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Temperature distribution during a fire in a glued laminated timber beam with holes

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ABSTRACT:
Currently, due to the high requirements regarding the ecology of the solutions used in construction, the use of wood for the construction of structural elements is experiencing a renaissance. Glued laminated wood is most often used for the construction of frame structures. In the case of high beams, it is possible to make holes in the beams to better use the space. Such holes weaken the load-bearing capacity, but they can also cause more unfavorable temperature distributions during a fire, which can result in faster charring of the wood and a decrease in the mechanical properties of the wood. The article presents a numerical analysis of beams with round and square holes. The comparative beam was a beam without holes. The analyzed beams were subjected to a thermal analysis of the time-varying fire load using a heat flux. The gas temperatures were calculated based on the ISO fire curve. The use of holes allowing for the conduction of various installations and the use of space negatively affects the temperature distributions during a possible fire. More unfavorable temperature distributions occur in beams with square holes.

KEYWORDS:
wood; numerical analysis; fire load; openings; fire

1. Introduction

Nowadays, a lot of attention is paid in many areas to the ecological nature of the solutions used in construction [1]. In relation to the above, wood is currently experiencing a renaissance. It is often used to build various objects, both with a frame structure and wall structure [2]. In the case of massive structures, a frequently used type of wooden elements is cross-laminated timber (CLT), while for the construction of frame structures, glued laminated timber (GLT) is most often used [3].

In the case of building structures using glued laminated timber girders, the spans of which are large, the height of the girder must also be relatively large. This space can be used to carry out various installations by making technological holes in the beam [4, 5]. The holes must be suitably located because they weaken the load-bearing capacity of the element. In order to strengthen the zone near the holes, reinforcement in various forms can be used [4-8].

In the case of wooden elements, an important aspect is the analysis of the fire resistance of the designed elements, as wood is a flammable material [9]. This may be particularly important when designing elements with holes [10], because flames during a fire can more easily penetrate the element through the hole, which can cause faster charring and a decrease in strength properties through the evaporation of water into the interior of the cross-section, and consequently a decrease in the mechanical properties. The aim of the article is to conduct a numerical analysis

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of the temperature distribution in beams with round and square holes and to compare the temperature distributions to a beam without an opening.

2. Thermal assumptions

The analysis was carried out using the methodology presented in Eurocode 0 [11] and Eurocode 5 [12]. It is based on the load of the analyzed element with a heat flux $\dot{h}_{net}$ (formula (1)) consisting of two components: convective flux $\dot{h}_{net,c}$ (formula (2)) and radiation flux $\dot{h}_{net,r}$ (formula (3)). The gas temperature can be determined using various fire curves, which are also presented in the aforementioned Eurocodes. The analysis in this article uses the ISO fire curve (Fig. 1), which is the most common for the analysis of building elements.

$$\dot{h}_{net} = \dot{h}_{net,c} + \dot{h}_{net,r} \tag{1}$$

$$\dot{h}_{net,c} = \alpha_c\left(\Theta_g - \Theta_m\right) \tag{2}$$

$$\dot{h}_{net,r} = \Phi\varepsilon_m\varepsilon_f\sigma[(\Theta_r + 273)^4 - (\Theta_m + 273)^4] \tag{3}$$

where:
α_c – heat flow coefficient [W/m^{2}K],
Θ_g – gas temperature during fire [°C],
Θ_m – surface temperature [°C],
Φ – observation coefficient,
ε_m – element surface emissivity,
ε_f – effective fire emissivity,
σ – Stefan-Boltzmann constant [W/m^{2}K^4],
Θ_r – effective fire radiation temperature [°C].

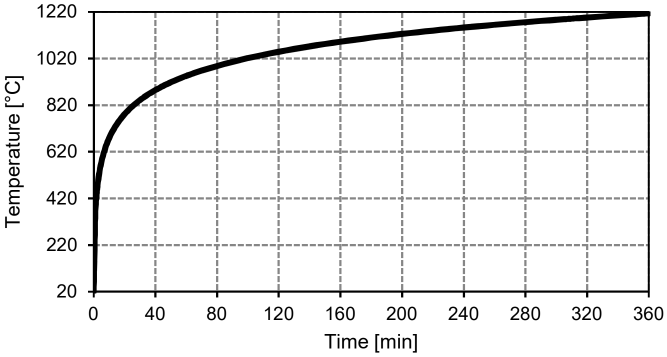

Fig. 1. Standard time-temperature curve (ISO 834-1:1999)

3. Numerical analysis

3.1. Thermal material data for timber

In this task, only beams made of wood were analyzed. Material data in the thermal range were adopted based on Eurocode 5 [12] and are presented in Figures 2-4.

