BEHAVIOUR OF COMPOSITE STRUCTURES EXPOSED TO NATURAL FIRES

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Abstract

Traditionally structural fire design complies with the conditions of fire tests. Structural members are classified to fire resistance classes in dependency of their behaviour under ISO-fire exposure. In this contribution the limit fire load density is defined as a new attribute to characterize the fire resistance of structural members. Structural members maintain their load bearing ability in natural fires, if the fire load density is below this limit value. On the basis of numerous numerical simulations it could be demonstrated that composite members, which are classified to the fire resistance class R60 following the traditional design method, have limit fire load densities higher than 1000 MJ/m² and do not fail under natural fires in general buildings.

1 Introduction

Building Regulations in Germany require 90 minutes fire resistance (R 90) for structural members in multi storey buildings. The classification of structural members in fire resistance classes refers to the standard fire curve (ISO-fire). In the last decade European codes (Eurocodes) have been introduced for structural fire design based on more or less sophisticated calculation methods. The ISO-fire curve does of course not represent realistic fire conditions in a compartment. Natural fires depend substantially on fire loads, openings and thermal properties of surrounding structure. In Eurocode 1 Part 2-2 [1] gas temperature time curves are defined taking into account realistic conditions of a compartment fire. In Europe great efforts have been made recently to get a more economic level for requirements concerning fire safety (“Natural Fire Safety Concept” [2]). Concerning these developments the fire resistance of composite structural members, classified in R 60 (ISO-fire), exposed to natural fires is illustrated with numerical simulations in this contribution.

2 Fire-Exposed Composite Beams and Columns

2.1 Scope

Investigations are carried out for composite structural members in general multi storey buildings. In Germany typical composite beams and columns are partially encased with concrete (see fig. 1).

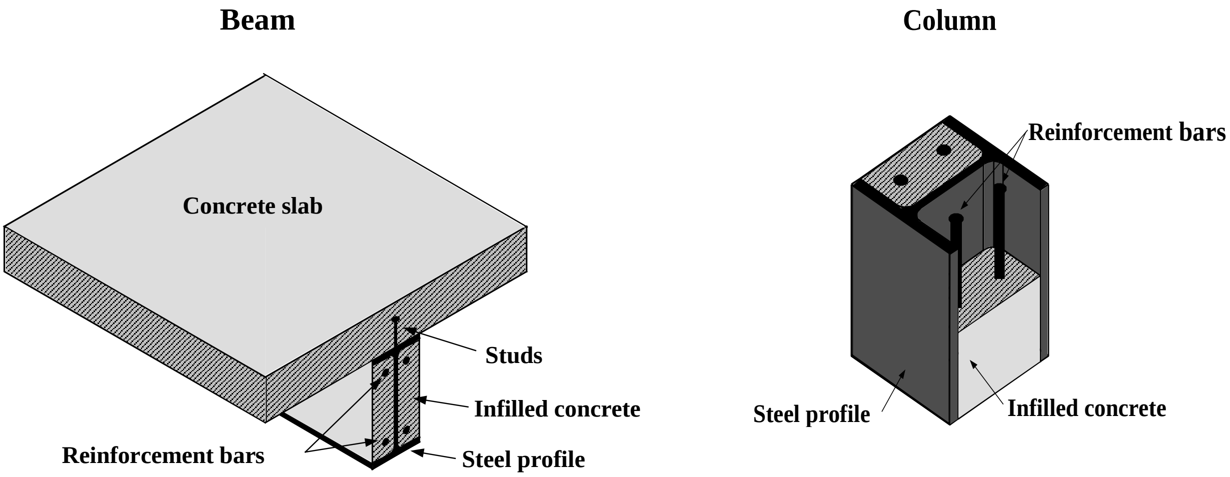


Fig. 1: Typical cross sections for composite members

2.2 Mechanical Actions

According to Eurocode the design of structural members in fire situations has to be carried out at the ultimate limit state. It shall be verified that $\mathbf{E_{fi,d,t}} \leq \mathbf{R_{fi,d,t}}$, where $E_{fi,d,t}$ is the design effect of actions in the fire situation determined from the accidental combination rule given in Eurocode 1 Part 2-2 [1], including fire actions, and $R_{fi,d,t}$ is the corresponding design load bearing resistance in the fire situation.

