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Examination of the Fire Resistance of Construction Materials from Beams in Chemical Warehouses Dealing with Flammable Dangerous Substances

Lajos Kátai-Urbán [1,*], Zsolt Cimer [2] and Éva Eszter Lublóy [3]

[1] Institute of Disaster Management, Faculty of Law Enforcement, University of Public Service, Hungária Körút 9-11, 1101 Budapest, Hungary
[2] Faculty of Water Sciences, University of Public Service, Bajcsy-Zsilinszky Utca 12-14, 6500 Baja, Hungary; cimer.zsolt@uni-nke.hu
[3] Department of Construction Materials and Technologies, Faculty of Civil Engineering, Budapest University of Technology and Economics, 1521 Budapest, Hungary; lubeva@web.de
* Correspondence: katai.lajos@uni-nke.hu

Abstract: The recent expansion of logistics capacities entails the installation of chemical warehouses, which operations increase the occurrence of compartment fires involving flammable dangerous substances. The aim of this research was to compare and analyze the fire behavior of beams made of different structural materials but with the same load capacity. It is assumed that wooden beams, which are less commonly used in industrial facilities, may have a similar or even better load-bearing capacity in case of a fire than the generally used steel beams. The authors—based on the relevant EU standards—performed load capacity calculations of three beams prepared from different materials under the influence of fire and analyzed the changes in the material properties. Then, they examined the possibility of reinforcing the beams with carbon fiber lamellae and proposed additional fire protection requirements. The test results not only proved the different degrees of fire resistance of various building materials in the event of a fire and after their reinforcement but also suggested the application of special technical, prevention and response measures for the safe storage of dangerous substances. The study outputs enable warehouse designers, operators and safety experts to ensure a higher fire safety level for chemical warehouses.

Keywords: bending capacity; carbon fire lamella; chemical warehouse; fire resistance; flammable dangerous substance; fire safety requirements; load capacity

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1. Introduction and Literature Review

In the present section, the authors will introduce in a general way their research topic and will assess the state-of-the-art examined research fields. In this context, they combine the scientific investigation of the fire resistance of structural materials of storage buildings with the safety aspects of chemical logistics warehouses, especially the risk assessment and management of major accidents involving flammable dangerous substances and also the connection points of risk management and fire prevention of chemical storage facilities. In addition to an analysis of international policies and practices, the authors also describe—where appropriate—the safety situation in Hungary.

1.1. Analyses of the Safety Aspects of Chemical Warehouses

Our daily lives are affected by internationalization and globalization, which lead to the expansion of international trade and production relations [1]. In meeting the growing needs of the population and the economy, the requirement to have adequate storage capacities for the continuous availability of products has come to the fore. The logistics of storage facilities for raw materials, intermediate materials and final products play an important role in production and processing procedures and activities [2].

In order to ensure business continuity, adaptation to changing market needs and continuous customer service, it is advisable to include a buffer capacity in the production and processing routes. As an impact of the recent pandemic, war, natural calamities and other crisis situations were influenced by the resilience of the just-in-time supply chain; consequently, the expansion of buffer storage capacities was observed [3,4].

The main manufacturing business activities such as the oil and gas industry, chemical industry, plastics manufacturing, battery production or pharmaceutical industry all require the storage of flammable dangerous substances [5].

Among the operational facilities used for the transport of dangerous goods by road, we consider the storage warehouses of dangerous goods. In these facilities, dangerous goods with packaging required by international road transport regulations [6] are stored.

Due to the changes generated by the global processes, it has resulted in the continuous installation of warehouse buildings for the storage of dangerous substances. Based on international convention [7] and the European Union (EU) directive [8] regulations, the concept of "storage activity" means the presence of a quantity of dangerous substances for the purposes of warehousing, depositing in safe custody or keeping in stock.

In accordance with the data of the EU Joint Research Center's research institute named the Major Accident Hazard Bureau, a significant number of major emissions, fires or explosions involving dangerous substances can occur on a yearly basis within the areas of storage warehouses dealing with dangerous substances [9]. Investigation data on the causes and circumstances of warehouse structure fires are contained in the studies of professional organizations, such as the publication of the United States of America's National Fire Protection Association [10].

1.2. Major Accident Hazards Prevention and Fire Prevention Requirements of Chemical Warehouses Dealing wtih Fammable Dangerous Substances

In the case of warehouses storing dangerous substances (chemical warehouses), the international literature dealing with the prevention of major industrial accidents [11–13] considers a warehouse fire to be one of the most important major accident scenarios. The EU directive—based on the already referenced international convention—considers flammable substances (like gases, liquids and aerosols) as physical hazards that are capable of causing major industrial accidents with major consequences on human health and the environment. The physical and chemical properties of dangerous substances in chemical warehouses are determined by the EU chemical safety regulations [14]. Based on the internationally widely accepted risk assessment technical guidelines [15,16], major industrial accidents have not only external effects but can also pose a significant threat to the built environment, including the building structure of a chemical warehouse. An analysis of the consequences of major accident scenarios was carried out by the Hungarian disaster management authorities using the software Det Norske Veritas [17].

The prevention of chemical warehouse fires and the elimination or mitigation of their possible consequences on building structures can therefore be considered as a priority safety issue [18]. When setting up chemical warehouses, the legal requirements of the various safety field's prescriptions must be taken into account, which appear mostly in the occupational safety, fire safety, explosion protection and environmental protection regulations [19]. Operators of hazardous activities—as a good practice—use several widely applied national and international guidelines [20–24] for the planning, construction and operation of chemical warehouses.

It should be underlined that most fire protection (prevention) regulations for the establishment and usage of warehouse facilities serve as the basis for other types of safety regulations.

The safe operation of dangerous technologies used in dangerous establishments (like chemical warehouses) is made sustainable by the operators through technical, management and control measures, which are largely based on the introduction of fire prevention measures [25].

In agreement with C. Zhang's evaluation, we mainly apply active and passive fire safety systems as preventive technical measures for fire protection purposes. Active fire safety systems mainly mean the installation and use of automatic fire detection, alarm and extinguishing systems. In the case of passive systems, the basic fire protection requirements are the installation of building structures (for example, fire doors and curtains, smoke dampers, etc.) that prevent the spread of fire as part of a layered protection system, as well as the utilization of appropriate fire-resistant building materials, structures and their coatings [26]. V. Kodur et al. prepared a critical review of the current fire protection measures and their applicability to fire hazards in buildings, as well as proposals for improving the fire safety of constructions [27].

It can be stated that, in addition to active fire safety systems, a number of passive fire safety requirements must be taken into account during the design procedures of storage building structures and usage of contraction materials. When designing a warehouse with chemical logistics, one of the most important challenges is defining the range of products to be stored because of the constant movement of the market needs. The chemical and physical properties of the products (dangerous substances) to be stored and the size of the warehouse's fire section clearly determine the fire protection requirements applicable to the chemical warehouse, including building structures and protection systems. If dangerous substances are stored on the territory of a chemical warehouse, additional special major accident prevention requirements must be introduced by the warehouse operators [28].

