BLAST LOAD OF BUILDING STRUCTURE

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The paper follows from the theory of explosion and interaction of an impact wave formed by the explosion and a structure. As a rule, a number of simplifying assumptions must be applied as regards the characteristics of the explosion and of the threatened structure to analyze the structure. An example of dynamic analysis of a new reinforced concrete structure, loaded with a blast wave was used to apply the principles of simplified engineering analysis of an explosion-loaded structure. The way of structure failure was analyzed based on time courses of calculated internal forces and displacements of individual structure elements. The criteria of structural elements failure due to explosion load effects were determined as a part of the dynamic structure response assessment.

Keywords: *explosion, blast wave, building, dynamic response, assessment*

1. Introduction

When a small charge explodes in the external space of a building, a pressure wave is formed by the explosion that applies a load on the surrounding building. The blast wave starts propagate from the point of explosion approximately in spherical wave fronts, and upon hitting the surface of a building structure (walls, ceilings, floors, equipment, etc.) or terrain, the wave front is reflected and modified. If the blasting charge explodes in an open area, the action of the pressure of the shock wave on a barrier depends on how the structure is situated with respect to the focus of the explosion, on the path from the explosion to the structure, on the characteristics of the loaded structure, and on the shock wave parameters on contact with the building. During an actual event, the specific course of action of the load depends on the whirl bypass of the surface of the structure, on the atmospheric pressure, on the temperature conditions and other factors which are usually neglected for a simplified analysis. The structure response to explosion load can be estimated, either more accurately by a calculation or approximately based on empiric formulas and criteria [4, 5]. In particular, this applies to the type and location of the pressure wave source compared to the structure under evaluation, characteristics of the pressure wave at the source, and especially the course of explosion pressure in time.

Properties of the structure as a unit or of its parts and its materials are decisive for the magnitude and nature of the response of any explosion-loaded structure. These include particularly mechanical characteristics of the material (especially its strength, way of failure, stress-strain diagram, behaviour beyond the elasticity limit, etc.), and distribution of masses and structure rigidity with corresponding frequency tuning of the structure, characteristics of surfaces loaded by the impact blast wave, structure geometry compared to explosion wave

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characteristics, any previous failures of the structure, including changes in the structure material properties in the course of time for existing structures, etc.

In our specific case, the explosion load effect is applied to the analysis of a control, single-storey building (porter's lodge) within the threatened premises. It is a reinforced concrete monolithic structure that should be resistant, based on the user's requirements, against external explosion charge.

2. Design principles

As a rule, failure of a limited part of the structure may be admitted in the structure design process providing that no crucial elements are included in such a part on which the stability of the entire structure depends. When calculating building or technological structures, two procedures can be applied in principle. Either maximum possible simplifications are used in the structure analysis in terms of explosion effects, both as regards the load itself and the analyzed structure, or the structure is analyzed in a way so that this analysis describes with the highest accuracy possible the actual state of the structure and its explosion load. Requirement to exclude an accident:

- The structure must tolerate design-based explosion load without collapsing, as a whole or in part, so that it maintains its structural integrity and residual bearing capacity after the explosion.
- The design-based explosion load, corresponding to the simplified course of load in time, is normally given by intensity of maximum overpressure and underpressure values of the impact wave and by the duration of both phases, and/or dynamic pressure and its duration. The load parameters should be considered based on the probability of explosion occurrence in the given locality, based on the structure, operation, etc.

Requirement of limited damage:

- The structure should resist any (higher) explosion load of higher occurrence probability than the design-based explosion load, with no damage and without any associated restrictions of operation, such that their price would be disproportionately high compared to the price of the construction.
- The resulting reliability against collapse and against limited damage is normally determined by national authorities for various types of buildings and engineering constructions according to the consequences of damage, or they are determined based on risk analyses for the appropriate operation, structure, etc.

