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PRINCIPLES OF FIRE MEASUREMENT OF STRUCTURAL ELEMENTS

Abstract

Nowadays, ensuring a high level of fire protection of buildings is of paramount importance both during the design and construction period and during the operation period. In determining the fire resistance of structural elements, fire design requires the close cooperation of several engineering disciplines. One of the most important tasks in the design of fire loads is that our buildings and structures are able to maintain their stability for as long as possible under the influence of fire. To this end, the sizing for the fire load must be carried out in the case of our building structures using the MSZ EN standard series, which reflects the requirements of the European regulation (Eurocode). In the framework of this article, we describe these sizing principles for the most commonly used reinforced concrete, steel, wood and masonry structures.

Keywords: passive fire protection, fire protection properties of building structures, standard fire effect, measurement for fire load

SZERKEZETI ELEMEK TŰZTESZT MÉRÉSÉNEK ALAPELVEI

Absztrakt

Napjainkban az építmények tűzvédelmének magas színtű biztosítása mind a tervezési és kivitelezési, mind az üzemeltetési időszakban kiemelt jelentőséggel bír. Az épületszerkezetek tűzzel szembeni ellenállóképességének meghatározásakor a tűzhatásra való tervezés több mérnöki szakág szoros együttműködését követeli meg. Az egyik legfontosabb feladat a tűzteherre való tervezés során, hogy az épületeink, építményeink képesek legyenek a tűz hatása alatt minél hosszabb ideig megőrizni állékonyságukat. Ennek érdekében a tűzteherre való méretezést az épületszerkezeteink esetében az Európai szabályozás (Eurocode) követelményeit megjelenítő MSZ EN szabványsorozat alkalmazásával kell elvégezni. Jelen cikk keretében ezen méretezési elveket ismertetjük a leggyakrabban alkalmazott vasbeton, acél, fa illetve falazott szerkezetekre vonatkozóan.

Kulcsszavak: passzív tűzvédelem, épületszerkezetek tűzvédelmi tulajdonságai, szabványos tűzhatás, tűzteherre való méretezés

1. INTRODUCTION

When determining the fire resistance of a building structure, fire design is a priority engineering task, the most important goal of which is to enable our buildings and structures to maintain their stability, integrity and insulating capacity for as long as possible under the influence of fire. In the event of a fire, several questions may arise regarding the load-bearing capacity of load-bearing structures. One of the main issues is sizing for fire effects, the other is the applicability, reinforcability, recoverability and usability of buildings and building materials after a fire. MSZ EN 1990:2011 Eurocode (principles) [1] and MSZ EN 1991-1-2:2005 Eurocode 1: [2] standards, as well as the National Fire Protection Regulation [3] (hereinafter referred to as: NFPR), issued as Decree 54/2014. (XII. 5.) by the Ministry of the Interior, contains general requirements related to sizing for fire loads. It is very important that in the event of a fire, while maintaining their stability, our building structures suffer the least possible damage. The tasks of fire protection can be formulated as follows:

- fire prevention,
- prevention of the spread of fire,
- passive fire protection,
- active fire protection,
- fire fighting and technical rescue.

In the field of fire protection, one of the primary tasks is to select the design of the materials of the building structural elements. If the fire resistance of the structure cannot be ensured only by the choice of material, then additional fire protection is required, which can be the use of fire protection paint, fire retardant, or fire protection coating. In the following, we will only deal with passive fire protection.

The design of fire sections is a very important task of *passive fire protection*, as this fire protection solution can prevent the spread of fire. The fire section is a self-contained unit of fire in the building or outdoor area, separated from adjacent units by fire-preventing structures with specified flammability and fire resistance limits, fire distances specified in the relevant legislation, national standard and the Fire Protection Technical Guideline, or built-in automatic fire extinguishing systems.

We also briefly summarize the principles of active fire protection. Within the framework of active fire protection, automatic fire alarm systems are installed, but extinguishing must be performed by the firefighter, while the use of automatic fire extinguishing equipment, which is also part of active fire protection systems, ensures that small fires are extinguished without fire intervention. Of course, if said active fire protection systems are installed, this can be taken into account in the calculation of the fire load during sizing, but only if this is supported by modeling of a computerized heat and smoke extraction.