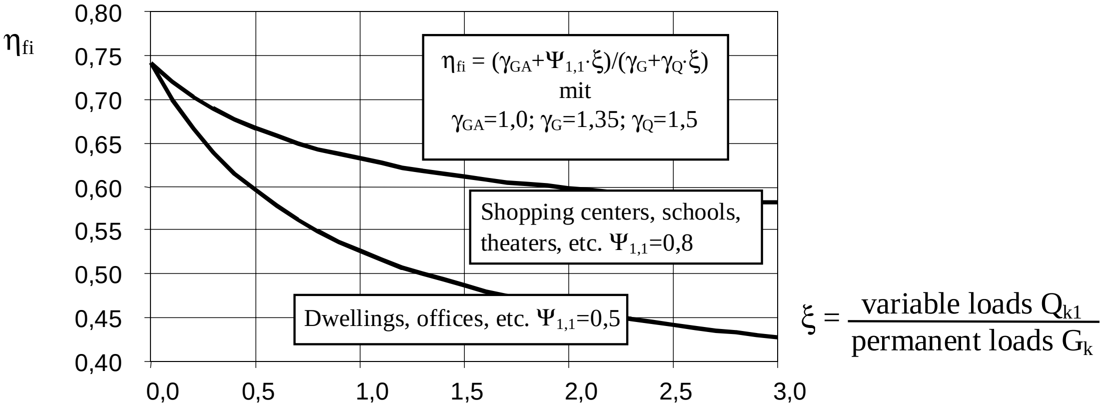


Fig. 2: Variation of reduction factor η_{fi} as a function of variable loads/permanent loads

As an approximation for the fire situation the design effect of actions may be obtained from the corresponding value determined for normal temperature design: $\mathbf{E_{fi,d} = \eta_{fi} \cdot E_d}$, where η_{fi} is a reduction factor depending on the ratio variable loads/permanent loads. E_d is the design effect of actions resulting from the fundamental combination rules for normal temperature design. For general buildings a reduction factor $\eta_{fi} = 0{,}6$ may be used.

2.3 Mechanical Properties

The mechanical properties of structural steel and concrete at elevated temperatures are specified in Eurocode 4 Part 1-2 [3]. These strength and deformation properties are taken into account in the numerical simulations. The strength and deformation properties of reinforcing steel may be obtained by the same mathematical model as for structural steel. For other steel grades and concrete see Eurocode 4 Part 1-2 [3].

