

ASSESSMENT OF THE RESPONSE OF PREFABRICATED HOUSE TO THE EXPLOSION OF GAS-AIR MIXTURE

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Research article

Abstract: In this contribution, simple computational approaches to the determination of blast load and its effects on the structure of prefabricated house are proved. Blast waves parameters are defined for chosen room during natural gas escape. Blast load parameters are calculated by several methods. Estimation of its effects on the structure is modelled using numerical modelling.

Keywords: Explosion, natural gas, structure response, building structure, prefabricated house.

Introduction

Statistical data of Fire Rescue Service of the Czech Republic points to long-term unfavourable state of high number of gas explosions in buildings. It especially concerns natural gas explosions. Despite all the efforts to intercept the controlled risk, an accident may occur. Work experience show more and more the necessity of paying attention to the management of health and safety. Both these aspects are above all involved in lives and health of persons but also in substantial financial costs in cases of serious accident or emergency. To reduce the influence of the accident associated with explosion, blast waves explosion parameters should be taken into consideration while designing the objects, equipment, systems or its surroundings. It is required to optimize the construction on the basis of blast load information. Wide and complex issue of shock wave propagation includes a series of uncertainties and solution procedures. Knowledge of blast waves parameters is necessary for the detailed solution of interaction with the structure. Following these parameters, blast load could be determined.

Materials and methods

Determination of blast load in a partly closed space

Standard (ČSN EN 1991-1-7, 2007) could be used for determination of load caused by the explosion for all parts of structural and civil engineering where gas is used or regulated, or where explosives (such as explosive gas or fluids forming explosion vapors) are stored, or where gas is stored or transported (e. g. chemical equipment, containers, tanks, facilities

for wastewaters, residential buildings with gas installations, energetic ducts, road and rail tunnels). For standard purposes, the explosion is defined as a rapid chemical reaction of dust, gas and vapor in the air. Throughout we have to take into consideration both the transfer of blast waves parameters (high overpressures and temperatures) from non-load bearing elements of the structure to load bearing elements and afterwards their reactions. The pressure caused by an internal explosion depends mainly on the type and homogeneity of explosive mixture, on its concentration, ignition source, on the turbulence caused by internal objects and on the size and quantity of the explosive mixture participating on the explosion effect. If the building should be relieved sufficiently from the effects of the explosion, it must be equipped with the necessary amount of exhaust (relief, vent) areas. For exhaust components, we can consider light roofs, walls, or even sub-areas in the external structures such as windows and doors. For windows and doors, we have to take into account the risk of personal injury caused by broken glass or frames of the filling shattered during the explosion (ČSN EN 1991-1-7, 2007).

Computational procedures for the determination of venting deflagration pressure

Venting of deflagration means that the enclosure is opened for a short time or permanently during the initiation of deflagration and after the reaching of predefined pressure. The principle of deflagration venting lies in the opening of a vent area after the development of deflagration and the reaching of certain level of vent element reaction pressure. Therethrough, primarily closed inner space is connected with external environment. This reduced

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pressure is called venting deflagration pressure or also reduced pressure (Damec, 2005). To determine venting (reduced) deflagration pressure, a large number of relations, formulas and procedures can be found. Computational methods according to Cubbage and Simmonds, Rasbash and European standard EN 1991-1-7 was chosen for practical application. Theory and computational relations of the above mentioned procedures were previously published in (Mynarz and Šimoník, 2010).

Practical application of computational procedures on the object

The study deals with the estimation of deflagration power in the case of natural gas leak in a kitchen supposing the creation of potentially explosive atmosphere. The analysis was performed on a prefabricated house of T 06 B-BTS type with 12 floors and 60 residential units, see Fig. 1. In the room, internal (partially bounded) deflagration of methane-air explosive mixture was simulated.

Scenario of the initiation of deflagration

In the kitchen of prefabricated house, the burner on a gas stove flames out. It can occur in several ways, e. g. while cooking on the stove, heated fluid flows out of a utensil; or due to the malfunction of burner and air circulation around the stove, thereby blowing out the flame; or while igniting gas burner, gas supply is turned off and then restarted again (the main gas valve). If the stove is not equipped with a flame failure safety device, gas supply is not interrupted when the flame extinguishes, and thus the gas begins to spread through the room. The leakage can also occur due to improper handling, leak or crack (hole) on the feed pipe or hose. Afterwards, explosive concentration is forming during mixing with surrounding air. The initiation of explosive mixture most likely occurs when turning on the electrical equipment. A light switch at the 150 cm distance from the stove was determined as the most likely source of ignition.