Specific fire case studies [29] focused attention on the close relationship between the structural deficiencies of warehouse construction and fire intervention procedures. During the planning process of chemical warehouses, during the selection of the warehouse structure and building materials—in addition to the general architectural requirements (such as, for example, the adequate load-bearing capacity of the building structure)—possible extreme emergency conditions must also be taken into account. Another important aspect is the speed of the firefighting intervention in the event of a delayed response, the "controlled burning" measure must be applied [30].

Thus, among other things, in the event of a fire, the following fire prevention aspects must be considered:

- Load-bearing structures fulfil the fire safety requirements for the period of time prescribed in the fire prevention technical regulations;
- Appropriate fire protection systems are installed to prevent the spread of fire;
- The arising combustion products and smoke must be appropriately removed;
- The reduction of the stability of the building structure under the influence of fire.

Planning considerations can also play an important role in the recovery works just after an elimination of the consequences of a possible fire. Thus, compliance with extreme emergency conditions must be repeatedly ensured in a cost-effective manner.

1.3. Fire Resistance of Construction Materials of Roof Structures

The roof structure and its beams are—in accordance with the opinion of the authors—the most endangered parts of the building structures in the case of a chemical warehouse fire. The early collapse of the roof structure can lead to severe material damage [31], personal casualties [32] and significantly reduces the effectiveness of extinguishing the fire [33]. The main reason for this process is the significant increase in temperature in the compartment area and the rapid reduction of the beams' fire resistance and, thus, their load capacity [34]. The solution to the problem rests primarily on the fire prevention measures.

Based on the literature review presented in the previous subsection, it can be underlined that one of the most important areas of fire prevention is ensuring the fire resistance of building structures. The fire resistance of different building structures is influenced by the load-bearing capacity under the influence of fire. The examination of fire resistance processes is particularly important in the case of chemical warehouses with a significant fire risk, which is connected to the authors' subject of investigation.

The development of building materials naturally also affects the developments of fire resistance tests. The application and improvement of validated and verified fire resistance test methods is also a daily research task. The fire resistance of the three main building structure materials, wood, steel and reinforced concrete, has been investigated by a significant number of authors [35–37]. Beyond this, we can experience relatively significant variations in the structural solutions of the buildings. The application of mixed material structures is to ensure higher fire resistance and, at the same time, prevent the structural collapse of roof systems under fire [38].

Various standardized tests are used to measure fire resistance. S. Chaturvedi and co-authors, in their recently published review study [39], made a comparison of different performance criteria of a wide range of fire resistance testing standards. They drew attention to the new research areas that require significant interest in experimental structural fire-resistant testing.

The fire resistance tests—in the case of Hungary—are mainly based on international, the European Union's and national level standards, which are closely related to each other [40]. Thus, for example, on the research topic of the authors, the relevant standards of the EU regarding the load-bearing capacity of wood, steel and reinforced concrete structures must be taken into account.

Paint coatings or other coatings applied to building structural elements can significantly increase, for example, the fire resistance of steel structures. Among the related literature, the review article of A. Lucherini and C. Maluk should be highlighted, from which we came to know the situation and rules of the use of the given material and, in particular, its fire resistance [41]. From the review article of D. de Silva et al., we learned that there is no complete information on the thermal properties of structural materials; therefore, the performances of the experimental results are of a great importance [42]. The use of fire-retardant impregnating materials and fire-retardant paints can be an important prescription for wooden load-bearing structures [43].

Based on a critical overview of the technical literature, it should also be noted that the load capacity of different supporting structures of buildings can be increased by different technical solutions, such as applying steel, polymer or cellulose fiber reinforcement materials. In this respect, one of the most important research activities is the examination of the fire resistance of load-bearing structures.

For this reason, O. Czoboly and co-authors addressed, in their study [44], improving the heat-resistant properties of concrete exposed to high temperatures using different fiber cocktail loadings. The use of fibers of different fiber materials (steel, polymer or cellulose)—due to the diversity of proposed technology and materials—is very diverse nowadays. V. Kodur et al., for example, performed, in their work [45], a numerical study in order to evaluate the fire resistance of concrete beams and slabs incorporating natural fiber-reinforced polymers. The importance of the relevant European Union standards in harmonizing test procedures and methods should also be emphasized.

In addition, the results of the authors' previous research on the subject [46,47] and well-founded fire safety standards provided significant information background in solving the scientific problem outlined above.

1.4. Presentation of the Research Objectives, Tasks and Limitation of the Scope of Article

The authors of this article—after the introduction of scientific problems—have identified the following main research objectives:

- performing a bending load test under the influence of fire on beams prepared from wood, steel and reinforced concrete materials;
- investigating the possibilities of strengthening the frame structures with carbon fiber lamellas, its effect on the load capacity and making proposals for the application of additional fire protection requirements.

In this article the authors planned to implement their research objectives in two main phases.

1. Firstly, the authors will present the calculations of the load capacities of three types of beams made of different materials under the influence of a fire lasting 180 min. The moment load capacity of the beams was assumed to be almost the same for easier comparison. The changes in the properties of the materials directly related to the bending load calculations are analyzed under the influence of fire.
2. Afterwards, assuming a fire load of one hour, after cooling down the materials, they will examine the possibility of reinforcing the beams with carbon fiber lamellas. Since the carbon fiber lamellas do not meet the fire protection requirements, they also propose additional fire protection solutions.

The authors will not take into account the physical and chemical properties of flammable dangerous substances and will not deal with paint coatings and other coatings for test materials; however, an analysis of the effects of these considerations can be part of further research work.

2. Materials and Methods

In this section, the authors will firstly deal with a presentation of the subject of their investigation, and then, they will elaborate the load capacity calculation procedures at high temperatures. Finally, they will introduce their research on reinforcement with carbon fiber lamellas.

2.1. Presentation of the Subject of the Investigation

In the introduction part of this study, the authors already determined that the subject of the study will be beams of floor systems prepared from three different contraction materials: wood, steel and reinforced concrete. Figure 1 shows that the three different cross-sections have different geometric dimensions due to the same moment load capacity.

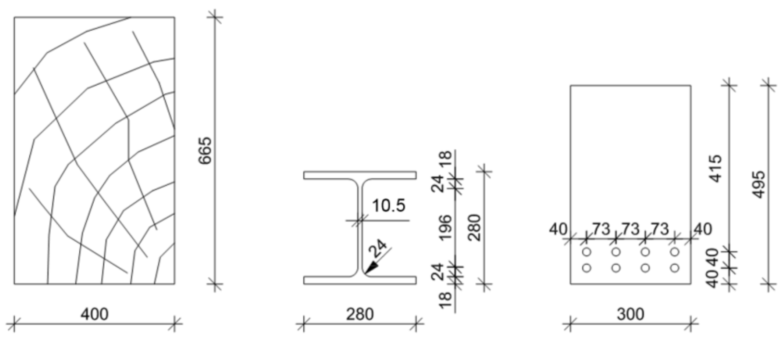

Figure 1. Cross-sections of beams made of wood, steel and reinforced concrete. Prepared by Ferenc Szabó.

