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METHODS FOR DETERMINING MASONRY WALLS FIRE RESISTANCE

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A b s t r a c t

In the paper, the general procedures for masonry wall design in fire situations are presented together with methods for determining the fire resistance according to EN 1996-1-2 [1] and its Polish version, PN-EN 1996-1-2 [2]. Special attention is paid to the practical application of presented methods (tabulated data and simplified methods based on reduced cross-section) and to pointing out possible problems and shortcomings. There is also brief comments on the process of introducing Euro code 6 (EN 1996-1-1 [3], EN 1996-1-2 [1]) for the design of masonry structures in Polish practice (codes: PN-EN 1996-1-1 [4], PN-EN 1996-1-2 [2]).

Keywords: masonry structures, fire resistance, verification methods

S t r e s z c z e n i e

W artykule przedstawiono metody weryfikacji odporności ogniowej ścian murowych według normy EN 1996-1-2 [1] i jej polskiej wersji PN-EN 1996-1-2 [2]. Szczególną uwagę zwrócono na praktyczne aspekty stosowania opisanych metod (danych tabelarycznych, uproszczonych metod bazujących na przekroju zredukowanym), wskazując ich potencjalne niedostatki. Skomentowano także proces wprowadzania normy Eurokod 6 (EN 1996-1-1 [3], EN 1996-1-2 [1]) do projektowania konstrukcji murowych do polskiej praktyki projektowej (normy: PN-EN 1996-1-1 [4], PN-EN 1996-1-2 [2]).

Słowa kluczowe: konstrukcje murowe, odporność ogniowa, metody weryfikacji

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1. Introduction

The basic requirements formulated for masonry structures in the case of fire include: load-bearing capacity (*R* function), integrity (*E* function) and thermal insulation (*I* function). In practice, these functions connected with fire resistance of specified structural elements are being transformed onto fire resistance classes expressed in minutes (30, 60, 90, ... , 240) for standard fire exposure. In the case of fire, the analysis of structure may be conducted on the level of isolated elements, for the part of the structure or for the whole structural system (global analysis). Fire models/scenarios used for the analysis may also exhibit different levels of complexity and accuracy – from nominal (standard) ones to real parametric fires. Within particular combinations of fire model and structural analysis level, different methods for verification of fire resistance may be applied: descriptive methods (using tabulated data), simplified or advanced engineering (calculation) methods, fire tests or a combination of tests and calculations.

For masonry structures, just as with structures constructed from other materials, for the specified time of fire duration it is necessary to satisfy the following general condition:

$$E_{fi} \leq R_{fi,t,d} \tag{1}$$

where:

E_{fi} – design value of actions effect for fire conditions according to EN 1991-1-2 [5], accounting for thermal strains effects,

$R_{fi,t,d}$ – appropriate design resistance for fire situations determined whilst taking into account the unfavourable effects of high temperature on the mechanical properties of masonry walls.

General principles as to the determination of fire resistance based on fire tests or tests combined with calculations are included in EN 1990 [6].

Due to practical reasons, tests in the fire chamber are usually carried out for isolated masonry walls, thus it is not possible to model the existence of other adjacent or restraining elements. Therefore, results can rather seldom be directly generalized onto elements with different geometry, load patterns or boundary conditions. However, the major advantages of fire tests over tabulated data or simplified calculation methods is the fact that they provide information about the real temperature distribution in walls and its deformations during heating as well as providing information about weak or sensitive points (e.g. connections) that are very difficult to detect by any other method. Results obtained from fire tests depend on the detailed procedures assumed, tests conditions, and the accuracy of applied measuring devices – hence the need for harmonisation of fire tests to have the possibility to compare results from different research centres in an univocal manner. In the case of masonry load-bearing walls, such procedures for fire testing are formulated and given in EN 1365-1 [7] and for non load-bearing walls – in EN 1364-1 [8].

