	0.20
	60			0.78	0.31			0.75	0.30			0.68	0.28
	75			1.70	0.47			1.62	0.45			1.48	0.41
	90				0.81				0.77				0.71
	105				2.09				2.00				1.83
Fire resistance (fire exposure on 4 sides), R [min]	0	0.41	0.28	0.16	0.10	0.39	0.27	0.15	0.10	0.36	0.25	0.14	0.09
	10	0.69	0.44	0.22	0.13	0.66	0.42	0.21	0.12	0.61	0.38	0.19	0.11
	15	0.96	0.56	0.26	0.15	0.91	0.54	0.25	0.14	0.84	0.49	0.23	0.13
	30	2.84	1.22	0.43	0.22	2.71	1.16	0.41	0.21	2.49	1.07	0.37	0.19
	45			0.75	0.32			0.72	0.30			0.66	0.28
	60			1.64	0.51			1.57	0.48			1.44	0.44
	75				0.94				0.90				0.82
	90				2.33				2.22				2.03
	105												

* The stated measurement unit refers to one meter in length.

Table 8. Display of fire resistance of the cross-sectional area when the fire acts on three or four sides of the section subjected to shear stress [1.0 = 100%].

Strength Classes		**C24**				**C27**				**C30**			
Area of the cross-section [mm^2]		10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000
Price for 1 m * [EUR]		3.15	4.54	8.06	12.60	3.80	5.47	9.73	15.20	4.50	6.48	11.52	18.00
Shear -ULS [1.0 = 100%]		1.000	0.694	0.391	0.250	1.000	0.694	0.391	0.250	1.000	0.694	0.391	0.250
Fire resistance (fire exposure on 3 sides), R [min]	0	0.41	0.28	0.16	0.10	0.41	0.28	0.16	0.10	0.41	0.28	0.16	0.10
	10	0.60	0.39	0.20	0.12	0.60	0.39	0.20	0.12	0.60	0.39	0.20	0.12
	15	0.76	0.47	0.23	0.14	0.76	0.47	0.23	0.14	0.76	0.47	0.23	0.14
	30	1.56	0.79	0.32	0.18	1.56	0.79	0.32	0.18	1.56	0.79	0.32	0.18
	45		1.57	0.47	0.23		1.57	0.47	0.23		1.57	0.47	0.23
	60			0.78	0.31			0.78	0.31			0.78	0.31
	75			1.70	0.47			1.70	0.47			1.70	0.47
	90				0.81				0.81				0.81
	105				2.09				2.09				2.09
Fire resistance (fire exposure on 4 sides), R [min]	0	0.41	0.28	0.16	0.10	0.41	0.28	0.16	0.10	0.41	0.28	0.16	0.10
	10	0.69	0.44	0.22	0.13	0.69	0.44	0.22	0.13	0.69	0.44	0.22	0.13
	15	0.96	0.56	0.26	0.15	0.96	0.56	0.26	0.15	0.96	0.56	0.26	0.15
	30	2.84	1.22	0.43	0.22	2.84	1.22	0.43	0.22	2.84	1.22	0.43	0.22
	45			0.75	0.32			0.75	0.32			0.75	0.32
	60			1.64	0.51			1.64	0.51			1.64	0.51
	75				0.94				0.94				0.94
	90				2.33				2.33				2.33
	105												

* The stated measurement unit refers to one meter in length.

Table 9. Display of fire resistance of the cross-sectional area when the fire acts on three or four sides of the section subjected to bending [1.0 = 100%].