The wood beam has a C30 quality rectangular cross-section, according to EN 338: 2016 standard "Structural timber. Strength classes" [48]. It is important to note that the cross-sectional dimensions of the wood beam are relatively large. They were included in the study only for the purpose of testing. In a real situation, of course, it is not customary to use such a cross-sectional size of solid wood. As for the steel beam, the authors selected a section of the first cross-section class, grade S275. The reinforced concrete beam was taken as a C30/37 rectangular cross-section with two bars of S500B quality at the bottom.

The authors also identified the fire protection standards related to each type of building material, which are as follows:

- The cross-sectional moment resistance of the wood beam can be calculated using Part 1-2: General—Structural fire design of EN 1995-1-2:2016 Eurocode 5: "Design of timber structures" (EN 1995-1-2:2016) [49].
- In the case of the steel beam, the authors use Part 1-2. "General rules—Structural fire design" of the EN 1993-1-2:2016 Eurocode 3: Design of steel structures—(EN 1993-1-2:2016) [50], which regulates the calculations of fire loads for steel structures.

- Based on Part 1-1: "General rules and rules for buildings" of standard EN 1992-1-2:2013 Eurocode 2: "Design of concrete structures" (EN 1992-1-2:2013) [51], the authors perform the relevant calculations of the reinforced concrete beam.

The authors consider the load capacity values obtained in this way as a benchmark, which are valid at room temperature.

As the next step, the authors examine the changes that occur as a result of the rising temperature. For this, the temperature–time curve must be recorded so that the temperature changes of the cross-sections over time can be followed. The temperature is taken based on the standard temperature–time curve based on the ISO-834 curve (ISO-834 curve) [52,53]. The evolution of temperature as a function of time in the case of the standard temperature–time curve based on the ISO-834 curve is described by the following equation:

$$\theta = 20 + 345 \cdot \log(8 \cdot t + 1) \quad (1)$$

where θ—temperature,

t—time of fire (min).

2.2. *Introduction of Load Capacity Calculation at High Temperatures*

In the following section, for all three examined structural materials, the authors define the basis of the calculation procedure for the load capacity at high temperatures.

2.2.1. The Behavior of the Wood Structure and Calculation of Load Capacity

Wood structures exposed to fire catch fire relatively quickly, and during their burning, a charred layer is formed on the surface exposed to the fire. The thickness of the layer increases at an approximately constant rate. The charred layer, which has practically no strength, causes a gradual decrease in the load-bearing capacity. Despite the fact that wood is a combustible material, it behaves very well against fire. Due to the nearly linear burning rate, the load capacity of wooden structures on fire can be easily determined. The fire resistance dimensions requires knowledge of the burning speed (β). It depends on the type of wood, which means the reduction of the cross-sectional dimensions by the unit of time during the fire resistance testing of the wooden support structures [54].

$$d_{char} = \beta \cdot t \quad (2)$$

where d_{char}—charring rate,

β—burning speed (mm/min),

t—time of fire (min).

The rate of charring also depends on the number of sides exposed to the fire and the type of wood. In our case, the carbonized layer formed on the lower, right and left sides of the test cross-section, which the authors did not take into account. The thickness of this layer increases linearly over time, so the load capacity decreases in parallel. Therefore, in the event of a fire, the degree of burning does not depend on the temperature. The exact description of the calculations can be found in the already referenced chapter of the EN 1995-1-2:2016 standard.

2.2.2. The Behavior of the Steel Structure and Calculation of Load Capacity

Due to its good thermal conductivity, the steel cross-section reaches high temperatures at almost all points. The most noticeable change is that the strength and stiffness characteristics of steel constantly decrease.

For the same stress level, there are larger deformations at higher temperatures. A distinction must be made between hot-rolled and cold-formed steels, because they behave differently when exposed to fire.

The yield stress of steel structure elements heated to a temperature θ after a time t due to fire is determined by the EN 1993-1-2:2016 standard from the values measured at a normal temperature. The standard reduces the yield strength of the raw material by the factor $k_{y,\theta}$

and applies partial (safety) factors for fire instead of factors for normal temperature. The values of the $k_{y,\theta}$ factor can be found in the mentioned standard. According to the standard, the partial factor that can be used in case of a fire is $\gamma_{M,fi}$ = 1.0 for the steel material. For bent beams, the standard allows the following approximation:

$$M_{fi,t,Rd} = k_{y,\theta} \cdot W(\frac{f_y}{\kappa_1 \cdot \kappa_2})/\gamma_{M,fi} \quad (3)$$

where $M_{fi,t,rd}$—moment in fire (N/mm^2),

$k_{y,\theta}$—reduction factor,

W—cross-section factor,

f_y—yield strength (N/mm^2),

κ_2 —constant exposed to fire from 3 sides are 0.7 and 1.0,

$\gamma_{M,fi}$—safety factor in fire 1.0.

κ_1 and κ_2 for unprotected beams exposed to fire from 3 sides are 0.7 and 1.0. The temperature values are read from the ISO-834 curve at certain intervals, and then, the $k_{y,\theta}$ reduction factor is interpolated based on this.

Since steel has a particularly good thermal conductivity, the temperature distribution can be assumed to be constant for the entire cross-section. Based on this, the steel's load capacity reduction can also be determined as a function of time.

The authors evaluate the calculation results in Section 3.

2.2.3. The Behavior of the Reinforced Concrete Beam Structure and Calculation

The properties of concrete deteriorate under the influence of fire. There are two main reasons for this. One is that the material structure of the concrete is transformed at high temperatures, and the other is that the surface of the concrete peels off in layers. The most important characteristic of concrete is that its compressive strength begins to decrease significantly around 400 °C. The strength of concrete decreases by 25% already at around 400 °C, and by increasing the temperature by another 200 °C, concrete loses more than 55% of its strength [55]. Deformations increase with the growing temperature. The deformation associated with failure increases by 0.5% per 200 °C. The changes in the compressive and tensile strengths of concrete due to fire have been investigated in many experiments. In general, strength values are obtained by multiplying the strength of concrete measured at a normal temperature by a factor read from a relative strength–temperature graph. The curve was determined from experiments. The standard EN 1992-1-2:2013 reducing factor was also established based on these diagrams.

The compressive strength is calculated using the following formula:

$$f_{ck}(\theta) = k_c(\theta) \cdot f_{ck}(20\ ^\circ\mathrm{C}) \quad (4)$$

where f_{ck} (θ)—characteristic value of the compressive strength at different temperatures,

k_c (θ)—reduction factor at different temperatures,

f_{ck}—characteristic value of the compressive strength at 20 °C.

At 400 °C, the concrete structure begins to lose a large amount of strength. It then decreases steadily for another 600 °C; after which, it practically completely loses its load-bearing capacity. Since concrete has less thermal conductivity than steel, a constant temperature distribution should not be assumed.