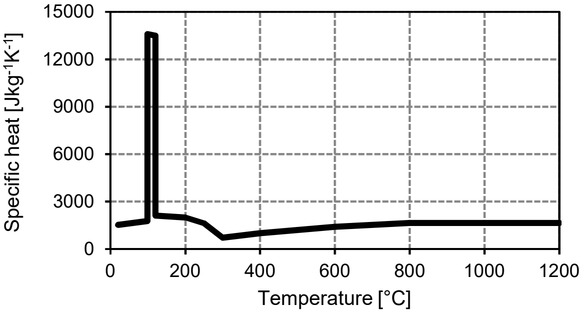

Fig. 2. Specific heat of wood depending on temperature (EN 1995-1-2)

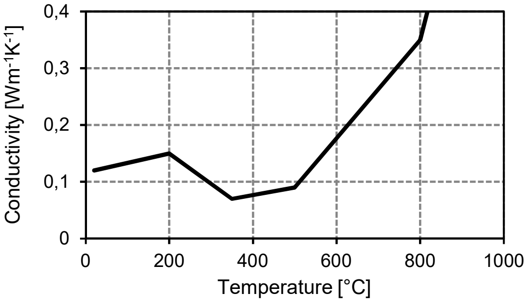

Fig. 3. Thermal conductivity of wood depending on temperature (EN 1995-1-2)

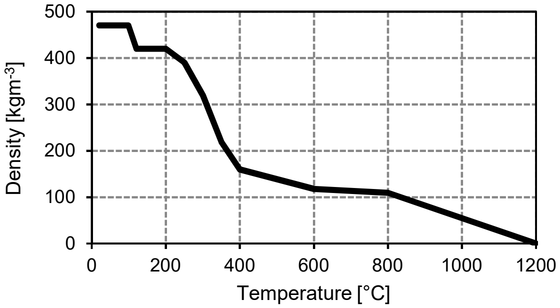

Fig. 4. Wood density depending on temperature (based on EN 1995-1-2)

3.2. Numerical model

The numerical model was created in ANSYS. The geometry of all tested beams was created using the Space Claim module. Three variants were analyzed: a beam without openings, a beam with a circular opening and a beam with a square opening (Fig. 4). Numerical calculations were performed in the Transient Thermal module. Three models were made using SOLID70 elements. This is an 8-node element with only one degree of freedom, which is temperature. On each tested beam, a heat flux load modeled as convection and radiation was assumed. The action of convection and radiation was assumed on three surfaces: two side surfaces and the bottom of the beam. The upper surface of the beam remained unloaded. Free access of flames was assumed also inside the opening. Three surfaces were loaded, and in the case of beams with openings, the interior of the openings (Fig. 5). The calculations were meticulously divided into many steps to ensure appropriate convergence and accuracy of the calculations due to the change in gas temperature over time. The gas temperature was assigned to each calculation step and calculated based on the ISO fire curve. The numerical models consisted of three spatial beams of equal dimensions. In the middle of the span of two of them, a square and a circular opening were modeled. The third beam is a comparative beam without any opening. The length of the modeled beams was 4.5 m and the cross-section was 34 cm × 72 cm. The dimension of the square opening was 40 cm and the dimension of the circular opening was modeled with a diameter of 40 cm.

