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CALCULATION OF LOCAL FIRE FOR DESIGNING BUILDING STRUCTURES

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Research article

Abstract: The issue of designing building structures for the effects of fire is resolved on the basis of data obtained by standardized values, tests, calculations, or a combination of the described procedures. The calculation methods are becoming more important with certain kinds of building structures, including steel and wood building structures. One way to define the thermal stress of building structures, which is usable especially immediately after the development of a fire, is the local fire method. This text summarizes the principles of calculation when using local fire; it evaluates its positive and negative aspects, and especially its practical applicability.

Keywords: Fire, Building structure, Design, Local fire.

Introduction

The stage of the development of the fire has long been of interest to professionals involved in fire protection, especially specialists in assessing the parameters of building structures. One of the most observed characteristics is their fire resistance.

Wooden and steel structures "pride themselves on" a range of positive qualities, but in terms of fire safety they often require the implementation of certain measures that will ultimately increase the final price of the building element or structure. Therefore, the interest in assessing the development of fire, and consequently the local fire, is understandable.

Materials and methods

Assessing Building Structures for the Effects of Fire

The requirements for building structures, and therefore also their fire resistance, are generally established by the Council Directive (89/106/EHS, 2008) on the approximation of laws and regulations of member countries related to construction products as amended by the Council Directive 93/68/EHS (hereinafter referred to as "Council Directive"). The requirements are further specified in the Interpretative Document No. 2 in the Council Directive, which describes the basic requirements and strategies in terms of fire safety, the philosophy of engineering principles, and forms of meeting the fire safety conditions. It also includes an assessment of building structures in terms of their fire resistance.

The European requirements have been implemented into the Czech legislation. In accordance with Act No. 183/2006 Coll., on planning and building regulations (Building Act), as amended, and Decree No. 268/2009 Coll., on technical requirements for constructions, as amended by Decree No. 20/2012 Coll., the buildings must meet, inter alia, *the fire safety requirements*.

Requirements *for the method of evaluating the fire resistance of building structures* are further specified by legal and technical regulations. The basic principles of Decree No. 23/2008 Coll., on technical conditions of building fire protection, as amended by Decree No. 268/2011 Coll. Details are further specified by the code of fire safety standards (standards of series ČSN 73 08xx) and Eurocodes. The Eurocodes currently contain approximately sixty design documents. In terms of fire protection Eurocode 1 is the most important: Actions on structures - Part 1 - 2: General actions - Actions on structures exposed to fire.

The evaluation of fire resistance of structures is ultimately subject of the fire safety solution elaborated as a part of the documentation of constructions according to Decree No. 499/2006 Coll., on construction documentation, to the extent stipulated in Decree No. 246/2001 Coll., on establishing the conditions of fire safety and the state fire supervision (decree on fire safety).

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Requirements and Certification of Fire Resistance of Building Structures

The fire resistance of structures is collectively expressed by the ability of the structures to resist the effects of fire. The evaluation of fire resistance consists of certifying compliance with the specified requirements.

Generally, the following exposures are established for thermal stress (89/106/EHS, 2008):

- a small source of ignition (e.g. a match),
- independently burning objects (e.g., burning furniture, stored materials in industrial premises),
- fully developed fire (e.g., actual fire stress, standard temperature/time curve).

Fire resistance is usually determined for *the standard course of the fire* or *the likely* (parametric) *course of the fire*. The standard course of the fire is in accordance with fire resistance determined by the calculation fire stress, or the equivalent fire duration. The likely course of the fire is determined by specific conditions of the part of the construction or technological object that is under consideration, usually with an aberrant development of temperatures in the burning area from the standard course of the fire. The likely course of the fire is determined by the likely duration of the fire and the likely fire gas temperatures) (ČSN 73 0804, 2010), or a temperature analysis of the parametric course of the fire (ČSN EN 1991-1-2, 2004).

The requirements for the fire resistance of structures in relation to the risk of fire compartments is determined *by the code of fire safety standards* (series ČSN 73 08xx), or *by other documents* (e.g. by ČSN EN 1991-1-2).

Fire Resistance of Structures (ČSN 73 0810, 2009):

- *is determined by classification* according to the results of the tests under corresponding test standards (see ČSN EN 13501-1 and ČSN EN 13501-2),
- *is determined by the standardized value* (according to ČSN 73 0821, a value in accordance with the Eurocodes, or a value specified in extended application), *or calculation* in cases when all factors affecting the fire resistance can be numerically formulated,
- *it can be determined by a test and calculation* in cases when a test cannot cover all the factors affecting the fire resistance, or when the test results for a specific application require further assessment.

Local Fire

Local fire represents a situation where the total combustion of substances is unlikely, and uneven temperature distribution in the space is presupposed.