The temperature gradually decreases from the outer surface of the concrete to the inner surface. The steel inserts reach the temperature around them almost immediately. To demonstrate the calculation process, the authors took the 60-min moment resistance determination as an example. The temperature distribution can be determined from an experiment on a reinforced concrete beam with the same parameters. For that purpose, the authors used the work of Y, Zandi, O. Burnaz and A. Durmuş [56] and concluded that the beam was also exposed to heat from three sides. It should also be mentioned that, when dimensioning reinforced concrete structures for fire loads, the location of the reinforcing bars is crucial.

During the calculations, the authors use the zone method prescribed in the EN 1992-1-2:2013 standard. Firstly, the height of the pressed concrete zone is determined, which depends on the strength characteristics and their surfaces.

The strength can be corrected depending on the temperature, so the useful height in this case is as follows:

$$x_{c,60} = \frac{2A_{\phi,20} \cdot f_{yd,800} + 4A_{\phi,20} \cdot f_{yd,600} + 2A_{\phi,20} \cdot f_{yd,400}}{9x \cdot f_{cd,200} + 4x \cdot f_{cd,400} + 2x \cdot f_{cd,600} + x \cdot f_{cd,800} + x \cdot f_{cd,1000}} \tag{5}$$

where $X_{c,60}$—height (mm),
A—surface area (mm^2),
f_{yd}—yield strength of steel (N/mm^2),
f_{cd}—compressive strength of concrete (N/mm^2).

When determining the moment load capacity, it is also calculated with the changed properties of the concrete and steel. We determine the bending resistance, assuming that the inserts are in a ductile state:

$$M_{c.Rd.60} = (9x \cdot f_{cd,200} + 4x \cdot f_{cd,400} + 2x \cdot f_{cd,600} + x \cdot f_{cd,800} + x \cdot f_{cd,1000}) x_{c,60} (d - \frac{x_{c,60}}{2}) \tag{6}$$

where $M_{c.Rd.60}$—moment load capacity (N/mm^2),
f_{cd}—compressive strength of concrete (N/mm^2),
x—axis distance (mm),
$x_{c,60}$—compressive strength of concrete (N/mm^2),
$\gamma_{M,fi}$—safety factor in fire 1.0.

When determining the moment load capacity, it is also calculated with the changed properties of the concrete and steel. We determine the bending resistance, assuming that the inserts are in a ductile state.

The authors evaluate the calculation results in Section 3.1.

2.3. Introduction of Reseach on Reinforcement with Carbon Fiber Lamellas

In this part of the article, the authors shortly introduce the main information on the reinforcement solution of beams with carbon fiber lamellas and calculation methods for the determination of the load capacity at high temperatures.

2.3.1. Introduction of Technical Information on Reinforcement with Carbon Fiber Lamellas

One of the commonly used methods of strengthening building structures is the use of carbon fiber lamellas produced by drawn pressing. Due to its high load capacity, this system is excellent for strengthening structures. The method can be used for reinforced concrete, prestressed reinforced concrete and steel and wooden structures. The system consists of glue and the carbon fiber lamellas. This type of method is used, for example, in cases of an increase in useful loads, reinforcement of beams, aged or fire-damaged structures, reduction of crack sizes, structural system changes, beam cutouts and design errors [57]. With this method, in most cases, the elements that are damaged to a lesser extent can be reconstructed. The glue for fixing the carbon fiber lamella used for reinforcement melts at a relatively low temperature of around 150 °C. Therefore, the glued lamellas must be provided with additional fire protection, which ensures the protection of the lamellas for at least 90 min.

In our case, elements damaged to a lesser extent after fire damage can be reused with sufficient reinforcement, which is preceded by the preparation of the surfaces to reinforce them.

2.3.2. Load Capacity Calculation at High Temperatures after the Reinforcement of Wooden Beam with Carbon Fiber Lamellas

Our objective is to compensate for a 60-min fire load reduction with carbon fiber reinforcement. The moment resistance of the cross-section can be determined based on what was presented in the previous subsection. Figure 2. shows the cross-section of beam made of wood after reinforcement.

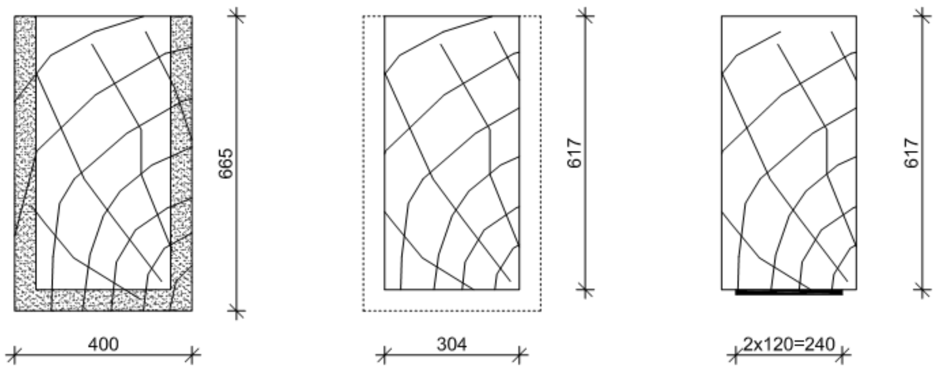

Figure 2. Cross-sections of beams made of wood after reinforcement. Prepared by Ferenc Szabó.

To calculate the lamella-reinforced beam, the authors took as a basis the determination of the moment load capacity of the reinforced concrete cross-sections.

In the first stress state, using the ideal cross-section, materials with different strength properties can be calculated. The calculation process begins with the determination of the ideal cross-section.

$$\alpha = \frac{E_f}{E_{0,mean}} \qquad A_{id} = A + \alpha \cdot A_f \tag{7}$$

where E_f—young modulus of lamella (N/mm^2),

$E_{o,\,mean}$—young modulus of wood (N/mm^2),

A_{id}—ideal cross-section (N/mm^2),

A—cross-section of wood (N/mm^2),

A_f—cross-section of lamella (N/mm^2).

After that, the static moment of the cross-section is calculated for the axis passing through the middle of the rectangle.

$$S_{id} = \left(\frac{h}{2} + \frac{t_f}{2}\right) \cdot A_f \cdot \alpha \tag{8}$$

where S_{id}—static moment (mm^3),

h—height of cross-section (mm),

t_f—thickness of lamella (mm),

A_f—cross-section of lamella (N/mm^2).

The distance and inertia of the center of gravity of the ideal cross-section can be determined using the following formula:

$$y_{id} = \frac{S_{id}}{A_{id}} \qquad I_{id} = \frac{b \cdot h^3}{12} + b \cdot h \cdot y_{id}^2 + \alpha \cdot A_f \cdot \left[\left(\frac{h}{2} + \frac{t_f}{2}\right) - y_{id}\right]^2 \tag{9}$$

where y_{id}—distance of the center of gravity (mm),

I_{id}—distance and inertia of the center of gravity (mm^3),

b—the width of the cross-section (mm),

h—height of cross-section (mm),

t_f—thickness of lamella (mm),

A_f—cross-section of lamella (N/mm^2).