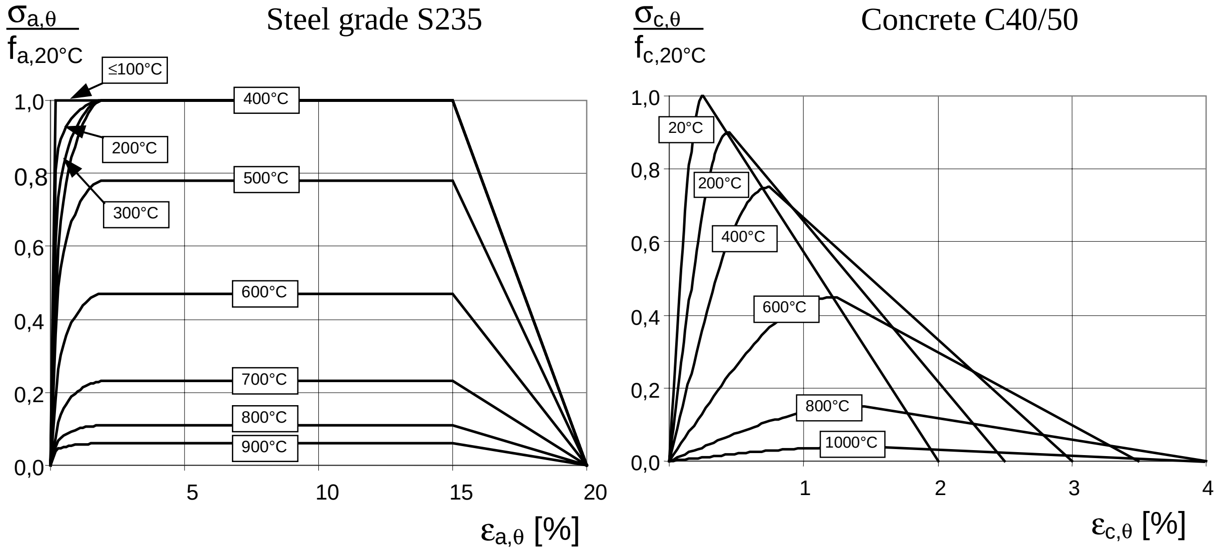


Fig. 3: Stress-strain relationships at elevated temperatures [3]

2.4 Fire Conditions

At present composite beams and columns are classified in fire resistance classes. Determining the fire resistance class of a structural member it has to fulfil the loadbearing function exposed to the standard fire for a certain period of time. The standard fire curve (ISO-fire curve) is defined by the equation $\mathbf{\theta_g = 20 + 345 \cdot \log_{10}(8t+1)}$ in [°C], t in [min] is a steady increasing logarithmic temperature time function without a cooling down phase (see Fig. 4).

Future realistic structural fire design will be based on gas temperature-time curves of design fires. The development of realistic fires depends on various complex physical processes. Modelling gas temperature time development in buildings with numerical simulations requires much experience in fire behaviour. In Eurocode 1 Part 2-2 [1] a simplified approximation is given to calculate gas temperature time curves for fully developed fires in compartments with areas up to

100 m^2. These simplified, so called parametric, fire curves depend on the three parameters fire load density, openings and thermal properties of walls and floors. In this investigation the compartment surroundings consist of brick-walls with an outside heat-insulating layer and concrete slabs with floating screed. The different wall and floor materials are considered in the b-value according to Eurocode 1 Part 2-2 Annex B [1]. The influence of the b-value on the fire development in a compartment is low compared to the influence of fire loads and openings. In this contribution $b = 1100\ J/m^2s^{0,5}K$ is taken constant in all parametric fire curves. The parametric fire curves normally consist of a heating phase with a fully developed fire followed by a cooling down phase. The influences of fire load density and openings are shown in Fig. 4. In the heating phase the temperature is ventilation controlled, whereas the maximum temperature and the decreasing temperature are mainly influenced by the fire load.

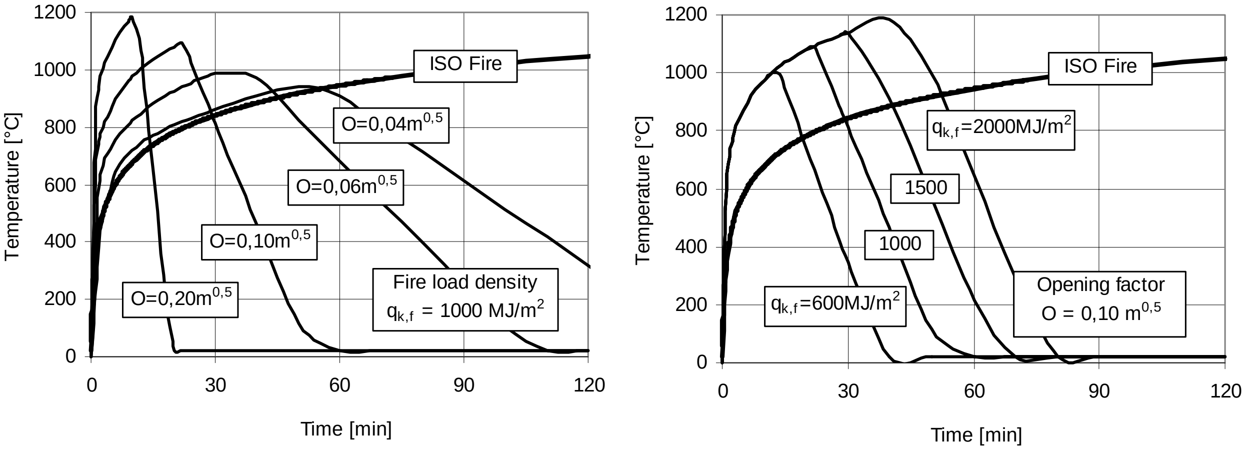


Fig. 4: Parametric fire curves according to Eurocode 1 Part 2-2 [1]