3. Explosion load

The explosion load is very often substituted as follows to achieve simplification [2, 3]:

a) Triangle-shaped development of the load in time with the maximum intensity corresponding to the sum of the pressures of the impacting and reflected wave and the duration of the action, usually corresponding only to the duration of the action of the overpressure phase of the shock wave;

b) The shock wave can be considered as having a flat front, meaning that the rise time to maximum intensity is neglected, and additionally that the load starts to act on the entire structure at one moment; the phase shift of the start of the action of the load at individual structure points is thus neglected;

c) It is usually assumed that the load acts on the building structure (walls, ceiling, windows, etc.), determined on the basis of shock wave propagation round the structure [2, 3], in a continuous and naturally simplified manner (any local effect of the focused load is neglected);

d) The response of the structure is usually considered on the basis of the superimposition of two triangular loads, which correspond to the overpressure phase and subsequently the underpressure phase of the shock wave.

The authors used empirical formulas [4, 5, 6] applicable to an explosive charge in an open area to calculate the dynamic load; the formulas were derived from tests using small explosive charges; then the overpressure value p_+ at the front of the aerial shock wave and its duration τ_+ are as follows:

$$p_+ = \frac{1.07}{\bar{R}^3} - 0.1 \quad [\mathrm{MPa}] \quad \text{for} \quad \bar{R} \le 1\,\mathrm{m/kg}^{1/3} \;, \tag{1a}$$

$$p_+ = \frac{0.0932}{\bar{R}} + \frac{0.383}{\bar{R}^2} + \frac{1.275}{\bar{R}^3} \quad [\mathrm{MPa}] \quad \text{for} \quad 1 < \bar{R} \le 15\,\mathrm{m/kg}^{1/3} \;, \tag{1b}$$

$$p_- = \frac{0.035}{\bar{R}} \quad [\mathrm{MPa}] \;, \tag{2}$$

$$\tau_+ = 1.6\times10^{-3}\,\sqrt[6]{C_\mathrm{w}}\,\sqrt{R} \quad [\mathrm{s}] \;, \tag{3}$$

$$\tau_- = 1.6\times10^{-2}\,\sqrt[3]{C_\mathrm{w}} \quad [\mathrm{s}] \;, \tag{4}$$

where values of the pressure intensity p_- and its duration τ_- are the parameters of the underpressure phase of the shock wave.

For reduced distance

$$\bar{R} = \frac{R}{\sqrt[3]{C_\mathrm{w}}} \quad [\mathrm{m/kg}^{1/3}] \tag{5}$$

where $\bar{R}$ is the reduced distance from the epicentre of the explosion, R is the distance from the explosion epicentre [m], and C_w is the equivalent mass of the explosive charge [kg TNT].

The wave motion from the explosion focus propagates in spherical wave fronts. In the event of a ground explosion (at the contact with the ground), the explosion energy value is about double, given that when there is complete reflection from the ground surface the shock wave propagates in semi-spherical wave fronts. For a ground explosion, this effect can be taken into account by substituting twice the magnitude of the actually used mass of charge C for the equivalent mass of charge C_w in formula (5). For an above-ground explosion at a height of more than 20 m above ground, the mass of the charge C is substituted directly (without any increase in its value) for the equivalent mass of the charge. For a charge placed between the ground level (zero height) and 20 m above the ground, linear interpolation can be used to determine the equivalent mass of the charge; in this case, the equivalent mass of the charge substituted to the formulas above will range between

$$C_\mathrm{w} = (1 \text{ to } 2)\,C \;. \tag{6}$$

When there is a normal (perpendicular) impact of the explosion wave against a solid barrier, a reflected wave is formed with the reflection overpressure $p_{\mathrm{ref}+}$, which loads the building structure from the front side. The overpressure value in the reflected wave corresponds to approximately twice the overpressure for low overpressure values p_+ approximately up to 5 MPa (up to eight times the value for high overpressures of several tens of MPa) in the impact wave for the given distance R. The duration of the action of the overpressure t_{D} is about the same as the duration of shock wave τ_+