In Hungary, the National Fire Protection Regulations contain the basic fire protection framework for the construction of structures. The National Fire Protection Regulations stipulate when active fire protection systems must be used in addition to passive fire protection. The technical solutions ensuring compliance with the NFPR requirements are included in the Fire Protection Technical Guidelines. Among the Fire Protection Technical Guidelines, which currently cover 14 professional fields, fire protection characteristics of building structures are included in Guideline No. 11. Accordingly, Chapter 3.2 of this Fire Protection Technical Guideline defines the classification of building structures into fire protection classes. Requirements for the fire protection class and fire resistance performance of building structures, depending on the relevant risk class and level of the given building, are contained in Annex 2 of the NFPR.

Building structures should be selected during design so that

- building structures retain their load-bearing capacity in the event of fire for the prescribed period,

- in the event of a fire, the building structures, materials and products for fire protection purposes must fulfill their role for the prescribed period of time, retain their function, and react effectively to the presence of fire,
- inhibit, impede or control the spread of fire and its accompanying phenomena in accordance with their function,
- the fire load they cause, the amount of heat, smoke and combustion gases generated from them should be as small as possible [4].

During fire protection, we have different requirements for building structures, each element must have a different function in terms of fire protection, e.g. the column must retain its stability, load-bearing capacity (R), the partition wall must retain its insulating (I) and integrity (E) function.

Building structures can be characterized based on specific properties as follows (here we highlight only the most important ones):

R – load-bearing capacity: the ability of structural elements to withstand the effects of fire for a period of time under specified mechanical stress on one or more sides without any loss of structural stability.

E – integrity: the ability of a building structure to have a separating function when it is resistant to exposure to fire on one side without the fire spreading to the other side due to the passage of flames or hot gases, which could cause inflammation either on an unexposed surface or any material adjacent to the surface.

I – insulation: the ability of a building structure to withstand fire on one side only without significant heat transfer from the exposed surface to the unexposed surface.

W – radiation: the ability of building components to reduce the likelihood of a fire transition in the event of a fire exposure on one side, either through the structure or by reducing significant heat radiation from an unexposed surface to adjacent materials.

M – mechanical effect: the ability of building structures to withstand impact in the event of an impact on that structure due to a structural failure of another component in the fire.

2. EFFECTS TO BE TAKEN INTO ACCOUNT WHEN PLANNING FOR FIRE EFFECTS AND BASIC RULES FOR PERFORMING STRENGTH TESTS

The MSZ EN 1991-1-2:2005 Eurocode 1: standard, which deals in general with the effects on structures exposed to fire within the effects on the supporting structures, formulates an important principle that if the fire resistance requirements are determined with a standard fire effect, indirect effects transmitted from adjacent elements (inhibited deformations, effects due to inhibition of thermal expansion, etc.) need not be taken into account. In contrast, the effects from the temperature gradient within the cell should be taken into consideration. Based on this, simplified methods such as tabular procedures or simplified calculation of stresses can be performed. In such cases, individual components are inspected separately.

In all other cases, particular attention should be paid to the following effects and their consequences:

- inhibited thermal expansion in structural elements (e.g. frame columns);
- unequal temperature change in statically indeterminate structures;
- uneven temperature distribution within the cross-section;
- thermal expansion of adjacent structural elements;
- the effect of thermal expansion of structural elements exposed to fire on the behavior of structural parts outside the fire section.

If a detailed examination is performed by treating the support structure as a complete unit, the indirect effects of temperature cannot be disregarded. The relevant standards provide guidance on the inclusion of values for indirect effects due to fire.

Fire design is considered to be an extraordinary design condition according to the classification of MSZ EN 1991-1-2:2005 Eurocode 1: standard, load combinations must be assembled accordingly.

3. MEASUREMENT METHODES

3.1. Measurement of Concrete Structures for fire

The measurement methods for concrete structures are contained in the MSZ EN 1992-1-2:2013 Eurocode 2: standard [5], according to which the regulation cannot be applied if layered detachment of concrete surfaces occurs and the fire load does not occur according to the standard fire curve.

Here we would like to describe what influences the layered detachment of concrete surfaces. There are two reasons for the delamination of concrete surfaces:

- water vapor from the concrete stretches the surface layers, or
- the zone under load is no longer able to absorb the additional forces due to thermal expansion and is dropped off and detached [6].

The detachment of the surface of high-strength concretes is usually caused by stresses due to the rise in temperature, in the case of normal concretes the water vapor escaping from the concrete usually strains the surface layers. One side of the concrete surface is subjected to a heat load, and the water vapor leaving the concrete results in the formation of a layer saturated with water vapor, where the water vapor pressure increases and stretches the concrete layers.