Strength Classes		**C24**				**C27**				**C30**			
Area of the cross-section [mm^2]		10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000
Price for 1 m * [EUR]		3.15	4.54	8.06	12.60	3.80	5.47	9.73	15.20	4.50	6.48	11.52	18.00
Bending -ULS [1.0 = 100%]		1.000	0.600	0.264	0.135	0.888	0.533	0.235	0.120	0.799	0.480	0.212	0.108
Fire resistance (fire exposure on 3 sides), R [min]	0	0.41	0.25	0.11	0.06	0.36	0.22	0.10	0.05	0.33	0.20	0.09	0.04
	10	0.68	0.37	0.15	0.07	0.60	0.33	0.13	0.06	0.54	0.30	0.12	0.06
	15	0.91	0.47	0.17	0.08	0.81	0.42	0.15	0.07	0.73	0.38	0.14	0.06
	30	2.27	0.93	0.27	0.11	2.01	0.82	0.24	0.10	1.81	0.74	0.22	0.09
	45		2.11	0.44	0.16		1.87	0.39	0.14		1.69	0.35	0.13
	60			0.81	0.23			0.72	0.21			0.64	0.19
	75			1.98	0.38			1.76	0.34			1.58	0.30
	90				0.72				0.64				0.58
	105				2.08				1.85				1.66
Fire resistance (fire exposure on 4 sides), R [min]	0	0.41	0.25	0.11	0.06	0.36	0.22	0.10	0.05	0.33	0.20	0.09	0.04
	10	0.90	0.47	0.17	0.08	0.80	0.41	0.15	0.07	0.72	0.37	0.14	0.06
	15	1.46	0.68	0.22	0.10	1.30	0.60	0.20	0.09	1.17	0.54	0.18	0.08
	30		2.18	0.47	0.17		1.94	0.42	0.15		1.74	0.38	0.14
	45			1.10	0.30			0.97	0.27			0.88	0.24
	60				0.61			3.16	0.54			2.84	0.49
	75				1.55				1.37				1.24
	90												
	105												

* The stated measurement unit refers to one meter in length.

Table 10. Display of fire resistance of the cross-sectional area when the fire acts on three or four sides of the section subjected to bending and tension parallel to the grain [1.0 = 100%].

Strength Classes		**C24**				**C27**				**C30**			
Area of the cross-section [mm^2]		10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000
Price for 1 m * [EUR]		3.15	4.54	8.06	12.60	3.80	5.47	9.73	15.20	4.50	6.48	11.52	18.00
Comb. M_d and $N_{t,d}$ -ULS [1.0 = 100%]		1.000	0.660	0.344	0.203	0.883	0.583	0.304	0.179	0.781	0.515	0.267	0.158
Fire resistance (fire exposure on 3 sides), R [min]	0	0.41	0.27	0.14	0.08	0.36	0.24	0.12	0.07	0.32	0.21	0.11	0.06
	10	0.64	0.39	0.18	0.10	0.57	0.34	0.16	0.09	0.50	0.30	0.14	0.08
	15	0.84	0.48	0.21	0.11	0.74	0.42	0.19	0.10	0.65	0.37	0.16	0.09
	30	1.92	0.87	0.31	0.15	1.69	0.77	0.28	0.13	1.50	0.68	0.24	0.12
	45		1.87	0.48	0.20		1.65	0.42	0.18		1.46	0.37	0.16
	60			0.83	0.29			0.73	0.25			0.65	0.22
	75			1.91	0.44			1.69	0.39			1.49	0.35
	90				0.80				0.71				0.62
	105				2.17				1.92				1.70
Fire resistance (fire exposure on 4 sides), R [min]	0	0.46	0.27	0.14	0.08	0.36	0.24	0.12	0.07	0.32	0.21	0.11	0.06
	10	0.79	0.46	0.20	0.11	0.70	0.41	0.18	0.10	0.62	0.36	0.16	0.09
	15	1.21	0.63	0.25	0.13	1.07	0.56	0.22	0.11	0.95	0.49	0.20	0.10
	30		1.72	0.47	0.20		1.52	0.41	0.18	4.07	1.35	0.37	0.16
	45			0.95	0.32			0.84	0.28			0.75	0.25
	60			2.67	0.58			2.36	0.51			2.10	0.45
	75				1.28				1.14				1.01
	90												
	105												

* The stated measurement unit refers to one meter in length.

Table 11. Display of fire resistance of the cross-sectional area when the fire acts on three or four sides of the section subjected to bending and compression parallel to the grain [1.0 = 100%].