2. Procedures for determining fire load capacity of masonry walls according to Eurocode 6 [1]

Behaviour of masonry walls in high temperature is conditioned by various factors:
- masonry unit material – ceramic, silicates, normal weight or lightweight concrete, cellular concrete, natural or artificial stone.
- type of masonry unit – solid, hollowed (type and magnitude of openings, their percentage participation in masonry unit volume), thickness of internal and external walls.
- type of mortar (normal, thin layer, lightweight),
- ratio of design load to design resistance of wall.
- wall thickness.
- load eccentricity.
- masonry unit density.
- type of wall structure (single-leaf, cavity wall, load bearing or non-load bearing wall)
- type and method of finishing the walls' surface.

Due to this fact, while applying any calculation method for masonry walls fire resistance, it is necessary to operate with temperature dependent properties that should be determined separately not only for each masonry material, but also for each type of masonry unit made from the same material, whilst taking into account the other major factors mentioned above.

2.1. Tabulated data for determining the fire resistance of masonry walls

Evaluation of fire resistance for masonry walls may be carried out in the simplest manner by using the tabulated data included in Appendix B of EN 1996-1-2 [1]. The tables provided give minimum thickness of walls necessary to achieve the required fire resistance for specified types of wall and for determined way of loading. Tables may be applied for walls that satisfy requirements of EN 1996-1-1[3], EN 1996-1-2 [1] and EN 1996-3 [9] for appropriate types and functions of walls. Values of minimum thicknesses are defined for the structural layer of walls, without taking into account the finishing layers.

In Table 1 there are presented requirements as to the minimum wall thicknesses for satisfying appropriate *REI* function for load-bearing walls (with normal mortar, constructed from elements from group 1) according to EN 1996-1-2 [1]. In cases where two lines of numerical values are given in the table, the first set determines fire resistance for the wall without a finishing layer, while the second – for walls with appropriate finishing layers but with a thickness of at least 10 mm from both sides for single-leaf wall or from the side of the fire action for the cavity wall. If there are two values given in one line (for ex. 70/90) it means that the recommended wall thickness is within the defined range (for ex. from 70 to 90 mm).

According to PN-EN 1996-1-1 [4] the minimum thickness for structural walls constructed from masonry units with $f_k \geq 5$ MPa should not be smaller than 100 mm, and for walls with $f_k < 5$ MPa – 150 mm (f_k – characteristic value of compressive strength for wall). The minimum thickness for shear walls is 180 mm. In practice, in Poland there are applied as structural elements walls with thickness at least equal to 180 mm, which means that they satisfy the criterion *REI* 90 and for some materials (even for minimum thicknesses equal to 180 mm) also *REI* 120.

Table 1

Minimum thickness for load-bearing brick wall (REI criteria) to satisfy fire resistance requirements according to EN 1996-1-2 [1] – walls with normal mortar made from elements of group 1