In terms of the development and spreading of the flames, two basic situations are distinguished (see Fig. 1):

- *the flames are not reaching the ceiling*; ($L_f < H$, the length of the flames is less than the height of the ceiling above the fire source),
- *the flames are reaching the ceiling*; ($L_f \geq H$, the length of the flames is equal to or greater than the height of the ceiling above the fire source). In this case it is necessary to determine the horizontal length of the flame L_h, which is demarcating the space of the radial expansion of the flames under the ceiling.

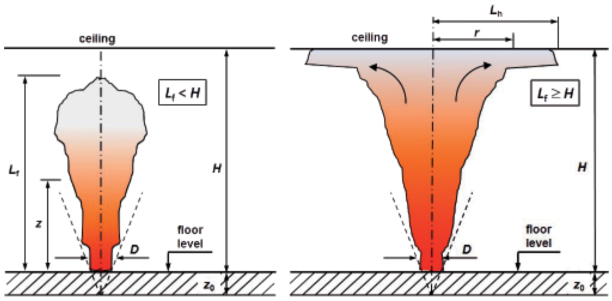

Fig. 1 Flames of fire in a confined space
(Kučera and Pokorný, 2010)

The input data for assessing the effect of local fire on building structures are the length of the flame L_f, the virtual beginning of the axis z_0, the convection of the heat release rate Q_c and others[1]. The methodology for the calculation according to Eurocode 1 is further determined by the temperature increase of the axis Fire Plume[2] and the heat flux incident on the surface of the structure (for cases where the flames do not reach the ceiling) or direct heat flux incident on the surface of the structure (for cases where the flames reach the ceiling). In principle, the solution procedure may be described by the following dependencies (ČSN EN 1991-1-2, 2004).

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1 The symbols in this and the following part of the text are copying the indications in Eurocode 1.

2 The development of the fire is accompanied by the emergence and development of a column of smoke gases. This is generally referred to as Fire Plume.

Assuming that $L_f < H$:

$$\theta_{(z)} = f(Q_c, z, z_0) \quad (1)$$

$$h_{net} = h_{net,c} + h_{net,r} \quad (2)$$

$$h_{net,c} = \alpha_c(\theta_g - \theta_m) \quad (3)$$

$$h_{net,r} = \varphi \,.\, \varepsilon_m \,.\, \varepsilon_f \,.\, \sigma . \left[(\theta_r + 273)^4 - (\theta_m + 273)^4 \right] \quad (4)$$

$$h = f(H, r, L_h, z') \quad (5)$$

$$h_{net} = h - \text{heat losses of construction} \quad (6)$$

where

L_f is the length of the flame (or the medium height of the flame) [m],

H the distance between the fire source and the ceiling [m],

$\theta_{(z)}$ the temperature in the cloud of burning gases along the symmetric vertical axis [°C],

Q_c the convective part of the heat release rate Q [W],

z height along the flame axis [m],

z_0 virtual beginning of the axis [m],

h_{net} the *net* heat flux per unit of the surface area [$W.m^{-2}$],

$h_{net,c}$ the net heat flux per unit of the surface area under convection [$W.m^{-2}$],

$h_{net,r}$ the net heat flux per unit of the surface area under radiation [$W.m^{-2}$],

α_c coefficient of heat transfer under convection [$W.m^{-2}.K^{-1}$],

θ_g temperature of gases near the element exposed to the effects of the fire [°C],

θ_m surface temperature of the element [°C],

φ positional factor [-],

ε_m surface emissivity of the element [-],

ε_f fire emissivity [-],

σ Stefan-Boltzmann constant [$W.m^{-2}.K^{-4}$],

θ_r the effective temperature of radiation of the environment of the fire [°C],

h the heat flux incident per unit of surface area abreast with the ceiling exposed to the effects of the fire [$W.m^{-2}$],

r the horizontal distance between the vertical axis of the fire and the point on the ceiling, for which the heat flux is calculated [m],

L_h horizontal length of the flame [m],

z' vertical position of the virtual heat source [m].

The calculation procedure of local fire described in Eurocode 1 is one of the usual, and also one of the simplest methods for determining the axial temperature of the Fire Plume and the heat flux incident on the building structure. The simplicity of the solution is also the reason for the significant limit to the use of the described method. This is especially *the calculation limit due to the vertical position in the space* (the position in the Fire Plume) and *the effect of the cumulating smoke*.

The presented relations can be used to determine the axial temperature of the Fire Plume in its final section, the smoke zone.[3] The application of calculation methods in other parts of the Fire Plume leads to unrealistically optimistic results (Kučera and Pokorný, 2010), (Pokorný, 2009).