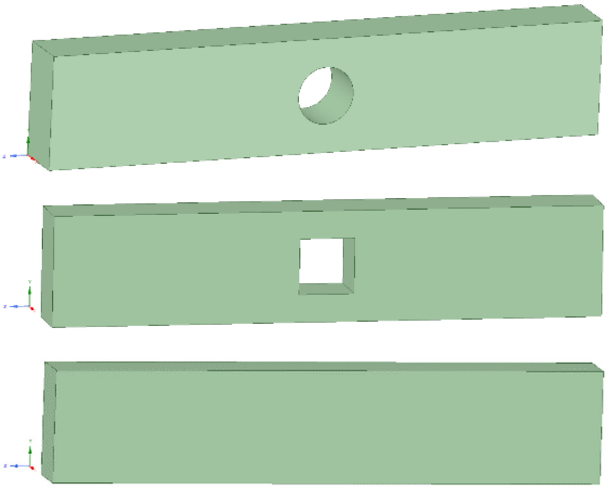

Fig. 4. Analyzed beam models

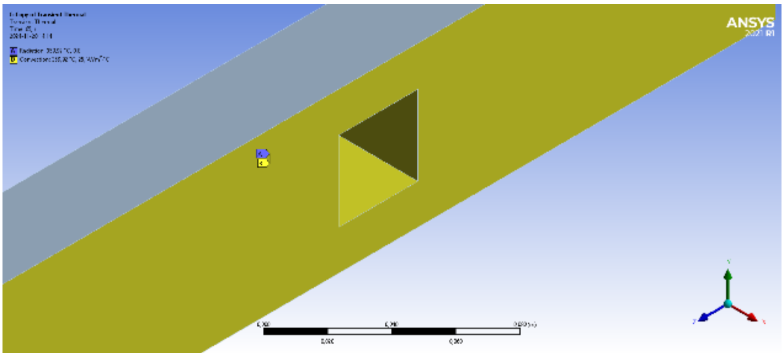

Fig. 5. Thermal boundary conditions

4. Results and discussion

Based on the calculations, the temperature distributions in the analyzed beams were determined (Figs. 6-9). The analyses were carried out for beams with a round and square opening. The results were compared with a beam without openings. In the temperature distributions presented in Figures 6-9, temperatures above 300 °C are marked in gray. Above this temperature, it is assumed that the wood is charred and has no mechanical properties. Based on Figure 6, it can be seen that lower temperatures occur in beams with a round opening, which causes the charring of the cross-section to occur more slowly.