Type of masonry elements in wall		Minimum wall thickness [mm] to obtain fire classification REI for time [minutes] $t_{fi,d}$					
		REI 30	REI 60	REI 90	REI 120	REI 180	REI 240
ceramic(1)	$A \leq 1{,}0$	90/100 (70/90)	90/100 (70/90)	100/170 (70/90)	100/140 (100/140)	170/190 (110/170)	190/210 (170/190)
	$A \leq 0{,}6$	90/100 (70/90)	90/100 (70/90)	100/140 (70/90)	140/170 (100/140)	140/170 (110/170)	190/200 (170/190)
silicate(2)	$A \leq 1{,}0$	90/100 (90/100)	90/100 (90/100)	100 (90/100)	140/200 (140)	190/240 (170/190)	190/240 (140)
	$A \leq 0{,}6$	90/100 (90/100)	90/100 (90/100)	100 (100)	120/140 (100)	170/200 (140)	190/200 (140)
normal weight concrete(3)	$A \leq 1{,}0$	90/170 (90/140)	90/170 (90/140)	90/170 (90/140)	100/190 (90/170)	140/240 (100/190)	150/300 (100/240)
	$A \leq 0{,}6$	70/140 (60/100)	70/140 (70/100)	90/170 (70/100)	90/170 (70/140)	100/190 (90/170)	140/240 (100/190)
lightweight concrete(4)	$A \leq 1{,}0$	90/170 (90/140)	90/170 (90/140)	100/170 (90/140)	100/190 (90/170)	140/240 (100/190)	150/300 (100/240)
	$A \leq 0{,}6$	70/140 (60/100)	70/140 (60/100)	90/170 (70/100)	90/170 (70/140)	100/190 (90/170)	100/240 (90/190)
cellular concrete $350 \leq \rho \leq 500$	$A \leq 1{,}0$	90/115 (90/115)	90/140 (90/115)	90/200 (90/200)	90/225 (90/225)	140/300 (140/240)	150/300 (150/300)
	$A \leq 0{,}6$	90/115 (90/115)	90/115 (90/115)	100/150 (90/115)	90/175 (90/150)	140/200 (140/200)	150/200 (150/200)
cellular concrete $500 \leq \rho \leq 1000$	$A \leq 1{,}0$	90/100 (90/100)	90/150 (90/100)	90/170 (90/150)	90/200 (90/170)	125/240 (100/200)	150/300 (100/240)
	$A \leq 0{,}6$	90/100 (90/100)	90/100 (90/100)	90/150 (90/100)	90/170 (90/125)	125/240 (125/140)	150/240 (150/200)

(1) 5 MPa $\leq f_b \leq$ 75 MPa; $1000 \leq \rho \leq 2400$ kg/m^3; (2) 12 MPa $\leq f_b \leq$ 15 MPa; $1400 \leq \rho \leq 2400$ kg/m^3
(3) 6 MPa $\leq f_b \leq$ 35 MPa; $1200 \leq \rho \leq 2400$ kg/m^3; (4) 2 MPa $\leq f_b \leq$ 15 MPa; $400 \leq \rho \leq 1600$ kg/m^3
f_b – normalized compressive strength for masonry elements [MPa]
ρ – volume density [kg/m^3]

2.2. Calculation methods for masonry walls fire resistance verification

Fire resistance of masonry walls may be also determined by calculation methods assuming appropriate failure mechanisms in case of fire action, appropriate temperature dependent material properties, wall thickness as well as effects of thermal strains and deformations. In EN 1996-1-2 [1] there are included two calculation methods for fire resistance determination: simplified (in Annex C) and advanced (in Annex D).

In introduction to calculation methods it is underlined that their accuracy is to be determined by comparison of calculated values with fire tests results.

According to the **simplified method** for fire design, the resistance is calculated using boundary conditions for reduced cross-section of the wall, for established time of fire duration and for loads as for normal temperature design. This method may be only applied for standard fire conditions. In the calculation procedure, it is necessary to determine temperature profiles within the cross-section, then to evaluate the reduced cross-section and calculate the capacity for ultimate limit state for reduced cross-section and finally – to verify if this capacity (calculated according to general assumption as for normal temperature conditions given in EN 1996-1-1 [3]) is not less than is required for appropriate combination of actions. In Fig. 1 (showing the horizontal cross-section for the wall) there is presented the general scheme for determination of appropriate zones for reduced cross-section of the wall in the case of fire acting from one side.

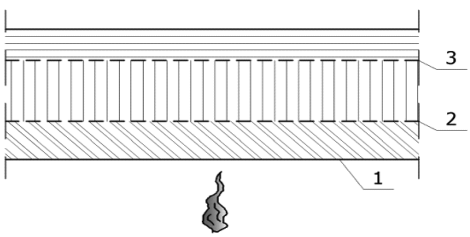

Fig. 1. Horizontal wall cross-section with zones up to the temperature θ_1, between θ_1 and θ_2 and above θ_2 (structurally non-effective zone): 1 – the edge of the initial cross-section, 2 – isotherm for $\theta = \theta_2$, 3 – isotherm for $\theta = \theta_1$