Strength Classes		**C24**				**C27**				**C30**			
Area of the cross-section [mm^2]		10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000	10,000	14,400	25,600	40,000
Price for 1 m * [EUR]		3.15	4.54	8.06	12.60	3.80	5.47	9.73	15.20	4.50	6.48	11.52	18.00
Comb. M_d and $N_{c,d}$-ULS [1.0 = 100%]		1.000	0.541	0.209	0.099	0.900	0.486	0.187	0.089	0.782	0.424	0.164	0.078
Fire resistance (fire exposure on 3 sides), R [min]	0	0.29	0.16	0.07	0.03	0.26	0.15	0.06	0.03	0.23	0.13	0.05	0.03
	10	0.52	0.26	0.09	0.04	0.47	0.23	0.08	0.04	0.41	0.21	0.07	0.03
	15	0.74	0.34	0.11	0.05	0.67	0.31	0.10	0.04	0.58	0.27	0.09	0.04
	30	2.36	0.78	0.19	0.07	2.12	0.70	0.17	0.06	1.84	0.61	0.15	0.06
	45		2.28	0.33	0.11		2.06	0.30	0.09		1.78	0.26	0.08
	60			0.71	0.18			0.64	0.15			0.56	0.13
	75			2.43	0.30			2.19	0.27			1.89	0.24
	90				0.69				0.62				0.54
	105				3.23				2.92				2.51
Fire resistance (fire exposure on 4 sides), R [min]	0	0.29	0.16	0.07	0.03	0.26	0.15	0.06	0.03	0.23	0.13	0.05	0.03
	10	0.69	0.33	0.11	0.05	0.62	0.29	0.10	0.04	0.54	0.26	0.09	0.04
	15	1.19	0.50	0.15	0.06	1.06	0.45	0.13	0.05	0.93	0.39	0.12	0.05
	30		1.83	0.33	0.11		1.65	0.29	0.10	6.08	1.44	0.26	0.09
	45			0.83	0.20			0.74	0.18			0.65	0.16
	60			3.12	0.43			2.81	0.39			2.45	0.34
	75				1.22				1.09				0.96
	90												4.47
	105												

* The stated measurement unit refers to one meter in length.