Based on statistical evaluation it may be assumed that fire load densities in general buildings as dwellings, offices, schools and shopping centres are lower than 1000 MJ/m^2 (see table 1). Building regulations in Switzerland for example divide multi storey buildings in classes depending on fire load. 1000 MJ/m^2 is the limit for a medium fire load density and more than 1000 MJ/m^2 means a high fire load density.

Table 1: Average values of fire load densities for different use of building

Occupancy	**Fire Load Density $q_{k,f}$ in[MJ/m^2]**		
	Germany [5]	**Europe [2]**	**New Zealand [6]**
Dwellings	300 – 600	780	900
Hospitals	500	230	300
Hotels	no specification	310	300
Libraries	2000	1500	2000
Offices	300 – 600	420	600 – 800
Schools	300 – 600	285	300
Shopping Centers	600	600	no specification
Theatres (movie/cinema)	1500	300	300
Transports (public space)	no specification	100	no specification

2.5 Numerical Simulation Models

Structural fire design of composite members exposed to realistic fires may performed according to Eurocode 4 Part 1-2 [3] with advanced calculation models. In the following investigations numerical analyses are carried out with the transient, non-linear, incremental computer code BOFIRE, written by the author [4]. The program includes different calculation models. One for calculating the development and the distribution of the temperature in the structural member (thermal response model) and another for considering the mechanical properties of the structure at elevated temperatures (mechanical response model). The mechanical actions in fire situations are taken into account in the first step, the thermal actions are applied by temperature-time curves. Time steps typically range between 2 and 10 seconds. In each time step temperature distribution and the resulting stress-strain distribution in the structure are calculated. Failure of the structure may occur due to loss of equilibrium (instability, kinematics or exceeding the material strengths). BOFIRE is validated by comparison to numerous test results.