For fire situation at the ultimate limit state it is necessary to satisfy the following condition:

$$N_{Ed} \le N_{Rd,fi(\theta)i} \tag{2}$$

Design value of walls capacity under vertical load is expressed as:

$$N_{Rd,fi(\theta)i} = \Phi\left(f_{d\theta1}A_{\theta1} + f_{d\theta2}A_{\theta2}\right) \tag{3}$$

where:

$A_{\theta1}$ – area of masonry wall zone with temperature not exceeding θ_1;
$A_{\theta2}$ – area of masonry wall with temperature between θ_1 and θ_2;

θ_1 – maximum temperature at which the strength of masonry walls may be assumed as for normal temperature conditions (see: Table 2);
θ_2 – temperature above which masonry wall strength is reduced (see: Table 2);
N_{Ed} – design value of vertical load;
$f_{d\theta 1}$ – design value of compressive strength for masonry walls in temperatures not exceeding θ_1;
$f_{d\theta 2}$ – design value of compressive strength in the temperature range between θ_1 and θ_2, assumed as $cf_{d,fi1}$;
c – constant determined from stress-strain relationship obtained from fire test for appropriate considered material (see: Table 2);
X – reduction coefficient for capacity in the middle of wall determined on the basis of EN 1996-1-1 [3] (where it is denoted as θ_m) whilst taking into account additional eccentricity $e_{\Delta\theta}$;
$e_{\Delta\theta}$ – eccentricity caused by fire load.

Eccentricity $e_{\Delta\theta}$ caused by fire action may be determined from fire tests or from the relationship:

$$e_{\Delta\theta} = \frac{1}{8} h_{ef}{}^{2} \, \frac{\alpha_t(\theta_2 - 20)}{t_{Fr}} \leq h_{ef} / 20 \tag{4}$$

where:

$e_{\Delta\theta} = 0$ when fire is acting from all sides,
h_{ef} – effective height of wall,
α_t – thermal elongation coefficient for masonry walls according to EN 1996-1-1 [3], p. 3.7.4,
20°C – temperature assumed on the non-heated surface of the wall,
t_{Fr} – thickness of cross-section for which temperature does not exceed θ_2.

In Table 2, there are listed values of parameters needed for masonry wall calculation under vertical loading according to equation (3). It is worth underlying that despite introducing and defining the constant *c*, there are not included the specified numerical values for that symbol. It is recommended to determine *c* values from fire tests separately for each different masonry wall material.

In Fig. 2 there is schematically presented the temperature distribution along the wall's thickness together with way of determination of reduced cross-section for calculation of fire resistance on the base of the simplified method.

Temperature distributions in wall cross-sections and the temperature at which a masonry wall is no longer structurally effective material in fire condition should generally be determined on the base of fire tests or using information from the fire test results base. As a design aid, temperature distributions included in Annex C of EN 1996-1-2 [1] may be used. In Fig. 3, there are presented exemplary temperature distributions within the cross-section for standard fire durations from 30 to 120/180 minutes for walls constructed from ceramic masonry units (Fig. 3a) and from silicate masonry units (Fig. 3b).

The basis for **advanced methods** of calculation constitute the general physical laws allowing for evaluation of behaviour of structural elements subjected to fire actions. Advanced methods of calculations make it possible to determine:

- thermal response – development and distribution of temperature within structural elements, based on the principles and assumptions of heat flow theory whilst taking into account appropriate thermal actions as well as thermal and physical properties of materials as temperature functions.
- mechanical response – evaluation of structural behaviour accounting for unfavourable effects of high temperature on mechanical properties of materials and for effects of thermal stress and strains.