Then, based on the calculated cross-section, the moment load capacity can also be determined.

$$M_{Rd} = \frac{\frac{I_{id}}{\left(\frac{h}{2}+\frac{t_f}{2}\right)-y_{id}}\cdot f_{t,0,k}}{\gamma_M}\cdot k_{mod} \tag{10}$$

where M_{Rd}—moment load capacity,

f_{t0k}—characteristic strength value of wood (N/mm^2),

γ_M—safety factor in fire 1,0,

k_{mod}—modification factor in fire,

I_{id}—distance and inertia of the center of gravity (mm^3).

2.3.3. Load Capacity Calculation at High Temperatures after the Reinforcement of Reinforced Concrete Beam with Carbon Fiber Lamellas

In the case of concrete, after a fire, for the sake of safety, the authors used an assumption based on the research work of A. Andre [58] that the remaining strength of the concrete is the same as the strength of the zones of the reinforced concrete beam exposed to fire for 60 min. In this case, we removed a concrete layer two cm thick from three sides of the beam to ensure proper adhesion to the lamella.

The calculations begin in line with the already mentioned product documentation, with the determination of the anchoring force. The formula used in the design guide is as follows:

$$N_{bfu} = 0.5 b_f k_b k_T \sqrt{E_f t_f f_{ctm}} \tag{11}$$

where b_f—the width of the reinforcing lamella in mm,

k_T—0.9 for outdoor structural elements where the temperature fluctuation is in the range of 20 °C and 30 °C,

E_f—modulus of elasticity of the reinforcing lamella in N/mm^2,

t_f—the thickness of the reinforcing lamella in mm,

f_{ctm}—the value of concrete surface tensile strength in N/mm^2,

b—the width of the beam in mm.

The bending resistance for 60 min changes as follows due to the glued lamella:

$$M_{c,Rd,m,f} = M_{c,Rd,m} + \left(\frac{h+t_f}{2}\right)\cdot N_{bfu} \tag{12}$$

where $M_{c.Rd.60}$—moment load capacity (N/mm^2),

N_{bfu}—anchoring force,

h—height of cross-section (mm),

t_f—the thickness of the reinforcing lamella in mm.

The authors evaluate the calculation results in Section 3.2.

3. Results and Discussion

In this part of the article, based on the calculation methods in Section 2, the authors first determine the results of the load capacity calculations and then examine the results of the tests related to the reinforcement of the beams damaged during the fire.

3.1. Results of Load Capacity Calculation at High Temperatures

The moment resistance values of the three beams with different materials can be seen in relation to the initial resistance in Figure 3.

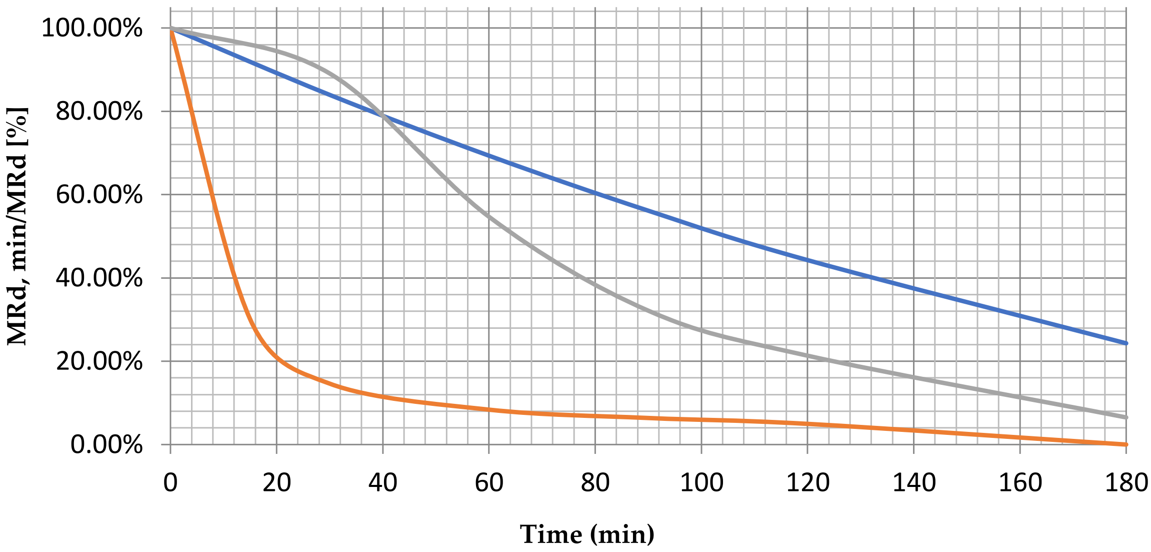

Figure 3. Load capacities of wood (blue line), steel (orange line) and reinforced concrete (grey line) beams as a function of time under the influence of fire. Prepared by Ferenc Szabó.

After analyzing the load capacity calculation results, the following main conclusions can be drawn:

1. The cross-section of the wood beam decreased continuously over time. Due to this, the load capacity of the wooden beam gradually decreased. The test also supports the claim that wood behaves well against fire. According to the calculations, the wooden beam performs best.
2. The steel cross-section proved to be very sensitive to fire, which was also visible on the curve. After about 15 min, the beam lost a significant part of its resistance. This material performs the worst according to the calculations.
3. The reinforced concrete cross-section initially performed well, but between 30 min and 60 min, it significantly lost its load capacity, and after that, it decreased even more. It can be said that reinforced concrete generally performs better than steel but worse than wood.

3.2. Results of Load Capacity Calculation at High Temperatures for Reinforced Structures

The results of the load capacity calculations at high temperatures for reinforced structures can be summarized by the following:

1. The load capacity of the reinforced cross-section increased by 25%, which can be satisfactory in most cases. The cost and labor requirements of the intervention are a fraction of the total replacement. However, the preparation of the surface is a key issue, as it is mandatory to follow the technology descriptions attached to the lamella.
2. In the case of hot-rolled steel cross-sections, post-fire reinforcement is not customary, since the cross-section practically completely recovers its load-bearing capacity after cooling down for 60 min after the fire, and if the structure bears such a load that results in even a small amount of utilization, then it is destroyed during the fire. In this case, the only solution is a complete replacement. In the case of steel structures, these two extreme situations typically occur.
3. As a result of the reinforcement, the bending capacity of the cross-section increased by around 50%. Again, it can be said that, even in this case, the costs of the complete replacement are a fraction of the costs of the reinforcement, so it is worth using.

The proposed design is shown in Figure 4.