A computational method is, among other things, based on the assumption that in the developing column of smoke gases there is suction of ambient air at a temperature corresponding to the standard ambient conditions (typically 20 °C). In real situations, however, with fires in enclosed areas in most cases layers of smoke are created under the ceiling construction, which progressively lowers. When the Fire Plume penetrates the hot layer of gases its axial temperature is affected due to changes in environmental conditions. When the Fire Plume is forming there is a suction of gases, which have a higher temperature than the ambient temperature, and thus a decrease in the temperature with the increasing distance above the surface of flammable materials is more gradual. The resulting values of the temperature of the Fire Plume axis with or without taking into account the hot layer of gases may vary significantly, and the results obtained by the procedure according to Eurocode 1 may be misleading in the case of the existence of a hot layer of gas (significantly undersized) (Kučera and Pokorný, 2010).

The limit to the calculation procedure according to Eurocode 1 is shown in Fig. 2. A case study evaluated the area of the hall, where metallic materials are processed and stored. The procedure according to Eurocode 1 determines the axial temperature of the Fire Plume below the roof structure in the 15th minute of fire of 164 °C. Assuming the same conditions using the zone model CFAST (2011).[4] The determined average temperature of the hot smoke layer is 335 °C. *„Is it possible for the average temperature of the hot gas layer determined*

[3] The Fire Plume is divided into the flame zone, the transition zone, and the smoke zone (Heskestad, 2008).

[4] CFAST is a zone fire model, which was developed by the National Institute of Standards and Technology.

by the CFAST model to be higher than the axial temperature of the Fire Plume determined by the process according to Eurocode 1?". No, it isn't. This result is obviously incorrect. The axial temperature of the Fire Plume should be higher than the average temperature of the hog gas layer. This error is caused by the limits of the procedure for assessing local fire according to Eurocode 1.

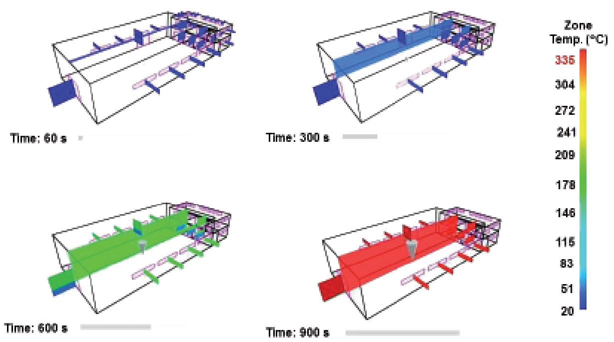

Fig. 2 Assessing the average temperature of the gas layer with the CFAST model

Results

The procedure for determining the axial temperature of the Fire Plume (local fire according to Eurocode 1 may be applied) is shown in Fig. 3.

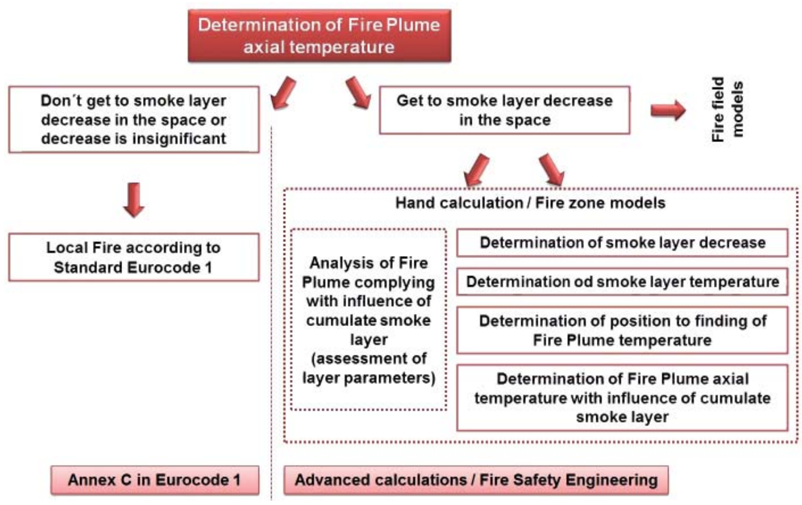

Fig. 3 The procedure for determining the axial temperature of the Fire Plume (Kučera and Pokorný, 2010)

The theory of the local fire is usable in the assessment of the ambient temperatures at the time of the required fire resistance of the structure, in which it is not necessary to set up fire protection of steel structure, in certain cases during the installation of the automatic fire extinguishing system or equipment for the outlet of smoke and heat, or without the installation of these device[5] (for special applications). Again, however, in most cases it is necessary to take into account the influence of the layer of hot gases that accumulate under the ceiling structure.

Conclusion

The methodology of the local fire according to Eurocode 1 can only rarely be applied in practice without additional calculation methods for the design of building structures under fire conditions. These are cases of buildings of large geometric dimensions, where the drop of the smoke layer is considerably slow and the short application time of the calculation methodology (low requirements for the fire resistance of building structures).

The simplicity of the procedure for the assessment of local fire according to Eurocode 1 significantly limits its wider application.

Acknowledgments

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5 Article 4.8 ČSN 73 0810 (2009).

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