Table 2

Basic parameters for masonry wall materials necessary for analysis of fire resistance according to simplified method of EN 1996-1-2 [1]

Masonry wall elements and mortar (unprotected surface)	Value c	Temperature °C	
		θ_2	θ_1
Ceramic elements with general purpose mortar	c_{cl}	600	100
Silicate elements with mortar for thin joints	c_{cs}	500	100
Lightweight concrete elements with general purpose mortar	c_{la}	400	100
Normal weight concrete elements with general purpose mortar	c_{da}	500	100
Cellular concrete elements with mortar for thin joint	c_{aac}	700	200

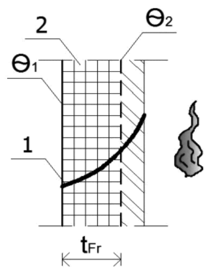

Fig. 2. Temperature distribution and definition of reduced vertical cross-section for calculating the fire resistance for wall by simplified method: 1 – temperature distribution, 2 – reduced cross-section maintaining the material strength ($A_{\theta 1} + A_{\theta 2}$)

Some information as to the values of parameters needed for thermal and mechanical analysis in fire situations are included in Annex C of EN 1996-1-2 [1]. In Fig. 4 and Fig. 5, there are shown selected relationships for ceramic and silicate masonry units in the form of design values of temperature dependant material physical and thermal properties (Fig. 4) and stress-strain graphs as a function of temperature (Fig. 5).

For relationships given in Fig. 5 it is worth noting that silicate masonry units (Fig. 5b) indicate within the certain range of temperatures the increase in strength in comparison with normal temperature condition (equal to 20°C), which is not observed for other materials, e.g. ceramic masonry units (Fig. 5a).

a) b)

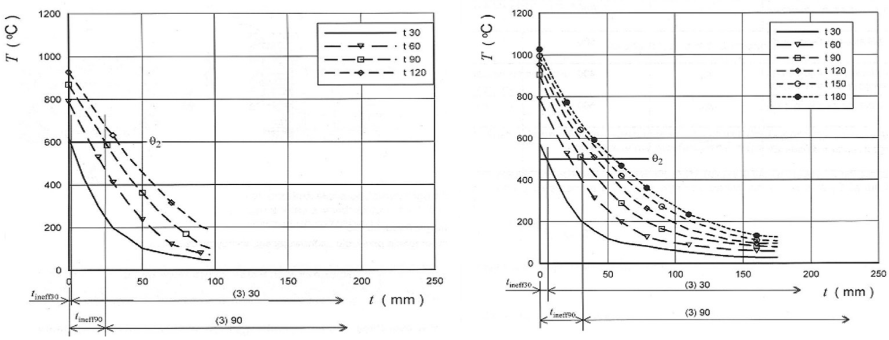

Fig. 3. Temperature distribution within the cross-section for standard fire duration from 30 to 120/180 minutes: a) ceramic masonry units (density 1000–2000 kg/m³), b) silicate masonry units (density 1500–2000 kg/m³)

a) b)

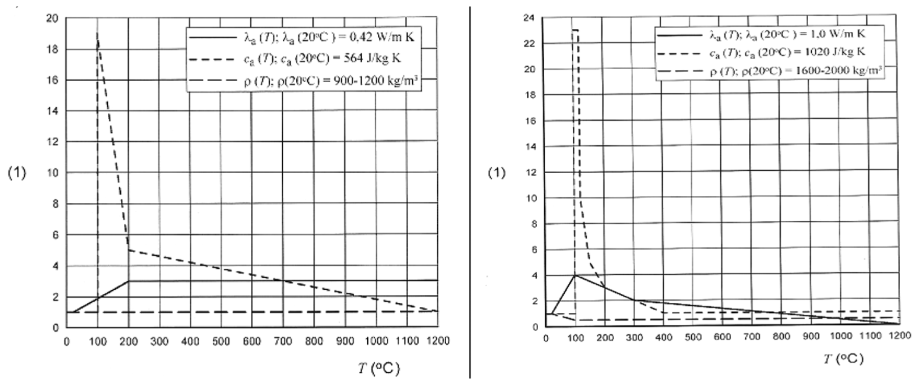

Fig. 4. Design values of temperature-dependent material properties for: ceramic masonry units (density 900–1200 kg/m³), b) silicate masonry units (density 1600–2000 kg/m³)

a) b)