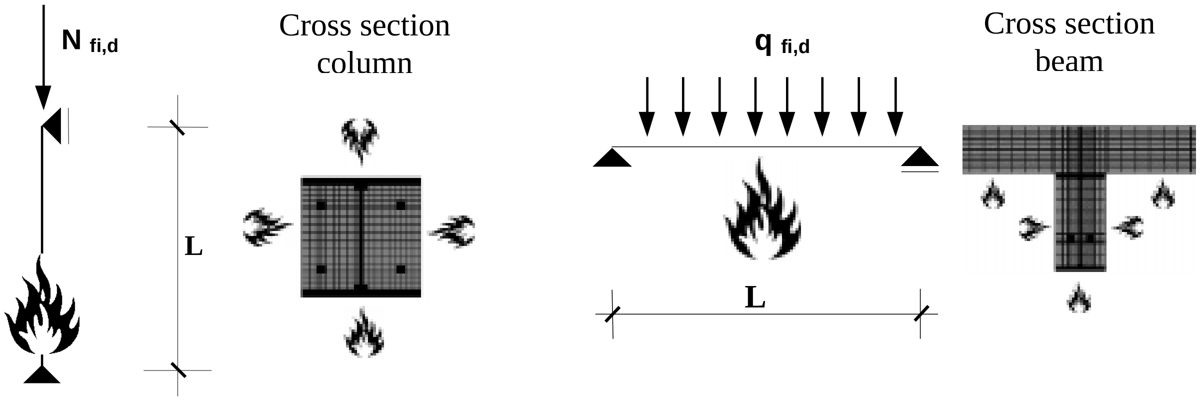
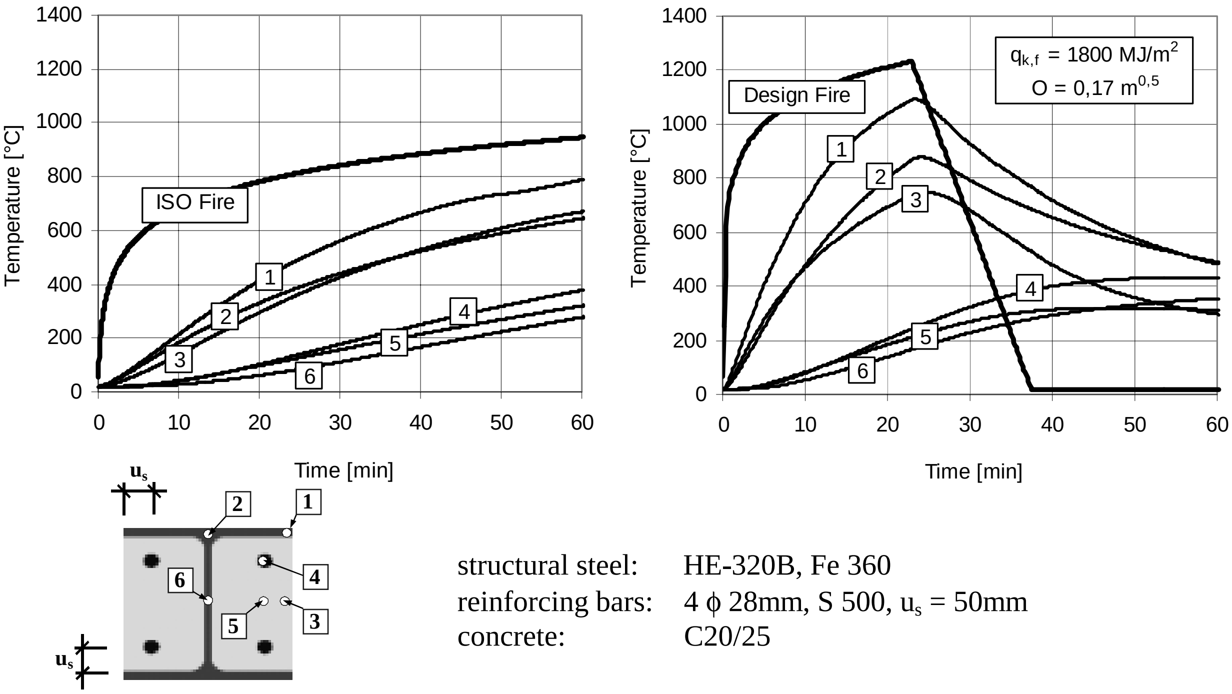


Fig. 6: BOFIRE-FEM-Model for columns and beams

2.6 Calculated Thermal Behaviour

The typical temperature developments in the cross section of a composite column exposed to ISO-fire (fig. 5,left) and a severe design fire (fig. 5, right) are illustrated in fig. 5. The concrete cools structural steel and isolates the reinforcement bars. Temperatures in the structural member are steadily rising under ISO-fire exposure, whereas temperatures at the surface rise faster than at inner parts of the cross section (fig. 5, left). This phenomenon is similar under natural fire up to the maximum gas temperature after about 23 minutes (fig. 5, right). Afterwards surface temperatures decrease, while inside of the cross section the temperatures of the inner parts converge to an uniform distribution. The consequence is that temperatures in the middle of the cross section are still rising after reaching the maximum of the design fire curve.



structural steel: HE-320B, Fe 360
reinforcing bars: 4 ϕ 28mm, S 500, u_s = 50mm
concrete: C20/25

Fig. 5: Temperature development in a cross section of composite column exposed to fire

3 Results

3.1 Limit Fire Load Densities

Fire exposure according to ISO-fire curve always leads to failure, because it only depends on the fire duration that material strength due to high temperatures becomes so small that the load bearing capacity falls below the loads applied. Under natural fire exposure the failure depends on the relation between the power of the fire (temperature-progression, -maximum and -duration) on one side and the fire resistance of the structural member on the other side.