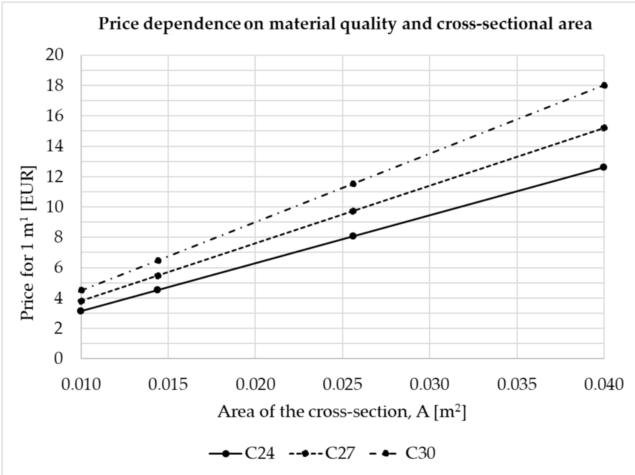
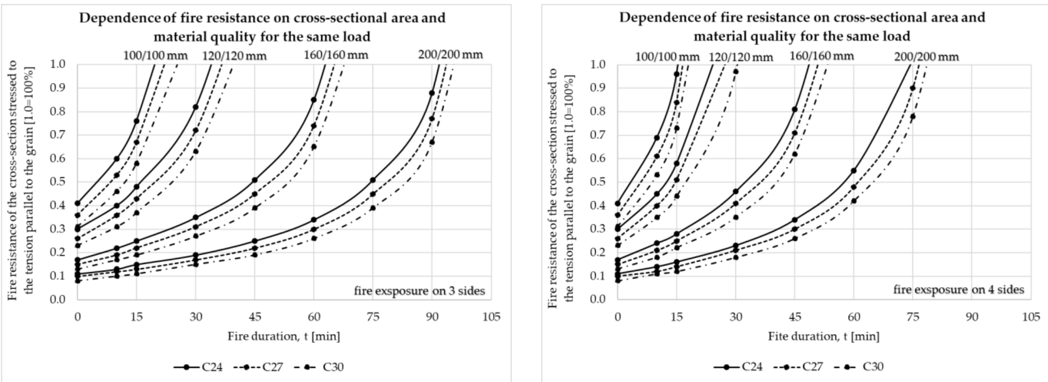
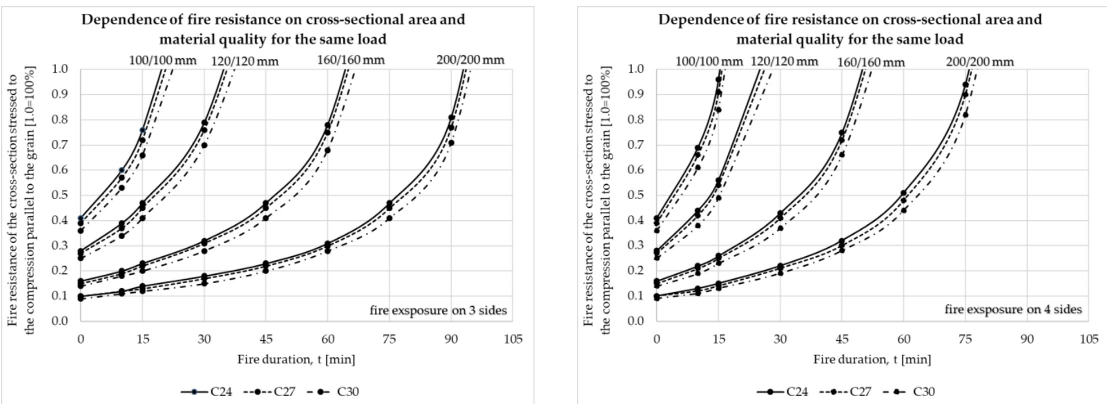


Figure 4. Display of material price depending on the strength class and cross-sectional area.



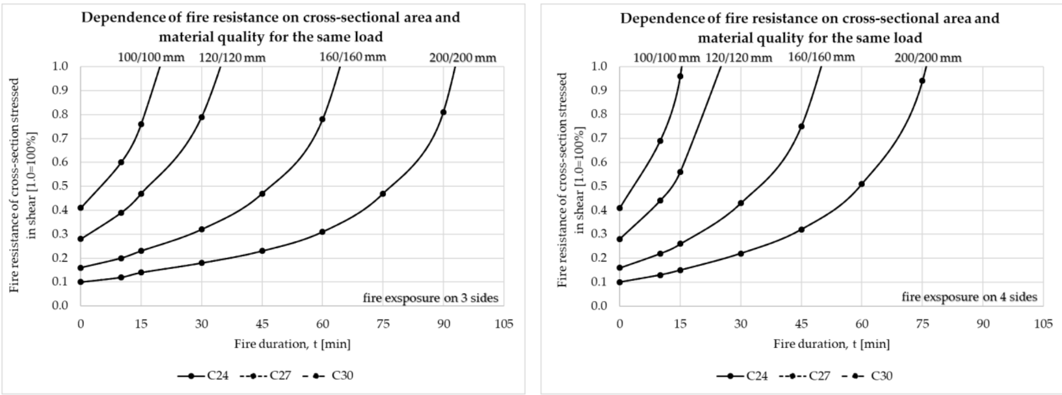
(**a**) (**b**)

Figure 5. Graphical representation of the fire resistance of the cross-sectional area (element) depending on the cross-sectional area and strength class: (**a**) Fire resistance for a cross-section subjected to tensile stress parallel to the grain when the fire acts on three sides of the cross-section; (**b**) Fire resistance for a cross-section subjected to tensile stress parallel to the grain when the fire acts on four sides of the cross-section.