Fig. 1 Prefabricated house T 06 B-BTS (Prefabricated houses, 2010)

Computation of gas leak amount and of the initiation time of explosive concentration

The kitchen room is of a rectangular shape with floor area 12,3 m² and clear height of 2,6 m. Gas stove is placed in the corner of the room with common kitchen furniture. Turning off the most powerful burner with nozzle diameter 1,25 mm and 2,6 kW power (Fík, 2004) was considered for the calculation of the initiation time of explosive concentration, see Tab. 1.

Tab. 1 Parameters for the calculation of explosive concentration in the kitchen of a prefabricated house

Room dimensions:	
• length	3,56 m
• width	3,38 m
• height	2,60 m
Room volume - $V_{místnosti}$	31,29 m ³
Gas rate - v_{CH_4}	0, 273 m ³ .hod ⁻¹
Minimal explosive concentration - C_{CH_4}	4,4 %

The estimation of minimal leaked methane amount for the formation of an explosive concentration V_{CH_4} :

$$V_{CH_4} = \frac{V_{místnosti} \cdot C_{CH_4}}{100} = 1,38 \text{ m}^3 \quad (1)$$

The estimation of minimum time of leakage for the formation of an explosive concentration t_{min} :

$$t_{min} = \frac{V_{CH_4}}{v_{CH_4}} = 5,05 \text{ hrs} \approx 5 \text{ hours } 3 \text{ minutes} \quad (2)$$

The calculation (2) shows that minimum time for the formation of explosive concentration in the room is 5 hours and 3 minutes. However, this time cannot be taken as an exact value because the formation of an explosive concentration is influenced by other factors. To achieve maximum pressure during venting deflagration, explosive mixture does not need to be found throughout the whole area; it just has to occur at the point of ignition source, see Tab. 2. In the case of leakage failure of outside wall, this calculation is irrelevant and it depends only on the size of these leaks; thus the initiation time of explosive concentration may be extended or the explosive concentration does not need to occur at all.

Tab. 2 Source data about the room and about a range of natural gas leak

Disposition of the room				A range of a leak			
Floor	Function of the room	Area [m ²]	Volume of the room [m ³]	Vent area [m ²]	Volume [m ³]	Weight [kg]	LEL [obj. %]
2 nd floor	kitchen	12,3	31,3	2,1	1,4	0,9	4,4

LEL - Lower Explosive Limit

For the determination of deflagration pressures during venting deflagration, three methods were used, see (Mynarz and Šimoník, 2010). Tab. 3 presents the values of deflagration pressures obtained by manual calculation.

Tab. 3 The values obtained from different calculations - comparison

Calculation according to:	Venting deflagration pressures [kPa]	Positive phase τ^+ [ms]	
		P_1	P_2
1 Cubbaga a Simmondse	P_1	7,43	300
	P_2	16,14	
2 Rasbash	p_m	23,78	
3 EN - 1991-1-7	p_d	5	
	p_d	14,11	

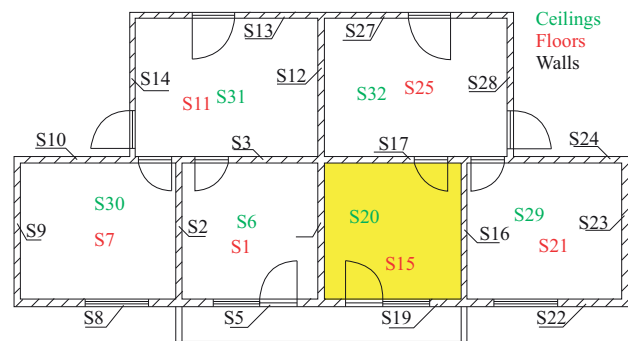


Fig. 2 Layout of involved parts of residential units with denoted structural elements (yellow section represents the room where the deflagration was simulated in)

Description of the structure and load

Assessed building has twelve floors. The structural system consists of non-prestressed reinforced-concrete prefabricated panels connected by welding of reinforcement and then pouring the cement mixture. The building forms a transverse load-bearing system with preceded cladding. At the tower house in the longitudinal way, a wing (tract) runs in a module of 3,6 m with a staircase at the facade and with elevators. Transversal walls with module of 7 x 3,6 m run perpendicularly to the hall, symmetrically on both sides. Building depth is 12 m and the construction depth of a floor is 2,8 m. The disposition of one room is presented in Fig. 2.