The chances of layered detachment of the concrete surface are influenced by the following factors:

- external factors: the nature of the fire, the magnitude of external loads acting on the structure;
- geometrical characteristics: geometrical data of the structure, size of the concrete cover, number and location of steel inserts;
- the composition of concrete: size and type of admixture, type of cement and admixture, number of pores, polypropylene fiber dosage, steel fiber reinforcement, moisture content, permeability, and strength of concrete [6].

3.1.1 Tabulated data

In the case of the tabuleted data method, the planned wall, column or beam cross-section is checked on the basis of the fire resistance performance values given in the tables. With this method we can only scale one highlighted structural element, the interaction of the structural elements is not taken into account. Conditions for the application of the tabulated data method according to MSZ EN 1992-1-2:2013 Eurocode 2: are:

- The tables are made for a standard fire curve, they cannot be used for other fire curves.
- For concrete strengths of C55/67 or higher, other tables must be used and the avoidance of layered separation of concrete surfaces must be verified or agreed with a concrete technologist or an experiment must be carried out.

It should be noted here that in order to use the tabular method, we need to know the definition of the axis distance of the rebar, which is different from the definition of the concrete cover.

3.1.2 Zone Method

The essence of the zone method is to divide the cross section into different zones (more than two zones) by means of isothermal lines and to calculate with reduced strength values in the given zones.

One variant of the zone method is the 500 °C isotherm method, the essence of which is to neglect the concrete parts of the cross-section with a temperature higher than 500 °C and to calculate with this reduced concrete cross-section. The maximum temperature of the rebar must be determined and then the strength values of the steel inserts must be reduced according to the maximum temperature formed.

Steps for the control calculation using the 500 °C isotherm method:

- isothermal lines shall be produced if they do not exist for the given cross-section, if they exist, the annex according to MSZ EN 1992-1-2:2013 Eurocode 2: should be used,
- the dimensions of the reduced cross-section at temperatures below 500 °C and the temperature of the reinforcing bars must be determined,
- measurement must be carried out with the modified cross-section and modified steel characteristics,

- based on this the fire resistance duration of the reinforced concrete beam can be determined.

The inspection is carried out in a similar way to the normal temperature calculation, but the following must be taken into account:

- cross-section parts of the concrete cross-section with a temperature higher than 500 °C must be neglected,
- the loss of strength of the tension strands due to high temperatures must be taken into account,
- the reduction in the tension of the tension strands due to the high temperature must be taken into account.

3.1.3 Application of a Finite Element Model

There are two generally accepted methods of finite element modeling in the case of fire:

- thermo-mechanical measurement and
- thermo-hydro-mechanical measurement.

Numerical methods allow engineers to determine temperature effects based on physical and chemical parameters. However, only thermo-hydro-mechanical sizing is suitable for taking into account the material characteristics, thus modeling the layered separation of concrete surfaces.

The isothermal lines of some cross sections are also included in the MSZ EN 1992-1-2:2013 Eurocode 2: standard, however, if we have other cross sections, we have to produce the isothermal lines.

The overheating of a concrete cross section depends on a number of thermodynamic characteristics, several of which are dependent on temperature. In order to obtain a result that reflects reality, these characteristics must be taken into account.

3.2. Measurement of Steel Structures for fire

The mesurement of steel structures for fire is dealt with in the MSZ EN 1993-1-2:2013 Eurocode 3: standard [7]. Accordingly, the standard offers the possibility to test fire-resistant steel structures on three levels, similar to reinforced concrete:

- determination of the load-bearing capacity of steel components exposed to fire on the basis of the critical temperature,
- determination of the load-bearing capacity of steel components exposed to fire on the basis of cross-sectional resistance,
- application of finite element model.

In the case of a test performed at the *level of a structural element:*

- the nominal (usually ISO) fire curve is used as the fire process,
- the effects of uneven temperature changes within the cross-section must be taken into account, but not the effects of uniform transverse and longitudinal temperature changes, nor the stresses arising from them,
- the boundary conditions for the supports can be considered unchanged during the fire,
- simple calculation procedures shall be used for the calculations to verify the fire resistance by testing the load capacity or by analyzing the critical temperature.

In the case of a test performed at the *level of a part of a structure* (e.g. steel main support frame):

- the component test shall take into account the temperature-dependent material properties, the varying stiffness values and any indirect effects due to the change in temperature,
- the boundary conditions at the supports and at the edges can be considered unchanged during the fire,
- simple calculation procedures can be used for the calculations, which can be used to check the fire resistance within the structural part by testing the load-bearing capacity of each structural element or by testing the critical temperature, or advanced calculation models can be applied.