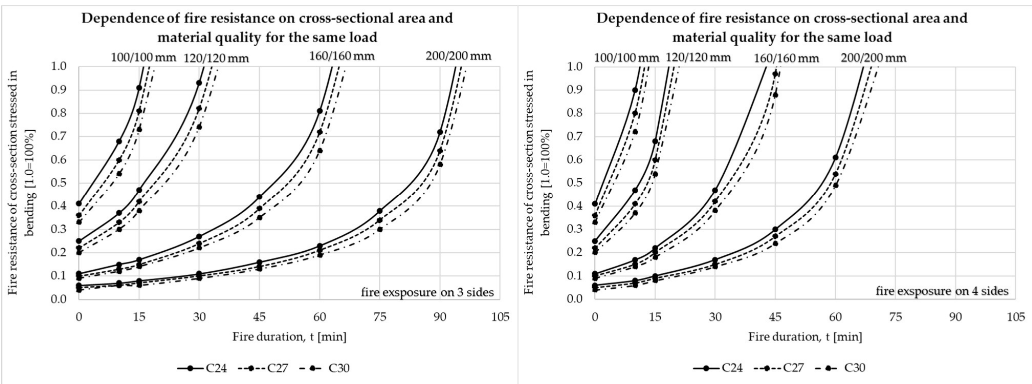
(**a**) (**b**)

Figure 6. Graphical representation of the fire resistance of the cross-sectional area (element) depending on the cross-sectional area and strength class: (**a**) Fire resistance for a cross-section subjected to compression parallel to the grain when the fire acts on three sides of the cross-section; (**b**) Fire resistance for a cross-section subjected to compression parallel to the grain when the fire acts on four sides of the cross-section.



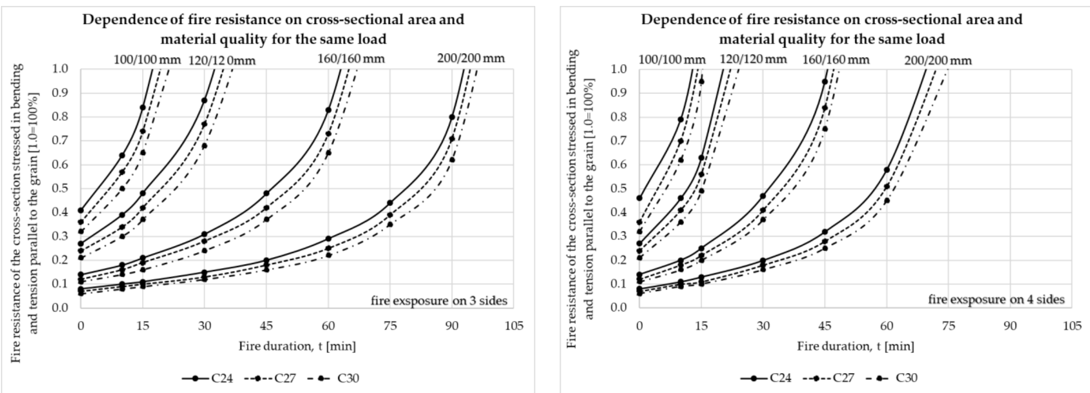
(**a**) (**b**)

Figure 7. Graphical representation of the fire resistance of the cross-sectional area (element) depending on the cross-sectional area and strength class: (**a**) Fire resistance for a cross-section subjected to shear stress when the fire acts on three sides of the cross-section; (**b**) Fire resistance for a cross-section subjected to shear stress when the fire acts on four sides of the cross-section.



(**a**) (**b**)

Figure 8. Graphical representation of the fire resistance of the cross-sectional area (element) depending on the cross-sectional area and strength class: (**a**) Fire resistance for a cross-section subjected to bending when the fire acts on three sides of the cross-section; (**b**) Fire resistance for a cross-section subjected to bending when the fire acts on four sides of the cross-section.



(**a**) (**b**)

Figure 9. Graphical representation of the fire resistance of the cross-sectional area (element) depending on the cross-sectional area and strength class: (**a**) Fire resistance for a cross-section subjected to bending and tension parallel to the grain when the fire acts on three sides of the cross-section; (**b**) Fire resistance for a cross-section subjected to bending and tension parallel to the grain when the fire acts on four sides of the cross-section.