In the case study, gas leak was considered on the second floor. Firstly, blast load was assumed as a uniformly distributed static pressure applied effectively at the same time to all the areas enclosing the space. Dynamic load was considered in the next stage. Opening of vent areas was supposed, i. e. venting deflagration is the matter. Positive phase duration of blast wave is a very important parameter for the estimation of blast effect. This time period ranges in the order of hundreds of milliseconds in the case of gas mixture explosion. In this study, the positive phase of blast wave was estimated as 300 ms, mainly based on our own measurements and experience.

Computation of wall failure of the room

After the estimation of deflagration pressures and according to the demands on results accuracy, the structure could be assessed, either by simplified way or by sophisticated calculation using numerical models. Software application based on the finite element method was used for the calculations. Blast wave is acting with uniformly continuous distribution perpendicular to the middle plain of the wall with duration of 0,3 s and overpressure value of 23,78 kPa. Reinforced concrete is considered a constructional material. The exact parameters of the material are given in Tab. 4. The dimensions of single surface elements are listed below in Tab. 5.

Tab. 4 Material characteristic of reinforced concrete of the prefabricated house

Concrete	C30/37
Reinforcement	B 400A
Unit weight	2500 kg.m ⁻³
Modulus of elasticity E	32800 MPa
Poisson's ratio	0,2
Logarithmic decrement	0,2

Tab. 5 Dimensions of structural elements

Type of structural element	Element (see fig. 2)	Dimensions (l x h x w) in mm
Wall panel	S 2, 4, 9, 16, 23	3560 x 2600 x 140
External panel	S 8, 22	3710 x 2600 x 200
External panel	S 5, 19	3380 x 2600 x 200
Wall panel	S 10, 24	3710 x 2600 x 140
Wall panel	S 3, 17	3380 x 2600 x 140
Wall panel	S 12, 14, 28	3450 x 2600 x 140
Wall panel	S 13, 27	4560 x 2600 x 140
Ceiling panel	S 11, 25, 31, 32	4560 x 3450 x 150
Ceiling panel	S 1, 6, 15, 20	3560 x 3380 x 150
Ceiling panel	S 7, 21, 29, 30	3710 x 3560 x 150

Structure response was investigated by static and dynamic computations. For the calculations, several simplifications were accepted (Makovička and Makovička, 2008). These are:

- blast wave with planar face (acting without phase shift),
- for static load, blast wave effect is consider a continuous, surface and uniform distribution of the whole element (perpendicular to its plane) or the whole structure,
- for dynamic load, blast wave effect is focused into the geometrical centres of single areas of the structure,
- a course of pressure rise (impulse) has a triangular shape and its peak value corresponds to the maximum overpressure during internal explosion after the opening of vent areas.

Results

Modal analysis

The executing of modal analysis provides the natural frequencies of the structure. For greater accuracy of results, mesh is refined to 0,2 m for the length of the side of surface element. A total of 10 natural frequencies were calculated on discretisation final-element model, see Tab. 6. The same number of free vibration mode shapes was solved; the first of them (Fig. 3) is usually the most important shape for the structure under blast load.

Tab. 6 Natural frequencies

N	1	2	3	4	5
f [Hz]	10,87	18,13	22,58	25,51	42,57
T [sec]	0,092	0,055	0,044	0,039	0,023
N	6	7	8	9	10
f [Hz]	43,75	44,59	45,81	46,25	47,26
T [sec]	0,022	0,022	0,021	0,021	0,021

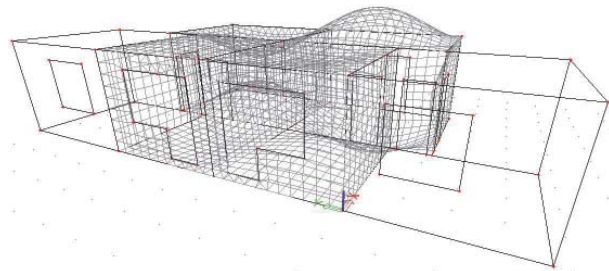


Fig. 3 The first free vibration mode shape

Equivalent static load

Equivalent static load is obtained by multiplying the calculated deflagration pressure by the dynamic coefficient δ . The dynamic coefficient value is computed according to the formula (3) after substituting the values from Tab. 7.