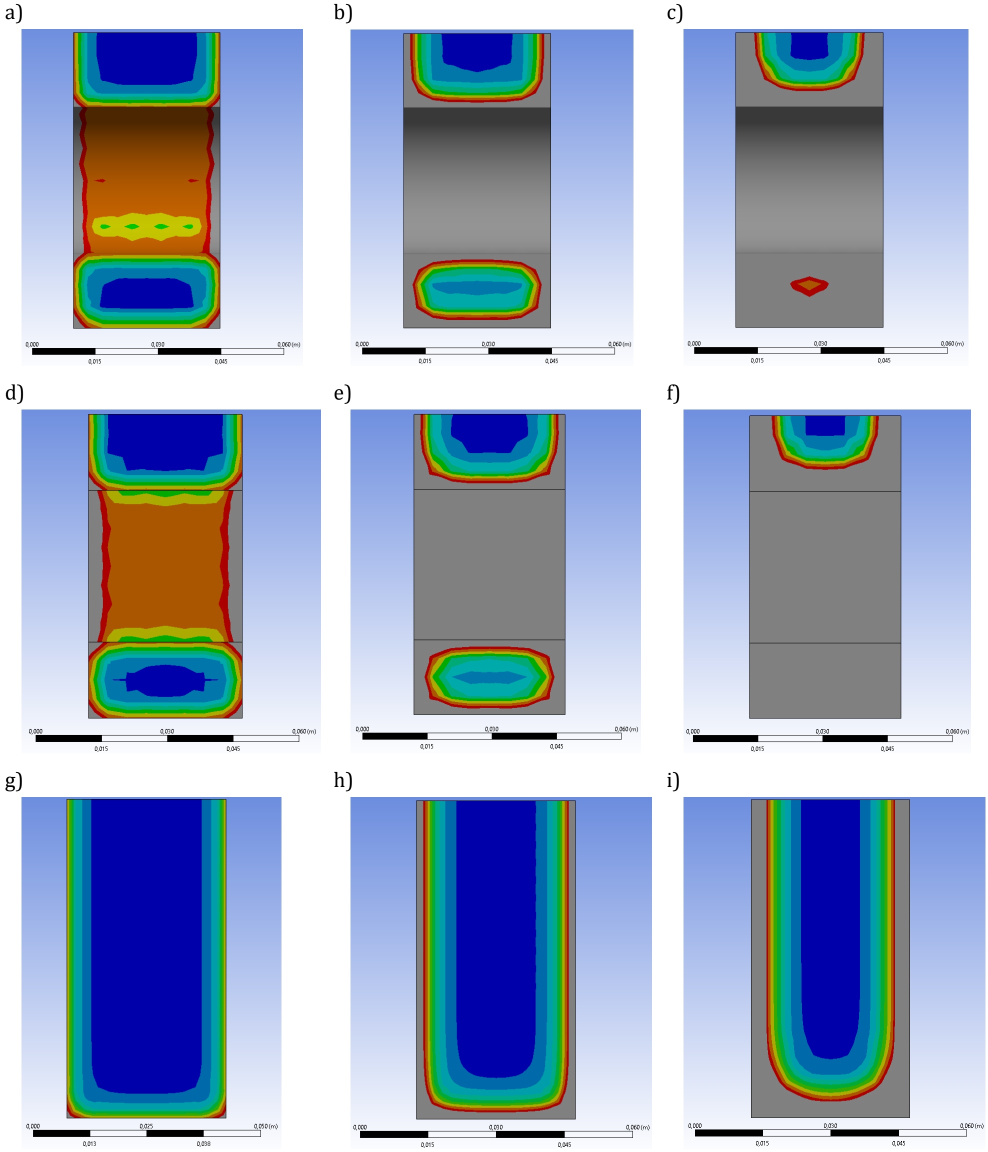

Fig. 6. Temperature distributions in the tested beams at the locations of openings and in the comparative beam: a) beam with a circular opening in the 90th second of the fire, b) beam with a circular opening in the 180th second of the fire, c) beam with a circular opening in the 360th second of the fire, d) beam with a square opening in the 90th second of the fire, e) beam with a square opening in the 180th second of the fire, f) beam with a square opening in the 360th second of the fire, g) beam without openings in the 90th second of the fire, h) beam without openings in the 180th second of the fire, i) beam without openings in the 360th second of the fire

Figure 7 shows the temperature distributions in the cross-sections of beams with holes. The cross-sections shown are 10 mm away from the edge of the hole. Comparing the temperature distributions with the beam without holes (Fig. 6a, 6b, 6c) shows the unfavorable influence of holes on the temperature distributions. The temperatures are further more favorable in the case of the beam with a round hole. As shown in Figures 8 and 9, the temperature increases faster at the edges of convex holes due to the increased penetration of the cross-section by the fire.