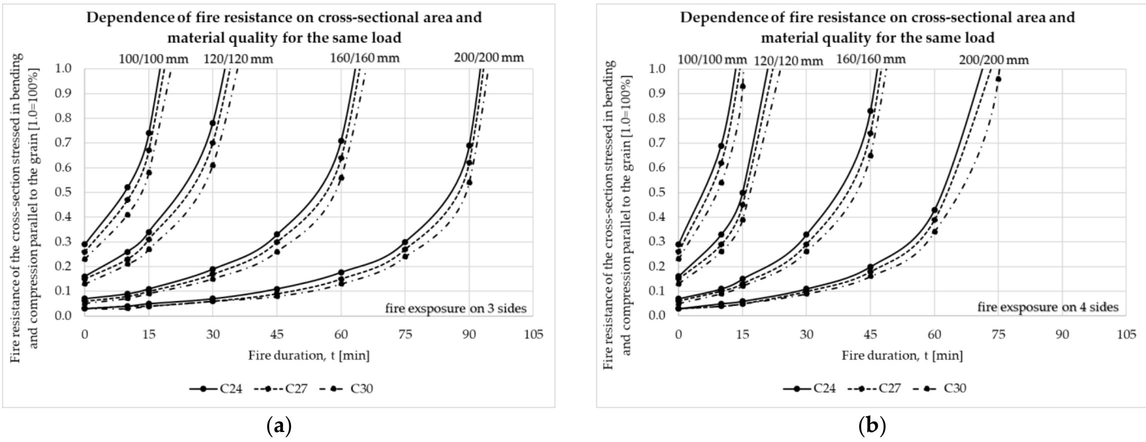


Figure 10. Graphical representation of the fire resistance of the cross-sectional area (element) depending on the cross-sectional area and strength class: (**a**) Fire resistance for a cross-section subjected to bending and compression parallel to the grain when the fire acts on three sides of the cross-section; (**b**) Fire resistance for a cross-section subjected to bending and compression parallel to the grain when the fire acts on four sides of the cross-section.

In Figures 5–10, it can be observed how all curves of fire resistance increase for each stress state depending on internal forces. Figures demonstrate an increase in fire resistance with an increase in the cross-sectional area and depending on the material quality.

In Figure 5a, the fire resistance curves for different strength classes and different dimensions of the cross-section are shown, if the cross-section is stressed by the tensile stress parallel to the grain. The curves show the dependence of the cross-sectional area in relation to the fire resistance of the cross-section and the duration of the fire. Compared to the cross-section 100/100 mm of quality C24, which was used 100% to the limit state of load-bearing capacity, the cross-section 200/200 mm has a six times longer duration of fire, i.e., greater fire resistance expressed in time, and at the same time, it was used to the limit state carrying capacity of 27.1%. By increasing the duration of the fire, the utilization of the fire resistance of the cross-section increases. By choosing a larger cross-section (element), a longer duration of fire is achieved. Different values of fire duration for all stress state observations are obtained for the case when the fire acts from four sides (Figures 5b, 6b, 7b, 8b, 9b and 10b).

In Figure 6a, the fire resistance curves for different strength classes and different dimensions of the cross-section are shown, if the cross-section is stressed by compression parallel to the grain. The curves show the dependence of the cross-sectional area in relation to the fire resistance of the cross-section and the duration of the fire. Compared to the cross-section 100/100 mm of quality C24, which was used 100% to the limit state of load-bearing capacity, the cross-section 200/200 mm has a six times longer duration of fire, i.e., greater fire resistance expressed in time, and at the same time, it was used to the limit state load capacity of 25.0%.

In Figure 7a, the fire resistance curves for different strength classes and different dimensions of the cross-section are shown, if the cross-section is under shear stress. The curves show the dependence of the cross-sectional area in relation to the fire resistance of the cross-section and the duration of the fire. Compared to the cross-section 100/100 mm of quality C24, which was used 100% to the limit state of load-bearing capacity, the cross-section 200/200 mm has a six times longer duration of fire, i.e., greater fire resistance expressed in time, and at the same time, it was used to the limit state load capacity of 25.0%.