The central item of this contribution is to find a limit value for the effect of fire, which leads to failure of the structure. This problem is solved by the following approach. For a given structural member with mechanical loads according to chapter 2.2 the effect of fire is varied by different values of the fire load density. For limitation of parameters the opening factor is taken constant as O = 0,04 m^{0,5} preliminarily. In fig. 7 the influence of the fire load density on failure of a composite column is illustrated. The horizontal part of the line stays for failure in the heating phase until reaching maximum gas temperature. An increase of fire load density has no more influence on the limit fire period, because the gas temperature-time curves in the heating phase are equal for a given opening factor and variable fire load densities (fig. 4, right). For fire load densities below the limit fire load density no failure occurs. In this example the limit fire load density is 1050 MJ/m^2.

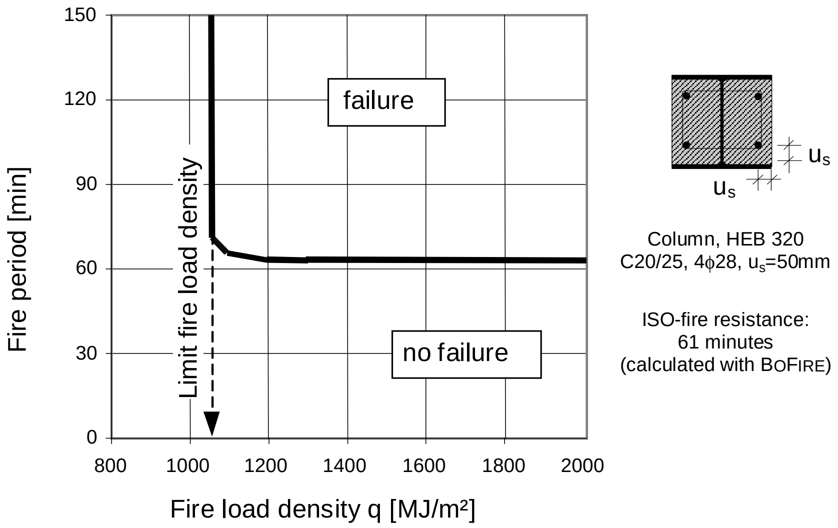


Fig. 7: Typical limit fire load density curve of a composite column

3.2 Influence of the Opening Factor

Opening factors in general building constructions for example in offices and dwellings range between 0,08 and 0,12 $m^{0,5}$. For composite beams and columns limit fire load densities depending on different opening factors from 0,04 up to 0,20 $m^{0,5}$ are calculated to demonstrate the influence on failure. For each opening factor the limit fire load density curve is calculated following the method described in chapter 3.1. The dependence is illustrated for columns (fig.8) and for beams (fig. 9). The limit fire load densities for beams and columns are greater than 1000 MJ/m^2 with the increasing opening factor. High opening factors mean short fire periods with very high temperatures (fig. 4, left). Consequently composite members have a higher load bearing capacity in this fires.