Tab. 7 The values for dynamic coefficient calculation

k_m - coefficient of ductility [-]	1,50
$T_{(i)}$ - i-th natural frequency; in this case it is T_1 [s]	0,0920
τ^+ - positive phase [s]	0,30

$$\frac{1}{\delta} = \frac{T_{(i)} \cdot \sqrt{2 \cdot k_m - 1}}{\pi \cdot \tau^+} + \frac{1 - \frac{1}{2 \cdot k_m}}{1 + 0,7 \cdot \frac{T_{(i)}}{\tau^+}} \Rightarrow \delta = 1,46 \quad (3)$$

The next step is to calculate the equivalent static load P_{ekv} which is obtained from the following equation:

$$P_{ekv} = \delta \cdot P_m = 34,62 \text{ kPa} \quad (4)$$

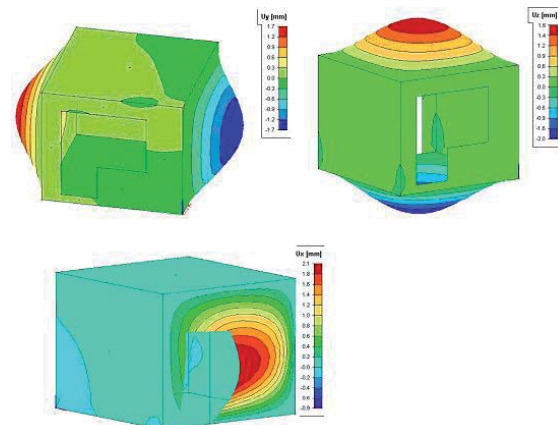


Fig. 4 Graphic visualization of slabs deflection at the equivalent static modelling of the explosion

Manual calculation of the response of the wall

For calculation, areas with the absence of windows (S4, S15, S16 and S20) were selected. The computational procedure is carried out according

to (Bareš, 1989). Tab. 8 shows the values used for calculation according to the formula (5); pin bearing around the perimeter of panels is assumed.

Tab. 8 The values for manual calculation of slabs deflection

	Wall S4, S16	Ceiling S15	Ceiling S20
Modulus of elasticity E [MPa]	32800	32800	32800
Sides ratio lx/ly [-]	1,37	1,05	1,05
Length of the side lx [m]	3,56	3,56	3,56
Deflagration pressure p [MPa]	0,034	0,034	0,034
Thickness of the structure h [m]	0,14	0,15	0,15
β [-]	0,024	0,044	0,044

$$w_s = \beta \cdot \frac{q \cdot l_x^4}{E \cdot h^3} \quad (5)$$

Discussion

The comparison of single values is given in Tab. 9. Therefrom, it is evident that dynamical loads implicate the largest deformations (deflections) in the structure. Equivalent static computation using software corresponds to the manual calculation. Deflections arising from the dynamic load are nearly double compared to the static load deflections but their values are still low, so the structure failure is not likely.

After the evaluation of final maximum structure deflections, it can be stated that in the case of shock wave occurrence, the blast effects (presented for example in (Damec, 2005), Table 6-1) impact the structure differently at the same pressure value. According to the (Makovička and Janovský, 2008), the shock wave of overpressure value of 24 kPa implicates considerable disturbance of urban building - that was not confirmed for the case of modelled structure.

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Tab. 9 Deflections comparison by blast effect on the structure

Calculated values [mm]	Maximum deflection in the X direction		Maximum deflection in the Y direction		Maximum deflection in the Z direction	
	wall S17	wall S19	wall S4	wall S16	ceiling S15	ceiling S20
Static	2,1	0,9	1,7	1,7	2	1,6
Dynamic	2,1	0,7	3,2	3,2	3,8	3,5
Manual			1,5	1,5	2,5	2

The authors drew the conclusion that, in the terms of prefabricated house, internal venting gas deflagration does not cause sufficiently strong overpressure to cause the failure of assessed structure.

Conclusion

According to (Damec, 2005) or (Makovička and Janovský, 2008), if the deflagration overpressure is known, it is possible to estimate probable damages to the structure. In the case when more detailed assessment of selected part of the structure is required, numerical modelling can be used. On the basis of venting deflagration computations in a dwelling space of prefabricated building, deflagration pressures were obtained according to different methods in the range from 14,11 kPa to 23,78 kPa (see Tab. 3). For calculated overpressure, partially confined explosion in assessed object should cause breaking the glass window panels or bursting the door wing. However, numerical computation did not make out the failure of wall or ceiling panels as a result of explosion. Calculated stresses and internal forces do not exceed the strength of the reinforced-concrete elements and neither is probable the considerable cracks development on the structure.