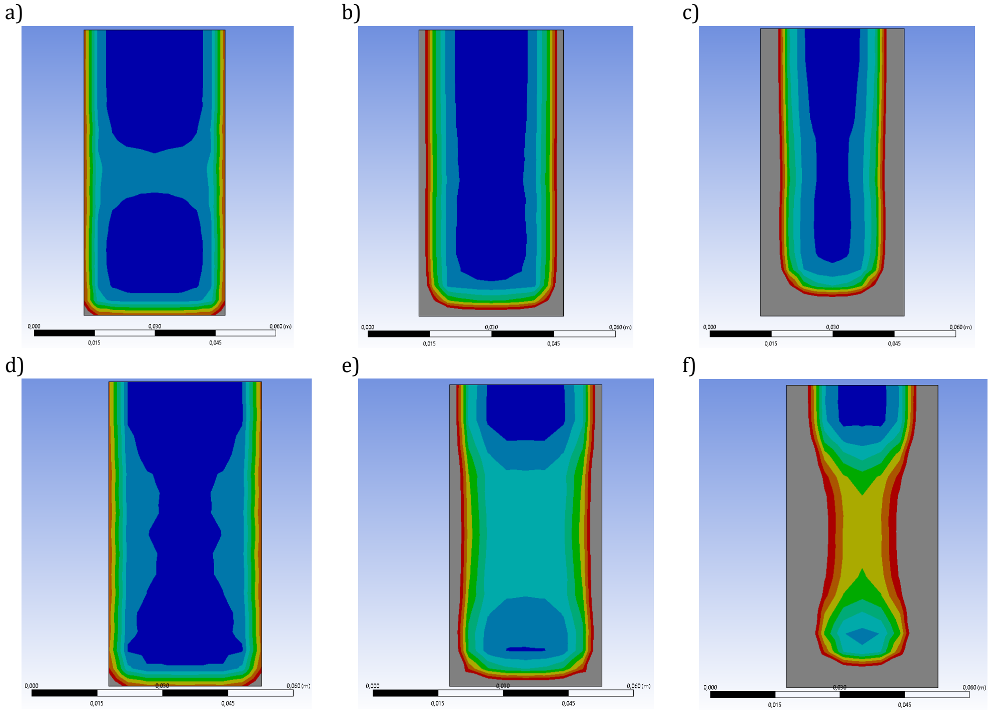

Fig. 7. Temperature distributions in beams with openings in the cross-section located 10 mm from the edge of the opening: a) beam with a circular opening in the 90th second of the fire, b) beam with a circular opening in the 180th second of the fire, c) beam with a circular opening in the 360th second of the fire, d) beam with a square opening in the 90th second of the fire, e) beam with a square opening in the 180th second of the fire, f) beam with a square opening in the 360th second of the fire

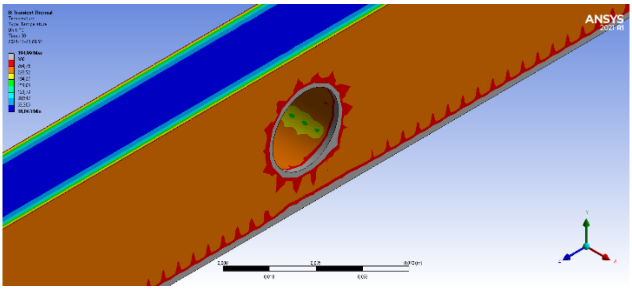

Fig. 8. Temperature distribution on the surface of a beam with a round hole

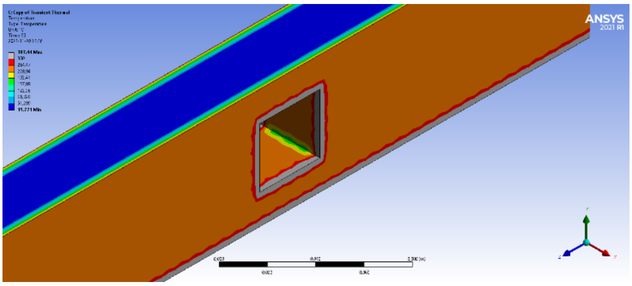

Fig. 9. Temperature distribution on the surface of a beam with a square hole

5. Conclusions

The article presents a thermal analysis simulating fire conditions. The analysis was performed on beams with round and square openings. For comparison, a beam without openings was analyzed. The presence of openings in beams adversely affects the temperature distribution, significantly increasing the rate of cross-section charring. This is related to the penetration of fire into the opening. A more unfavorable temperature distribution occurs in beams with a square opening. If, during the design of structural timber elements, it is necessary to make openings for technological reasons, attention should be paid to the significantly increased rate of cross-section charring around the openings. In addition, it is suggested to make circular openings, if possible due to better temperature distributions.

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Rozkład temperatur podczas pożaru w belce z drewna klejonego warstwowo z otworami

STRESZCZENIE:
Obecnie ze względu na wysokie wymogi odnośnie do ekologii stosowanych rozwiązań w budownictwie renesans przeżywa zastosowanie drewna do budowy elementów konstrukcyjnych. Do budowy konstrukcji

szkieletowych najczęściej wykorzystuje się drewno klejone warstwowo. W przypadku wysokich belek, aby lepiej wykorzystać przestrzeń, możliwe jest wykonanie otworów w belkach. Otwory takie osłabiają nośność, ale mogą także powodować powstanie bardziej niekorzystnych rozkładów temperatur podczas pożaru, co może skutkować szybszym zwęgleniem drewna oraz spadkiem właściwości mechanicznych drewna. W artykule przedstawiono analizę numeryczną belek z otworem okrągłym oraz kwadratowym. Belką porównawczą była belka bez otworów. Analizowane belki zostały poddane analizie termicznej zmiennej w czasie obciążenia ogniem za pomocą strumienia ciepła. Temperatury gazów zostały obliczone na podstawie krzywej pożarowej ISO. Zastosowanie otworów pozwalających na przeprowadzenie różnych instalacji i wykorzystanie przestrzeni wpływają negatywnie na rozkłady temperatur podczas ewentualnego wystąpienia pożaru. Bardziej niekorzystne rozkłady temperatur występują w belkach z otworami kwadratowymi.

SŁOWA KLUCZOWE:
drewno; analiza numeryczna; obciążenie ogniem; otwory; pożar