In the case of a test performed at the *level of the whole structure:*

- the structural tests shall take into account the temperature-dependent material properties, the varying stiffness values and all the indirect effects due to the change in temperature, and shall determine the method of destruction by fire,
- calculations can be performed using advanced calculation models.

The methods that can be used in simple tests are described in detail in the indicated standard, and in the case of advanced computational models, the conditions and rules of application are defined by the same standard. Methods that allow a full structure to be studied require finite element models and advanced numerical methods that take several temporal variations into account.

3.2.1. Determination of the load-bearing capacity of steel components exposed to fire on the basis of critical temperature

This simplest method can be used only if no loss of stability or deformation limit state can occur in the tested element and the temperature distribution is uniform in the cross section. Accordingly, it can only be used on drawn elements or laterally supported beams where no bending can occur. The critical temperature θ_{cr} of a structural element is the temperature at which the failure of the structural element occurs under a given load.

3.2.2. Determination of load-bearing capacity of steel components exposed to fire on the basis of cross-sectional resistance

After t time due to fire, the load-bearing capacity of steel structural elements heated to Θ_a can be calculated from the strength determined at normal temperature by reducing the yield strength of the raw material by a factor $k_{y,\Theta}$ and the partial safety factor is set to 1.0.

Within the cross-section, a distinction must be made between unequal and uniform temperature distribution during the calculation, the course and details of which are given in the indicated standard. The standard indicates in the index whether the temperature distribution is uniform within the tested section. If so, the resistance is given an index Θ (i.e. temperature-dependent), and if the individual cross-sections are not necessarily at the same temperature, then t is denoted (i.e. time-dependent).

3.2.3 Application of a finite element model

In the case of steel structures, of the already mentioned thermo-mechanical and thermo-hydro-mechanical measurement, only thermo-mechanical measurement can be considered, since the steel structure is not porous and therefore does not contain water.

3.3. Measurement of Wooden Structures for fire

The MSZ EN 1995-1-2:2013 Eurocode 5: standard [8] recommends the following methods for the sizing of wooden structures for fire effects:

- reduced cross-sectional method,
- method of reduced material properties,
- sizing of protected wooden structures.

3.3.1 Method of Reduced Cross Sections

The thickness of the charred layer formed on the wood structure as a result of the effect of the fire also includes the zone of thermal decomposition, so that in fact the part outside the intact cross section is determined. The thickness of the charred layer and thus the rate of charring were measured experimentally by removing the charred layer after the fire test. The specified standard nominally specifies the 300 °C isotherm as the carbonization depth, adapted to the temperature of the thermal decomposition zone.

The rate of charring depends, among many other parameters, mainly on the type of wood, the compactness of the wood and the geometrical conditions of the cross section.

On a flat surface in case of one-sided (one-dimensional) fire effect - e.g. edge boards, plywood, OSB - the carbonization depth and the carbonization rate can be well measured and defined.

In the case of multi-sided fire, which typically affects bar structures, there is a multidimensional heat flow and increased charring around the flat surfaces near the intersecting edges. This phenomenon can be taken into account by rounding the charring front, which was still applicable under the previous pre-standard, but complicates engineering calculations unnecessarily in practice.

Another possibility is to record a substitution, i.e. a nominal charring front parallel to the planes delimiting the cross section, and to determine the charring depth or velocity.

The burning rate of sawn wood beams or columns is higher compared to a laminated-glued wood of the same cross-section due to drying cracks.

In an extraordinary design situation - such as a fire effect - Eurocode requires a reduced level of safety, similar to the concept of the previous Hungarian standard. In the case of wood, it allows design for a 20% quantile of strength. The quotient of the 20% quantile and the 5%

quantile (characteristic value) is shown by the factor k_{fi}, the values of which can be taken into account for different woods according to the relevant standard.

The method of reduced cross-sections is a simple design method, it is used in the vast majority of engineering practice, and the annex to the MSZ EN 1995-1-2:2013 Eurocode 5: standard also recommends its application. Depending on the geometry, unilateral or multi-sided charred cortex is disregarded and the solidity of the transitional, nominally 7 mm thick zone under the thermal decomposition front is considered to be zero as well.

The low-temperature part of the intact wood cross-section (ideal cross-section) can be taken into account with a strength value of 20 ºC [5].