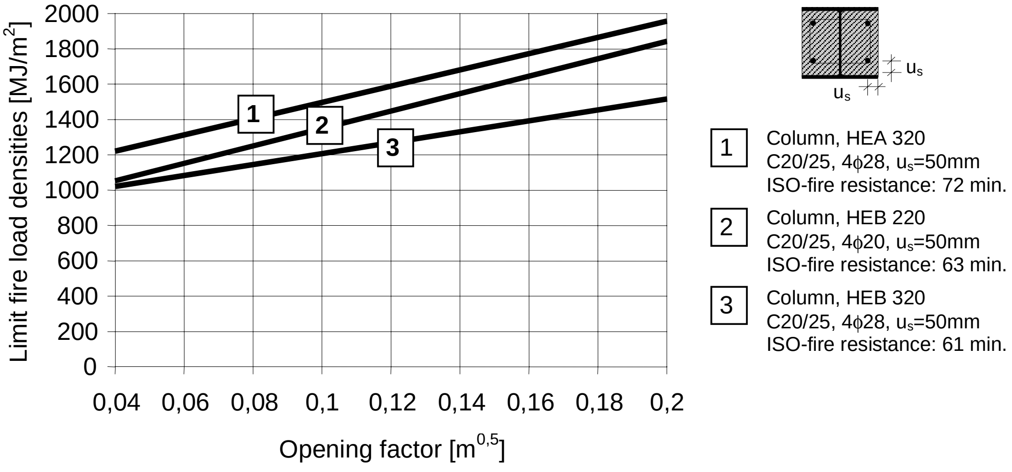


Fig. 8: Limit fire load densities of columns depending on openings

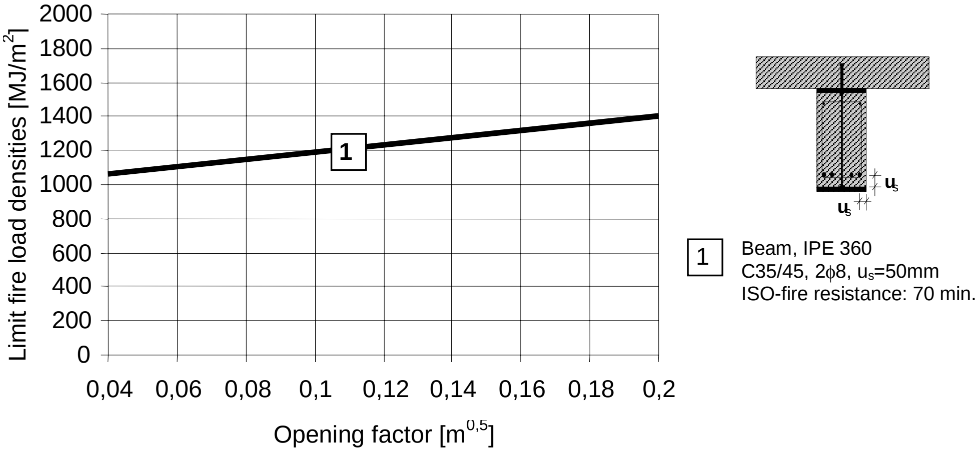


Fig. 9: Limit fire load densities of a beam depending on openings

4 Conclusion

Numerous numerical simulations to determine the fire resistance of steel beams and columns with partial concrete encasement under natural fires are carried out. A limit fire load density is defined as a new attribute to characterize the fire resistance of structural members. Structural members maintain their load bearing ability in natural fires, if the fire load density is below this limit value. It could be demonstrated that composite members, which are classified to the fire resistance class R60 (ISO-fire) following the traditional design method, have limit fire load densities higher than 1000 MJ/m² and do not fail under natural fires in general buildings.

5 References

[1] ENV 1991-2-2 Eurocode 1 – Basis of design and actions an structures, Part 2-2: Actions on structures – Actions on structures exposed to fire, February 1995, European Committee for Standardization, Central Secretariat, Rue de Stassart 36, 1050 Brussels, Belgium
[2] PROFIL ARBED, Centre de Recherches: “Competitive Buildings through Natural Fire Safety Concept, Research Report”, Part 1 (Main Text), Luxembourg, March 1999
[3] ENV 1994-1-2 Eurocode 4 – Design of composite steel and concrete structures, Part 1-2: General rules – Structural fire design, October 1994, European Committee for Standardization, Central Secretariat, Rue de Stassart 36, 1050 Brussels, Belgium
[4] Schaumann, P.: “Zur Berechnung stählerner Bauteile und Rahmentragwerke unter Brandbeanspruchung” (To the Calculation of Steel Members and Frames exposed to Fire), Technisch-wissenschaftliche Mitteilungen Nr. 84-4, Institut für konstruktiven Ingenieurbau, Ruhr-Universität Bochum, Dissertation, 1984 (in German)
[5] Bundesministerium für Verkehr, Bau- und Wohnungswesen – BMVBW: “Brandschutzleitfaden für Gebäude besonderer Art und Nutzung” (Fire Protection Guide for Buildings with special type and use), November 1998 (in German)
[6] Buchanan, A. H.: “Fire Engineering Design Guide”, Center for Advanced Engineering, University of Canterbury, New Zealand, 1999

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