Fire Resistance of the Rafter Used in the Steel Portal Frame

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Abstract. This paper presents an analysis of the main member of a steel frame in a fire situation. The authors of this article used prescriptive rules and simple calculation models to present an impact of the roof bracing on the fire resistance of a rafter. Designers often have problems with the fire protection of the roof bracing made of steel round bars (⌀). This article presents a solution to this problem.

1. Introduction
Thanks to parts of the Eurocodes dedicated to fire, structural fire design rules have become transparent. Designers may analyse a member, a part of a structure or an entire structure in a fire situation. Member analysis is the simplest analysis and it was used in [1-5]. A part of a structure (a roof made of thin-walled purlins restrained by sheeting) at an elevated temperature was analysed in [6]. Three bay frame on local fire was analysed in [7]. Maslak et al. evaluated the fire resistance of a steel sway frame structure using the linear programming [8]. The impact of a fire situation on the static and stability response of the bearing steel structure was presented in [9]. Nonlinear analysis of steel frame exposed to fire was presented in [10]. The behaviour of an entire structure (a barrel-shaped shell structure) in a fire situation was studied by Malendowski et al. [11]. A single-compartment frame structure under natural fire was analysed in [12].

In this paper, member analysis was used to obtain the fire resistance of the steel rafter. A failure mode of the steel rafter may be associated with lateral torsional buckling. The results obtained in the research project entitled "Lateral buckling of steel I beams under fire conditions" were summarised in [13]. The lateral-torsional resistance of I-beams under fire conditions was also analysed in [14-21].

2. Problem formulation
The fire resistance requirements for buildings are specified in the national Building Regulation. Industrial halls have to retain their stability for a reasonable period during fire. For this reason, many halls need to have steel members covered with proper fire protection materials. Some halls are designed with diagonal bracing made of steel round rods (⌀). In a braced frame building, two bracing systems (vertical and horizontal) provide the resistance to horizontal forces caused by wind and imperfections. In a fire situation, horizontal forces are lower than in a normal situation, because wind loads are limited by the coefficient ψ₁ (0.2). However, these loads should not be ignored; neither should the equivalent horizontal forces, which replaced initial imperfections. An unbraced rafter may bend laterally and twist at a critical moment. Braced bars are connected with the compressed flange of
a rafter to prevent relative displacement. The bars are round and have a high section factor ($A_m/V$). Round bars ($\varnothing$) are difficult to protect against fire and their fire resistance time is short (less than 15 minutes). When these bars stop working, the rafter will lose stability. For this reason, the bracing system should have the same fire resistance as the rafters. It is difficult to achieve that when the rafter should have a standard fire resistance of more than 15 minutes.

To solve this problem, the authors of this article propose to divide a hall into two separate fire compartments, using a compartment wall in the centre of the building. Thanks to this, the fire will not spread to the other compartment. As a result, one of the two horizontal bracing systems will not be heated and will provide resistance to horizontal forces. The longitudinal elements, which connect both horizontal bracing systems, rafters and columns, should be protected against fire (see Figure 1).

The second option is to use diagonal bracing bars with a low section factor ($A_m/V$) instead of round bars ($\varnothing$), e.g., angle bars (L). These bars may be protected against fire and they will provide resistance to horizontal forces. The longitudinal elements, which connect two horizontal bracing systems, the rafters and the columns, should both also be protected against fire. In this solution, a compartment wall may not be used and both horizontal bracing systems will be heated. However, due to fire protection, the horizontal bracing system will ensure the stability of the rafters.

The last option is to use modified structural steel, which has increased fire resistance [22]. The modification is based on adding carefully selected alloying elements to achieve a high-temperature strength of this material. The structural elements do not require any special protection against fire. However, the steel modified in this way is more expensive to produce.

![Figure 1. Fire compartments [23].](image)

3. Engineering example
The authors of this article analysed a rafter used in a 1-bay industrial hall. They use prescriptive rules presented in [24-26]:

- A standard fire was used to heat up the rafter.
- The effects of actions were determined for time $t = 0$.
- Indirect fire actions were not taken into consideration.
- The boundary conditions at the supports and ends of the member were assumed to remain unchanged throughout the fire exposure.
A simplified calculation method was used to verify the resistance of the member under fire condition.

The utilization of the joint (rafter-column) was lower than the maximum utilization of the rafter.