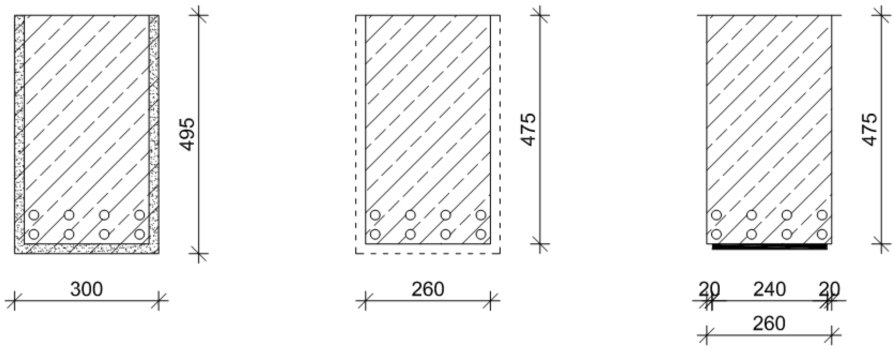

Figure 4. The reinforced concrete beam. Prepared by Ferenc Szabó.

4. Based on Figure 4, it can be concluded that the amount of concrete covering can be significantly reduced. It is likely that reinforcement with concrete next to it would be more resistant in the long term. However, in the case of this research, the aim of the authors was to compare the behaviors of three different materials with the same reinforcement form.

3.3. Discussion Concerning the Construction Materials's Fire Resistance Tests

During the implementation of the research work and verification of the results, several important design aspects of the test methodology were taken into account by the authors, which are as follows:

1. The primary research objective of the study was to compare the behaviors of different building materials against fire. When determining the size of the test materials, the primary consideration was that the load capacities of the tested elements should be the same. As a result, the authors indeed used a larger size of wooden beam than usual. Thanks to this, the behaviors of the structural materials could be compared much better. According to the assumptions of the authors, the use of a few beams would have influenced the test results, mainly due to the larger combustion surface.
2. Flammable dangerous substances stored in chemical warehouses typically have a wide range of physical and chemical properties. The heat load of the dangerous substances present is taken into account—among other things—during the consequence assessments of major accident scenarios.

Various software tools are available for the monitoring of the physical effects of events, which can be used for the performances of more precise fire resistance calculations and tests.

In the case of the present research work, the authors used the method validated by the already presented test standard. Thus, for example, in the case of reinforced concrete and wooden structures with a different types of fire curves, the calculations should be verified by using individual experiments. In the case of wood and reinforced concrete materials, the standard accurately records the applicable fire curve. This is especially true in the case of reinforced concrete beams, as the change in the nature of the fire can also significantly affect the strength of the concrete. It was decided that, in order to make the experiments of three separate materials comparable, it was necessary to standardize the parameters, so that only the heat load of the samples could be used for the purposes of the analysis.

Therefore, the authors did not take into account the widely different properties of the dangerous substances stored at chemical warehouses for the purposes of the present study. At the same time, this technical aspect can be the basis for further research.

3. Various paint coatings or other coatings are available and used for the providence of fire resistance of steel structures that guarantee the fire resistance of these elements for a period of 30–60 min.

By using paints and other special coatings, the degree of comparability of material behaviors decrease. For example, in the case of paints and coatings, these agents will be the dominant ones, and the behaviors of the materials against fire are primarily determined by the coatings. However, the objective of the present study was to compare the fire behaviors of sample structures without coatings.

After the present basic tests, it is possible to examine these additional safety features, but this should be the subject of further research work.

3.4. Discussion Related to Warehouses Dealing with Dangerous Substances

In the following, the authors examine how the outputs of the tests completed in this study (Section 2) are related to the harmful effects of dangerous substances and their related fire protection aspects.

The authors already carried out a general literature review in the introduction section of this article (Sections 1.2 and 1.3) when they covered a few important theoretical aspects of industrial fire protection. The issue of industrial fire protection raises several fire protection planning and design issues in the case of processing industry and logistics activities dealing with dangerous substances. A large part of the scientific problem is related to the so-called "built-in fire protection" of production and warehouse storage buildings. The use of active and passive fire protection systems depends significantly on the behaviors of materials incorporated in production and warehouse structures at high temperatures.

In accordance with our experience, chemical warehouses are typically built from steel or reinforced concrete structures. In their case, in the event of a fire, the hazardous properties of the dangerous substances released must also be taken into account, which may cause additional damage to warehouse structures.

The examinations clearly prove that, if a fire occurs in a chemical warehouse of steel contraction and there is no effective passive protection fire protection system (for example, a thermal foaming and fire protection coating system) and/or active fire protection system (like an automatic signaling and extinguishing system), then the intervening fire brigade does not have enough time to control the fire. In this case, good firefighting practice is the application of "controlled burning" measures. Compared to buildings with steel structures, reinforced concrete structures have a better chance of being restored after a fire, but for this case, cost-effective "built-in fire protection measures" must be introduced.

Another important issue is the possible environmental damage that occurs as a secondary effect during the intervention. This would be the spilling out of contaminated fire water and propagation of released dangerous substances. In the case of fire in reinforced concrete warehouses, the fire brigade theoretically has enough time to start extinguishing procedures; however, on those occasions, special attention must be paid to the harmful effects of the chemical vapors—generated at high temperatures—on the concrete structure.

Finally, a question arises regarding the determination of research directions in the possible future. According to the experiences of the authors, researchers are extensively involved in examining the fire resistance of load-bearing structures of individual building structures. At the same time, scientific studies concerning the chemical resistance of building structures are available only to a limited extent. Therefore, it is also necessary to study and model the combined effects of high-temperature steam and thermal effects on building structures.

4. Conclusions

Based on the research carried out in this study, the following final conclusions can be drawn:

1. The material characteristics of the wood, steel and reinforced concrete cross-sections and their moment capacities were modified according to the relationships applicable in the event of a fire, thus obtaining the characteristic behaviors of the three materials under fire loads. Wood behaves very well under fire loads, unlike steel, which can only last half an hour without fire protection.
2. This research work was followed by the examination of the reinforcement procedure, when carbon fiber lamellas were used for the purposes of the test. In the case of steel,

it is not appropriate to talk about reinforcement after a fire, because if the steel has not been destroyed by the fire, it can be used without reinforcement due to its residual load capacity.

3. By reinforcing the beam structures with carbon fiber lamellas, we can avoid the complete replacement of the structure. A reinforced structure, of course, requires even stricter maintenance than the original. The structure will have to be checked more frequently than the original one.
4. In the event of a fire in chemical warehouses, in addition to the thermal effect, the vapors of the flammable dangerous substances also damage the structural elements, so the possibilities for firefighting interventions are also reduced.
5. The present study can be used by designers of chemical warehouses, because fires of flammable substances have a significantly higher impact on the beams of roof structures. Therefore, the selection of the correct building structure materials can be an important design consideration.