In Figure 8, the fire resistance curves for different strength classes and different cross-section dimensions are shown, if the cross-section is under bending stress. The curves show the dependence of the cross-sectional area in relation to the fire resistance of the cross-section and the duration of the fire. Compared to the cross-section 100/100 mm of quality C24, which was used 100% to the limit state of load-bearing capacity, the cross-section

200/200 mm has a six times longer duration of fire, i.e., greater fire resistance expressed in time, and at the same time, it was used to the limit state carrying capacity of 13.5%.

In Figure 9a, the fire resistance curves for different strength classes and different dimensions of the cross-section are shown, if the cross-section is subjected to bending and tension parallel to the grain. The curves show the dependence of the cross-sectional area in relation to the fire resistance of the cross-section and the duration of the fire. Compared to the cross-section 100/100 mm of quality C24, which was used 100% to the limit state of load-bearing capacity, the cross-section 200/200 mm has a six times longer duration of fire, i.e., greater fire resistance expressed in time, and at the same time, it was used to the limit state carrying capacity of 20.3%.

In Figure 10a, the fire resistance curves for different strength classes and different dimensions of the cross-section are shown, if the cross-section is subjected to bending and compression parallel to the grain. The curves show the dependence of the cross-sectional area in relation to the fire resistance of the cross-section and the duration of the fire. Compared to the cross-section 100/100 mm of quality C24, which was used 100% to the limit state of load-bearing capacity, the cross-section 200/200 mm has a six times longer duration of fire, i.e., greater fire resistance expressed in time, and at the same time, it was used to the limit state load capacity of 9%.

Figures 6–11 it can be observed how all the curves of fire resistance increase for each stress state depending on internal forces, and they vary with changes in the cross-sectional area to some extent with changes in material quality and significantly with the exposure of the cross-sectional area to fire. It is noticeable that only in the case of shear force or shear stress (Figure 7a,c) does the material quality have no effect on the fire resistance of any cross-section because the characteristic shear strength, $f_{v,k}$, is the same for all observed strength classes (Table 1) [9].

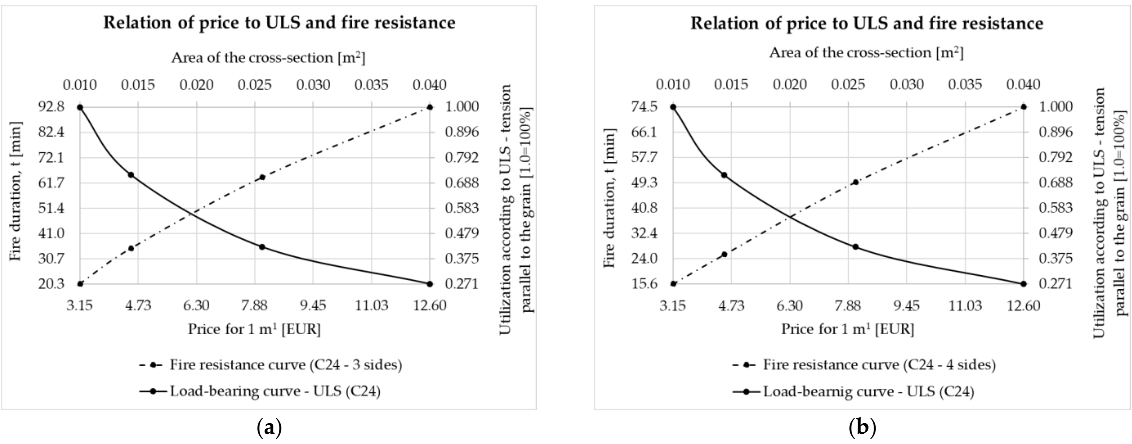


Figure 11. Display of price depending on the limit state of load-bearing capacity (tension parallel to the grain) and fire resistance: (**a**) Cross-section (element) exposed to fire on three sides; (**b**) Cross-section (element) exposed to fire on four sides.