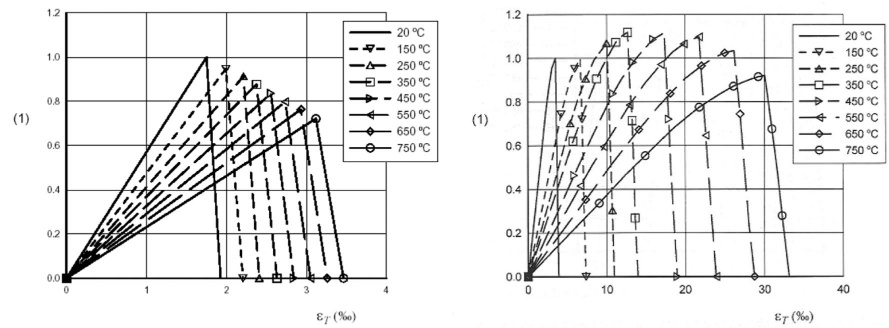

Fig. 5. Design values of temperature-dependent stress-strain relatioships: a) for ceramic masonry units (group 1) with the strength 12 N/mm²–20 N/mm² and density 900 kg/m³–1 200 kg/m³, b) for silicate masonry units (group 1) with the strength 12 N/mm²–20 N/mm² and density 1600 kg/m³–2000 kg/m³

Note: vertical axis expresses the ratio of strength in fire temperature T to strength in temperature 20°C

2.3. Fire tests for masonry walls

For all types of masonry walls, the fire resistance may be estimated by fire tests that should be conducted according to appropriate codes [7–8]. In analyzing tests results, it may be necessary to take into account the amendments resulting from possible different systems of loading the walls in comparison with those given in codes.

Fire tests for masonry walls are necessary to determine directly the fire resistance for masonry elements and walls. But they also constitute the source for the evaluation and calibration of appropriate material parameters of different types (physical, thermal, mechanical) applied for calculation methods or advanced models. It concerns for example the value of *c* in simplified method of calculation, which is essential for determining appropriate zones with different values of the compressive strength of masonry units.

From information of the fire test course and results, included in reports collected by authors from different laboratories (Fires, Batizovce – Slovak Republic; MPA TU Braunschweig – Germany; ITB, Warsaw – Poland) from tests on various masonry units (ceramic, silicate, concrete) that were carried out on masonry units producers' orders, it may be concluded that due to significant differentiation in properties of materials of masonry units, the behaviour of walls constructed from various units in fire tests may be significantly diversified – with various phenomena occurring during heating or different failure modes. For example, ceramic masonry units (especially hollow ones) exhibit severe loss of external surfaces (spalling) from the side exposed to fire that may reach even 50–70% of the total area of wall (Fig. 6a) and the failure mode is usually due to formation and propagation of vertical cracks. For silicate elements there are observed, vertical and horizontal cracks in masonry elements and in joints at failure, while for cellular concrete elements during heating there is observed process of moisture condensation along joints and cracks on non-heated side of wall (Fig. 6b).

a) b)

Fig. 6. Examples of typical phenomena occurring while carrying out fire tests: a) spalling from the wall side exposed to fire for ceramic masonry hollow units (Report from fire tests on walls made from THERMOPOR masonry hollowed units – LEIER, Poland), b) condensation zones along the joints and cracks for walls made of concrete blocks on non-heated surface (Report from fire tests on walls made from OPTIROC masonry units – MAXIT, Poland)