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References

1. Christofi, M.; Pereira, V.; Vrontis, D.; Tarba, S.; Thrassou, A. Agility and Flexibility in International Business Research: A Comprehensive Review and Future Research Directions. *J. World Bus.* **2021**, *56*, 101194. [CrossRef]
2. Min, H. Smart Warehousing as a Wave of the Future. *Logistics* **2023**, *7*, 30. [CrossRef]
3. Santhi, R.; Muthuswamy, A.P. Pandemic, War, Natural Calamities, and Sustainability: Industry 4.0 Technologies to Overcome Traditional and Contemporary Supply Chain Challenges. *Logistics* **2022**, *6*, 81. [CrossRef]
4. Ferreira, C.; Cardoso, C.; Travassos, M.; Paiva, M.; Pestana, M.; Lopes, J.M.; Oliveira, M. Disorders, Vulnerabilities and Resilience in the Supply Chain in Pandemic Times. *Logistics* **2021**, *5*, 48. [CrossRef]
5. Szakál, B.; Cimer, Z.S.; Kátai-Urbán, L.; Sárosi, G.Y.; Vass, G.Y. *Industrial Safety II: Consequences and Risks of Major Accidents involving Dangerous Substances*; TERC: Budapest, Hungary, 2013; p. 182. (In Hungarian)
6. Agreement Concerning the International Carriage of Dangerous Goods by Road, ADR. Available online: https://unece.org/transport/standards/transport/dangerous-goods/adr-2023-agreement-concerning-international-carriage (accessed on 25 July 2023).
7. UN Economic Commission for Europe. Convention on the Transboundary Effects of Industrial Accidents—As Amended on 15 December 2015. Available online: https://unece.org/info/Environment-Policy/Industrial-accidents/pub/21645 (accessed on 5 July 2023).
8. Official Journal of the European Union. Directive 2012/18/EU of the European Parliament and of the Council of 4-th of July 2012 on the Control of Major-Accident Hazards Involving Dangerous Substances, Amending and Subsequently Repealing Council Directive 96/82/EC. Available online: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0001:0037:EN:PDF (accessed on 5 July 2023).
9. Directorate-General Joint Research Centre of the European Commission. The Minerva Portal of the Major Accident Hazards Bureau. Available online: https://emars.jrc.ec.europa.eu/en/emars/statistics/statistics (accessed on 5 July 2023).
10. Campbell, R. *Warehouse Structure Fires*; National Fire Protection Association: Quincy, MA, USA, 2022; Available online: https://www.nfpa.org/News-and-Research/Data-research-and-tools/Building-and-Life-Safety/Warehouse-Structure-Fires (accessed on 25 July 2023).
11. Heinälä, M.; Gundert-Remy, U.; Wood, M.H.; Ruijten, M.; Bos, P.; Zitting, A.; Bull, S.; Russell, D.; Nielsen, E.; Cassel, G.; et al. Survey on methodologies in the risk assessment of chemical exposures in emergency response situations in Europe. *J. Hazard. Mater.* **2013**, *244*, 545–554. [CrossRef]

12. Directorate-General Joint Research Centre of the European Commission Major Accident Hazard Bureau. Learning from Emergency Response—Evacuation and Sheltering. Ispra, Italy. 2015. Available online: https://minerva.jrc.ec.europa.eu/en/shorturl/minerva/10_mahb_bulletin_no10_emergency_response_part1mwclean (accessed on 25 July 2023).
13. Mannan, S. *Lees' Loss Prevention in the Process Industries: Hazard Identification, Management and Control*; Butterworth-Heinemann: Kidlington, Oxford, UK, 2012; p. 3776.
14. Regulation (EC) No 1272/2008 of the European Parliament and of the Council of 16 December 2008 on Classification, Labelling and Packaging of Substances and Mixtures, Amending and Repealing Directives 67/548/EEC and 1999/45/EC, and Amending Regulation (EC) No 1907/2006. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008R1272 (accessed on 25 July 2023).
15. National Institute of Public Health and the Environment. Reference Manual Bevi Risk Assessments Version 3.2.—Introduction. Netherlands. 2009. p. 23. Available online: https://www.rivm.nl/documenten/reference-manual-bevi-risk-assessments-version-32 (accessed on 30 June 2021).
16. National Institute of Public Health and the Environment. Methods for the Calculation of Physical Effects. CPR 14E. Available online: https://content.publicatiereeksgevaarlijkestoffen.nl/documents/PGS2/PGS2-1997-v0.1-physical-effects.pdf (accessed on 25 July 2023).
17. Det Norske Veritas, QRA Software—Safety. Available online: https://www.dnv.com/services/qra-software-safeti-1715 (accessed on 25 July 2023).
18. National Institute of Public Health and the Environment. Guidelines for Quantitative Risk Assessment. CPR 18E. Available online: https://content.publicatiereeksgevaarlijkestoffen.nl/documents/PGS3/PGS3-1999-v0.1-quantitative-risk-assessment.pdf (accessed on 25 July 2023).
19. Burke, R. *Fire Protection: Systems and Response*; CRC Press: Boca Raton, FL, USA, 2007. Available online: https://books.google.hu/books?hl=hu&lr=&id=R8ahgLlUTLEC&oi=fnd&pg=PP1&ots=MrE1RdzCxD&sig=wRt_VqXpt234DJDSzin7BBwyypY&redir_esc=y#v=onepage&q&f=false (accessed on 25 July 2023).
20. UN Economic Commission for Europe. Safety Guidelines and Good Practices for the Management and Retention of Firefighting Water. Geneva, 2019. Available online: https://unece.org/fileadmin/DAM/env/documents/2019/TEIA/Publication/1914406E_web_high_res.pdf (accessed on 25 July 2023).
21. GMBI. TRGS 510—Technical Rules for Hazardous Substances. Storage of Hazardous Substances in Nonstationary Containers. 2013. Available online: https://www.baua.de/EN/Service/Legislative-texts-and-technical-rules/Rules/TRGS/pdf/TRGS-510.pdf?__blob=publicationFile&v=2 (accessed on 25 July 2023).
22. CEFIC. 2022 Warehouse—Questionnaire & Guidelines. Available online: https://www.sqas.org/download-questionnaire.php (accessed on 25 July 2023).
23. VROM Ministry of Housing, Spatial Planning and the Environment. PGS-programmaraad. PGS 15. Opslag van Verpakte Gevaarlijke Stoffen. Hague. 2016. Available online: https://content.publicatiereeksgevaarlijkestoffen.nl/documents/PGS15/PGS_15_2016_versie_1_0_sept_2016_definitief.pdf (accessed on 25 July 2023).
24. BG RCI. Storage of Hazardous Substances. 2013. Available online: https://www.vci.de/vci/downloads-vci/m062e-code-of-practice-storage-of-hazardous-substances.pdf (accessed on 25 July 2023).
25. Szakál, B.; Cimer, Z.S.; Kátai-Urbán, L.; Sárosi, G.Y.; Vass, G.Y. *Methodological Manual for Experts Involved in the Prevention of Major-Accident Hazards Involving Dangerous Substances*; HVESZ: Budapest, Hungary, 2020; p. 78. (In Hungarian)
26. Zhang, C. Review of Structural Fire Hazards, Challenges, and Prevention Strategies. *Fire* **2023**, *6*, 137. [CrossRef]
27. Kodur, V.; Kumar, P.; Rafi, M.M. Fire hazard in buildings: Review, assessment and strategies for improving fire safety. *PSU Res. Rev.* **2019**, *4*, 1–23. [CrossRef]
28. Cimer, Z.; Vass, G.; Zsitnyányi, A.; Kátai-Urbán, L. Application of Chemical Monitoring and Public Alarm Systems to Reduce Public Vulnerability to Major Accidents Involving Dangerous Substances. *Symmetry* **2021**, *13*, 1528. [CrossRef]
29. Fire Brigades Union. Fatal Accident Investigation. 2007. Available online: https://logic.sf.bg.ac.rs/wp-content/uploads/LOGIC_2022_ID_30.pdf (accessed on 25 July 2023).
30. UK NFCC. National Fire Chiefs Council. Control measure—Controlled Burning. Available online: https://www.ukfrs.com/guidance/search/controlled-burning (accessed on 25 July 2023).
31. Zhang, C. Analysis of Fire Safety System for Storage Enterprises of Dangerous Chemicals. *Procedia Eng.* **2018**, *211*, 986–995. [CrossRef]
32. Koivisto, R.; Nielsen, D. FIRE—A database on chemical warehouse fires. *J. Loss Prev. Process Ind.* **1994**, *7*, 209–215. [CrossRef]
33. Ju, W.H. Study on Fire Risk and Disaster Reducing Factors of Cotton Logistics Warehouse Based on Event and Fault Tree Analysis. *Procedia Eng.* **2016**, *135*, 418–426. [CrossRef]
34. Kang, R.; Gui Fu, G.; Yan, J. Analysis of the Case of Fire Fighters Casualties in the Building Collapse. *Procedia Eng.* **2016**, *135*, 343–348. [CrossRef]
35. Odeen, K. Fire resistance of wood structures. *Fire Technol.* **1985**, *21*, 34–40. [CrossRef]
36. Mackiewicz, M.; Krentowski, J.R.; Knyziak, P.; Kowalski, R. The influence of the fire temperature on the condition of steel roof structure. *Eng. Fail. Anal.* **2023**, *46*, 107080. [CrossRef]
37. Lubloy, E. How does concrete strength affect the fire resistance? *J. Struct. Fire Eng.* **2020**, *11*, 311–324. [CrossRef]