3.3. Relation of Price on ULS and Fire Resistance

By applying the limit states method and the reduced cross-section method, the relation of price on the evidence of one or the other method can be obtained. In Figure 11, the relation of price and the limit state of load-bearing capacity and fire resistance can be observed when the cross-section (element) is stressed to the tension parallel to the grain, depending on the area of the cross-section or its utilization. In short, lower utilization of the cross-section means greater fire resistance but also a higher cost. Figure 11 also shows the position of the optimal point by comparing the load-bearing curve and the fire resistance curve. The same conclusion could be drawn for other cases of stress on the cross-section or strength classes of solid softwood.

4. Discussion

The continuation of the research focuses on the impact of stability proofs of elements on the fire resistance of those elements, including buckling, lateral buckling and the interaction between buckling and lateral buckling. Additionally, it examines the influence of passive fire protection measures on the overall cost of the protected element for a specific duration of fire exposure. Furthermore, the upcoming release of a new generation of Eurocodes will provide an opportunity for comparison with existing Eurocodes, which will be interesting to explore.

5. Conclusions

- In recent times, primarily due to regulations, fire resistance has certainly received significant attention from designers and researchers alike. Experimental tests for fire resistance in timber are still costly, and not everyone has the means to conduct them. After conducting research and obtaining numerical results for each of the described methods, observed cross-sections and timber strength classes, the following can be concluded.
- By checking the limit state of the load-bearing capacity, fire resistance is directly affected in timber structures when applying the reduced cross-section method. This is not the case for structures made of other characteristic materials, such as concrete or steel.
- The utilization of cross-sections (elements) significantly affects fire resistance. If a cross-section (element) is 100% utilized for any internal force or combination of internal forces, a cross-section made of any analyzed timber strength class (element) does not achieve greater fire resistance than R15. Increasing the surface area of the cross-section reduces the utilization of the cross-section (element), thereby increasing fire resistance. If the fire acts on three sides, a twice larger cross-section, regardless of the quality of the material, provides a six-times longer fire duration (R90) with the fact that its utilization of the cross-section at the observed limit states of stress is, on average, 5.7 times lower. Twice the cross-section, 200/200 mm for the duration of the fire R90, has the same average fire resistance utilization as the cross-section 100/100 mm, but for the duration of the fire R15 for the case where the fire acts on three sides. When the fire acts from four sides, a double cross-section, regardless of the quality of the material, provides four or five times the duration of the fire (R60 or R75), which depends on the stress state of the cross-section, while its utilization of the cross-section at the observed limit states of stress is the same on average 5.7 times smaller.
- Exposure of the cross-section to fire has a significant impact on fire resistance. In the results shown in the tables, if a cross-section meets fire resistance at R30 when the fire acts on three sides of the cross-section, the same cross-section will not meet the specified fire resistance if the fire acts on four sides of the cross-section.
- Increasing the observed timber strength classes based on the obtained numerical results, for any internal force, does not significantly contribute to fire resistance. The contribution of increasing timber strength classes is evident only in reducing the utilization of the cross-section in fire resistance. For cross-sections (elements) tested for shear, increasing the observed timber strength classes has no effect on fire resistance.
- The price of materials also has a significant impact on achieving a certain level of fire resistance, according to the mechanical resistance criterion R. Depending on the required fire resistance and the action of internal forces on the cross-section (element), it can increase from 1.44 to 4.0 times.
- This study provides the possibility of optimizing the choice of the cross-sectional area, fire resistance and price, depending on the state of stress to which the cross-section (element) is exposed.
- The conclusion of this research is that checking the limit state of load-bearing capacity has a decisive impact on the fire resistance of structural timber obtained according to the load-bearing criterion. The results presented in this study, especially the results

regarding fire resistance of cross-sections, will certainly assist in the early design phase, where the utilization of the cross-section (element) can immediately affect the required fire resistance, considering the proof of fire resistance according to the mechanical resistance criterion R.

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