The hall was 27.0 m long and 18.0 m wide and was constructed from a series of portal frames spaced at 4.5 m (see Figure 2). The height of the building was 6.8 m. The structure was designed according to Eurocode standards. Columns were made of HEA 300 and rafters were made of IPE 450. The columns were simply supported and they were connected with the rafters using bolted extended end-plate moment connections. Horizontal and vertical bracings were made of 20-mm round steel bars (Ø) and square hollow sections SHS (70x70x4). The roof was made of corrugated steel sheeting spanning between the frames. All sections were made of S235 grade steel. The requirement was that the building should have a fire resistance of 60 minutes to a standard fire.

The compressed flange of the rafter was connected with the braced bars every 4.5 meters to prevent buckling (see Figure 3). The buckling length out of the plane of the rafter was 4.5 m and in the plane of the rafter was 18.0 m. The elastic critical moment was calculated taking into account the unrestrained length of the beam (4.5 m).

The section factor of the rafter was evaluated. The modified section factor was used to take into account the shadow effect \( k_{sh} A_m/V = 117.0 \text{ m}^{-1} \). The critical temperature of the element was calculated using the iterative method. The maximum bending moment in the rafter was 81.6 kNm, the
axial force was 16.7 kN and the shear force was 37.1 kN in the fire situation. The stability of the rafter was ensured by two horizontal bracing systems.

First, the authors of the article calculated the critical temperature and the fire resistance time of the horizontal bracing presented in Figure 4. Two load combinations in a fire situation were taken into account. In the first combination, wind load \( w_{d,fi} \) was limited by the coefficient \( \psi_1 \) (0.2) and amounted to 0.32 kN/m, whereas the equivalent horizontal force which replaced initial imperfections of the rafters was 0.36 kN/m. In the second combination, there was no wind load and the equivalent horizontal force was 0.43 kN/m. The critical temperature of the round diagonal bars (\( \varnothing \)) \( (T_{cr} = 631.1 ^\circ C) \) was calculated taking into account the utilization of the sections of these bars \( (\mu_0 = 0.37) \). The critical temperature of the longitudinal elements with SHS section \( (T_{cr} = 545 ^\circ C) \) was calculated using the iterative method \( (\mu_{545} = 1.0) \).

![Figure 4. Horizontal bracing with round diagonal bars.](image)

The diagonals of the bracing systems were made of round bars (\( \varnothing \)), which are difficult to protect against fire and their fire resistance time was only 13.3 minutes. As a result, the bracing systems ensured the stability of the rafter for a time, which was shorter than the required 60 minutes. When the rafter without the bracing system was analysed, the buckling length out of the plane of the rafter was 18 m in the fire situation. The rafter without the bracing system had no stability, and a 0.0 fire resistance.

Next, to solve the problem of rafter instability, the hall was divided into two fire compartments. During the fire, one of the two horizontal bracing systems was not exposed to fire and ensured the stability of the rafters. It was proven that one bracing system was enough to provide resistance to horizontal forces. In this situation, the buckling length out of the plane of the rafter was 4.5 m in the fire situation. The critical temperature of the rafter \( (T_{cr} = 580 ^\circ C) \) was calculated using the iterative method and taking into account: the reduction factor due to flexural buckling \( \chi_{580} = 0.3 \) and the reduction factor due to lateral-torsional buckling \( \chi_{LT580} = 0.43 \). To obtain the required fire resistance of R60, the columns, rafters and longitudinal elements (which connected both horizontal bracing systems) should have had fire protection. However, this solution required the expensive compartment wall. For this reason, the authors of this article also analysed the solution in which bars with angle sections (L) replaced round bars (\( \varnothing \)) in the bracing system (see Figure 5). All the bars of the bracing systems were protected against fire and their fire resistance time was 60.0 minutes. Due to this, the bracing systems ensured the stability of the rafters for the required 60 minutes. To obtain the required fire resistance of R60, columns and rafters should also be protected against fire.
4. Conclusions
This article discussed the problem of the stability of a rafter in a fire situation, when diagonals are made of round bars ($\varnothing$). Round bars ($\varnothing$) are difficult to protect against fire and their fire resistance time is short (less than 15 minutes). The rafter without a bracing system had no stability. In halls, which are required to have a fire resistance of more than 15 minutes to a standard fire, the bracings systems should work during fire. The authors of this article presented simple engineering solutions to this problem. It is possible to divide a hall into two separate fire compartments using a compartment wall in the centre of the building. Thanks to this, the fire may be contained in one compartment. One of the two horizontal bracing systems will not be exposed to fire and will provide the resistance to horizontal forces. However, this solution may be expensive because of the price of the compartment wall. For this reason, it is possible to use diagonal bracing bars with square hollow section (SHS) or angle sections (L), which may be protected against fire. In this solution, both horizontal bracing systems will be heated. However, due to fire protection, the horizontal bracing system will ensure the stability of the rafters.

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