38. Nguyen, M.H.; Ouldboukhitine, S.-E.; Durif, S.; Saulnier, V.; Bouchair, A. Passive fire protection of steel profiles using wood. *Eng. Struct.* **2023**, *275 Pt A*, 115274. [CrossRef]
39. Chaturvedi, S.; Vedrtnam, A.; Youssef, M.A.; Palou, M.T.; Barluenga, G.; Kalauni, K. Fire-Resistance Testing Procedures for Construction Elements—A Review. *Fire* **2023**, *6*, 5. [CrossRef]
40. Sun, X.; Cai, N.; Zhang, W. Discussing the development of domestic and foreign fire protection technical regulation and fire protection technical standard systems. *J. Saf. Sci. Resil.* **2023**, *4*, 26–29. [CrossRef]
41. Lucherini, A.; Maluk, C. Intumescent coatings used for the fire-safe design of steel structures: A review. *J. Constr. Steel Res.* **2019**, *162*, 105712. [CrossRef]
42. De Silva, D.; Nuzzo, I.; Nigro, E.; Occhiuzzi, A. Intumescent Coatings for Fire Resistance of Steel Structures: Current Approaches for Qualification and Design. *Coatings* **2022**, *12*, 696. [CrossRef]
43. Zmaha, M.I.; Pozdieiev, S.V.; Zmaha, Y.V.; Nekora, O.V.; Sidnei, S.O. Research of the behavioral of the wooden beams with fire protection lining under fire loading. In Proceedings of the International Scientific Conference Energy Efficiency in Transport (EET 2020), Kharkiv, Ukraine, 18–20 November 2020. [CrossRef]
44. Czoboly, O.; Lublóy, É.; Hlavička, V. Fibers and fiber cocktails to improve fire resistance of concrete. *J. Therm. Anal. Calorim.* **2017**, *128*, 1453–1461. [CrossRef]
45. Kodur, V.; Venkatachari, S.; Bhatt, P.; Matsagar, V.A.; Singh, S.B. Fire Resistance Evaluation of Concrete Beams and Slabs Incorporating Natural Fiber-Reinforced Polymers. *Polymers* **2023**, *15*, 755. [CrossRef] [PubMed]
46. Szabó, F.; Lublói, É. Examination of wooden, reinforced concrete and steel beams under the influence of fire. *Véd. Kat. Szemle.* **2014**, *21*, 13–17. (In Hungarian)
47. Kátai-Urbán, L.; Szabó, Á. Evaluation of the industrial safety regulatory environment of dangerous goods warehouse logistics. *Hadtudomány* **2014**, *24*, 115–125. (In Hungarian)
48. *EN 338:2016*; Structural Timber—Strength Classes. CEN: Brussels, Belgium, 2016.
49. *EN 1995-1-2:2016*; Eurocode 5: Design of Timber Structures—Part 1-2: General—Structural Fire Design. CEN: Brussels, Belgium, 2016.
50. *EN 1993-1-2:2013*; Eurocode 3: Design of Steel Structures—Part 1-2: General Rules—Structural Fire Design. CEN: Brussels, Belgium, 2016.
51. *EN 1992-1-2:2013*; Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings. CEN: Brussels: Belgium, 2013.
52. *ISO 834-10:2014*; Fire Resistance Tests—Elements of Building Construction—Part 10: Specific Requirements to Determine the Contribution of Applied Fire Protection Materials to Structural Steel Elements. ISO: Geneva, Switzerland. 2014. Available online: https://www.iso.org/obp/ui/en/#iso:std:iso:834:-10:ed-1:v1:en (accessed on 25 July 2023).
53. Promat. International Fire Curves—Useful Tool for Designing Fire Safety. Available online: https://www.promat.com/en/tunnels/your-project/expert-area/159981/international-fire-curves-fire-safety/ (accessed on 25 July 2023).
54. The International Federation for Structural Concrete. Fib Bulletin 46: Fire Design of Concrete Structures—Structural Behavior and Assessment. 2008. Available online: https://www.fib-international.org/publications/fib-bulletins/fire-design-of-concrete-structures-structural-behaviour-and-detail.html (accessed on 25 July 2023).
55. Lublóy, É.; Mészáros, D.T.; Takács, L.G.; Cimer, Z.; Norbert, H. Examination of the fire performance of wood materials treated with different precautions. *J. Therm. Anal. Calorim.* **2023**, *148*, 4129–4140. [CrossRef]
56. Zandi, Y.; Burnaz, O.; Durmuş, A. Determining the Temperature Distributions of Fire Exposed Reinforced Concrete Cross-Sections with Different Methods. *Res. J. Environ. Earth Sci.* **2012**, *4*, 782–788.
57. Sika. CarboDur Composite Strengthening Systems. Technical Manual. Available online: https://gcc.sika.com/en/documents-resources/pds.html (accessed on 25 July 2023).
58. André, A. Fibres for Strengthening of Timber Structures. Luleå Uiversity of Technology, Luleå. 2006. Available online: https://www.researchgate.net/publication/251494186_Fibres_for_Strengthening_of_Timber_Structures (accessed on 25 July 2023).