3.3.2 Method of Reduced Material Properties

The method of reduced material properties is more labor intensive but more accurate than the previous one. In engineering practice, it is typically used to verify slender wooden cross-sections, e.g. plank-thick elements of nailed wood beams. The charred outer crust is not taken into consideration for load-bearing capacity, but the transitional zone of about 7 mm below the thermal decomposition front is.

The transition zone is located at the edge of the residual cross-section, at the location of the expected maximum normal stresses, so the total remaining wood cross-section can be considered with reduced strength and stiffness characteristics corresponding to the higher temperature of the transition zone.

The higher temperature of the transition zone is a concept that is difficult to grasp from an engineering point of view, so its effect is described by an indirect measure of compactness characteristic of warming, depending on the perimeter and area of the intact cross section.

Calculation procedures that take into account the charring (burning) of unprotected wood can usually only justify limited fire resistance limits (typically 30, possibly 60 minutes). One way to achieve higher fire resistance limits is to clad the wood with fire protection building boards, e.g. covering it with refractory gypsum plasterboard or treating it with fire-retardant paint. However, the fire-resistance enhancing effect of paints on wood cannot be taken into account in the calculations of the relevant standard. [5]

3.3.3 Measurement of Protected Wooden Structures

In the case of timber structures with a fireproof covering, the fire resistance limit of the covering can be taken into account in the calculation, as follows:

- charring is shifted by t_{ch} time,
- charring may begin before the failure of the refractory casing, but at a reduced rate,
- after the failure of the refractory casing (t_f), the rate of charring shall be assumed to be twice the time until t_a,
- after the time t_a is equal to the depth of charring without the cover or 25 millimeters.

When using two layers of type A or H gypsum board, the thickness of the inner layer can be taken into account by 50% for the replacement thickness. When installing two layers of F-type gypsum board, 80% of the thickness of the inner layer can be taken into account for the replacement thickness. There are three possible ways to destroy a fire enclosure:

- charring or mechanical degradation of the casing material,
- inadequate penetration depth of the cover fastening components,
- inadequate distribution and distance between the components fixing the cover. [5]

3.4. Measurement of Masonry Structures for fire

The MSZ EN 1996-1-2:2013 Eurocode 6: standard [9] recommends the following methods for the fire sizing of masonry structures:

- tabulated data method,
- zone method.

3.4.1 Tabulated Data

When comparing with tabulated data or limits, the presence of a minimum wall thickness is checked after the masonry structure has been classified. The presence of a minimum wall thickness is intended to ensure load-bearing capacity (R), integrity (E), insulation (I) and resistance to mechanical impact (M). The required minimum wall thickness is determined by the combination of the masonry material, the strength and the quality of the mortar.

Mortar is a mixture of one or more inorganic binders, additives, water, or possibly additives, as defined in the relevant standard.

Fire resistance sizing can be carried out based on Table 1.2 of the MSZ EN 1996-1-2: 2013 Eurocode 6: standard. The value pairs without parentheses given in the table give the minimum wall thickness without plaster, where the first number is the brick thickness and the second number is the wall thickness together with the mortar. The first number of the value pair in parentheses indicates the minimum thickness of the walls with fire protection covering, while the second number indicates the minimum thickness of the walls with plaster.

Step 1: Find the appropriate table of the indicated standard based on the brick class, density, masonry compressive strength and utilization. This also includes meeting the requirements for load bearing, integrity, insulation and mechanical resistance.

Step 2: Select the fire resistance period based on the wall thickness.

3.4.2 Zone Method

In the zone method, the brick wall is divided into 3 zones. The innermost zone is defined by the total strength value, the middle zone by the reduced strength values and by neglecting the outer side affected by the fire, the load-bearing ability of the cross-section is determined.

In the application of the zone method, after determining the location of the isothermal lines, the cross-section is divided into sections, the strength and stiffness characteristics are determined and the sizing is performed with these data.

4. SUMMARY

The fire design of structures has a key role in ensuring the fire resistance of building structures. We have seen that the purpose of planning for a fire effect, which is considered to be an extraordinary design condition, is to keep our buildings and structures as stable as possible during the heat load caused by fires. Based on the sizing principles presented for reinforced concrete, steel, wood and masonry structures in the framework of this article, it can be concluded that depending on the function of fire-exposed building structures, different parameters such as load-bearing capacity, integrity and insulation must be met. It can be stated that there are approximate calculation methods for the different structural elements, which, of course, have to comply with the strict boundary conditions specified in the relevant standards. If the boundary conditions are not met, we can use more accurate calculation models or perform finite element modeling of the structure.

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