3. Comments on introducing EN 1996-1-2 [1] into Polish practice

Until the time of introducing the code PN-EN 1996-1-2 [2] into Poland, for determination of minimum masonry wall thickness for required fire resistance (*REI*) there were applied recommendations formulated and included in the ITB Instruction [10]. Minimum wall thicknesses that were given in [10] are within the ranges proposed by PN-EN 1996-1-2 [2] or are greater than the upper limits for these ranges. In PN-EN 1996-1-2 [2], introducing EN 1996-1-2 [1] into Polish practice, there were accepted as a rule – without any changes – recommendations of European code. At the same time, there was worked out the National Annex (with Nationally determined parameters) for the code EN 1996-1-1 [3], assuming different values of coefficients for determining the masonry walls compressive strength. Compressive strengths (f_k) evaluated from relationships included in EN 1996-1-1 [3] are significantly greater than those calculated on the basis of PN-EN 1996-1-1 [4]. Differences are also visible while determining masonry walls elasticity modulus (E) which results in the fact that the wall's load-bearing capacity determined on the basis of relationships included in codes [3] and [4] may differ even about 30%. It plays an important role in evaluating coefficient α, defining the level of exertion of wall (ratio of design load to design resistance of wall), for which the minimum wall thickness is given as a function of the required *REI* value. Lower values of f_k calculated on the basis of PN-EN 1996-1-1 [4] determines higher values of α in comparison with those obtained from EN 1996-1-1 [3], which finally results in the necessity to accept the thicker walls by tabulated data method. Such values of $f_{k,}$ according to National Annex, are due to the insufficient number of experimental results within this scope considered and from the necessity to operate with the safe/conservative values. According to PN-EN 1996-1-1 [4], values of f_k may also be determined on the basis of experimental results. From these reasons, it would be desirable in Poland – in fire test preparations and programming – to determine experimentally the basic mechanical parameters for masonry walls. Such a procedure would make it possible to widen the existing test results base and to refer to the obtained results with those from foreign research centres.

4. Conclusions

In the paper, methods for determining masonry walls' fire resistance according to EN 1996-1-2 [1] are presented and commented on from the point of view of their practical application and with regard to fire tests. Based on that, the following general conclusions may be drawn:

1. Due to significant differentiation in thermal, physical and mechanical properties of various masonry materials, types of masonry units and mortar, while calculating the fire resistance of masonry walls, it is necessary to operate with values determined separately for each combination of these variables. Moreover, additional important factors have to be taken into account – wall thickness, load eccentricity, ratio of load design to wall's design resistance. This need may be satisfied by working out and taking advantage of the base for fire test results conducted in different research centres on numerous various masonry materials and elements (the authors are trying to collect such results from different countries and laboratories – see: p. 2.3).

2. Application of the simplest method based on tabulated data is easy and straightforward, but has some practical shortcomings and limitations. Usually in tables (see: Table 1) there are included not the specific values, but ranges of minimum wall thicknesses. In many cases – especially for units made of normal weight, lightweight and cellular concrete, but also of silicates and masonry for higher fire resistance – these ranges are quite wide and in extreme examples, the highest thickness may be even twice the lowest from the admissible wall thickness range. That may lead to quite serious problems with practical application of tabulated data by designers.
3. Calculation methods given in EN 1996-1-2 [1] are based on many parameters that should be determined by fire tests. Though some numerical values or functions are included in Annex C (for ex.: values of temperatures θ_1 and θ_2 needed for determination of zones indicating different level of design compressive strength for masonry wall, design values of temperature-dependent physical and thermal properties for various materials, design values of temperature-dependent stress-strain relationships for masonry walls materials), there is still a lack of some indispensable data (for example: value of constant c for different masonry wall elements in simplified method, being reduction coefficient for design compressive strength in the intermediate zone between the temperature θ_1 and θ_2). This, once again, strongly underlines the importance of fire tests and manifests the need for existence of a fire test results base.
4. As to the process of introducing Eurocode 6 (for masonry structures design in normal temperature conditions and for accidental fire situation) into Polish practice, it is worth pointing out some incoherencies existing in final versions of PN-EN 1996-1-1 [4] and PN-EN 1996-1-2 [2] due to the presence of National Annexes. They were briefly discussed in p.3 of the paper and concern mainly the questions of the determination of basic mechanical parameters (f_k and E) for masonry walls at normal temperatures, but which also results in operating with a different value α (ratio of design load to design resistance of wall) while using tabulated data – and in consequence with various resulted values of minimum wall thickness for specified required fire resistance.

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