$$p_{\mathrm{ref}+} \approx 2\,p_+ \ , \tag{7}$$

$$t_{\mathrm{D}} \approx \tau \ . \tag{8}$$

4. Evaluation of the structure response

The magnitudes of the internal forces in the structure are considered as a part of the evaluation of the limit bearing capacity conditions, based on load combinations when they are reduced using ductility factor q ([5,6] and [1]). The dynamic response to the effects of the load due to an explosion must be superimposed on the effects due to static loads. The resulting internal forces are then evaluated on the basis of Eurocode design standards for the appropriate structure material type, or as a variant, also according stress-strain ratio. These are usual procedures, but it should be noted that when the structure is loaded due to an explosion, inelastic deformations occur at a number of sections, causing damage to the structure by crack formation. However, this procedure entails two important uncertainties in the case of bent structures, i.e. a suitable choice of plastic reserves, on the one hand, and the material strengthening factor, on the other. During very rapid reshaping of the structure, which is typical for explosion loads, both factors may achieve numeric values of the order of tens, and not only of units, as mentioned above. Thus they may lead to considerable overdesigning of the structure.

Evaluations of structures loaded by an explosion based on dynamic displacement and rotation round the central line of plate, wall or beam systems during the action of a dynamic load of this type have been of very topical interest in recent times, as regards the process of evaluating the effects of an explosion on a structure. In earlier publications [4,5,6], the authors applied this procedure to various types of materials and structure systems, and on the basis of an experimental comparison they determined the failure angle $\psi_{\max}$, i.e. the angle where damage is caused to the structure by breaking. The stability of the structure with the cracks should be assessed in order to prevent any collapse of the structure due to the formation of plastic joints and cracks.

The dynamic rotation round the central line of an appropriate structure element is therefore the criterion used to evaluate the response occurring at the following angle

$$\psi = \mathrm{arctg}(x_{\mathrm{m}}/(0.5 h_{\mathrm{span}})) \ , \tag{9}$$

where x_{m} is the maximum achieved dynamic displacement caused by the explosion load and h_{span} is the span of the plate ceiling structure or the height of the wall structure within one storey, or the span of any beam, the height of a column, etc.

Type	Structure material	$\psi_{\max}$ [°]
1	Concrete C16/20 to C40/50	6.5
2	Masonry, full bricks 10, mortar 4 or mortar 10	5.0
3	Masonry, cement bricks, mortar 4	4.5
4	Masonry, cellular concrete or perforated precise blocks, mortar 4	4.0
5	Steel S235	10.5
6	Wood, hard and soft	12
7	Window glass, thickness 3 mm	6

Tab.1: Limit failure angle $\psi_{\max}$ [°] upon breaking of the material [4]

Structure	Expected damage to elements		
	Mean	High	Hazardous
Reinforced concrete structures, plates and beams with one-sided reinforcement	2	5	10
Reinforced concrete structures, plates and beams with two-sided reinforcement and with web reinforcement	4	6	10
Prestressed concrete, beams and plates	1	1.5	2
Masonry, common, non-reinforced	1.5	4	8
Masonry, reinforced	2	8	15
Steel bars	3	10	20

Tab.2: Angle ψ [°] of the expected damage to bent elements ([4] in comparison with [7, 8])

The approximate failure angle value on reaching the rupture limit value is shown in Tab. 1. More conservative limit values of angle ψ were derived according to [7, 8], which correspond to the chosen structure rupture risk. These values have been adapted and are shown in Tab. 2. However, hazardous occurrence of damage approaches emergency level damage, and its failure angle is found at the lower limit, below the maximum failure angle value $\psi_{\max}$, in the Tab. 1.

5. Description of the threatened structure and its computational model

The reinforced concrete wall structure of the building was made of concrete C25/30, wall in thickness 200 mm, ceiling and floor slab in thickness 250 mm, and it was sufficiently reinforced using classic reinforcement in both directions (crosswise) along both surfaces. Window and door openings of such a building are usually fitted with special windows and doors resistant against explosion given that regular window glasses do not transfer the effects. The subsoil of the building is of gravel-sand nature and was modelled using the Winkler-Pasternak two-parametric subsoil model. The computational model for the building structure response analysis is shown in Fig. 1. The particular dimensions of individual structure parts were respected in order to obtain the true model of the building's mass and rigidity. Besides structure dead load, the permanent component of the variable load was included in the structure mass.

During an explosion, the specific course of load also depends on vortex flow around the structure surface, atmospheric pressure, temperature conditions and other factors that are

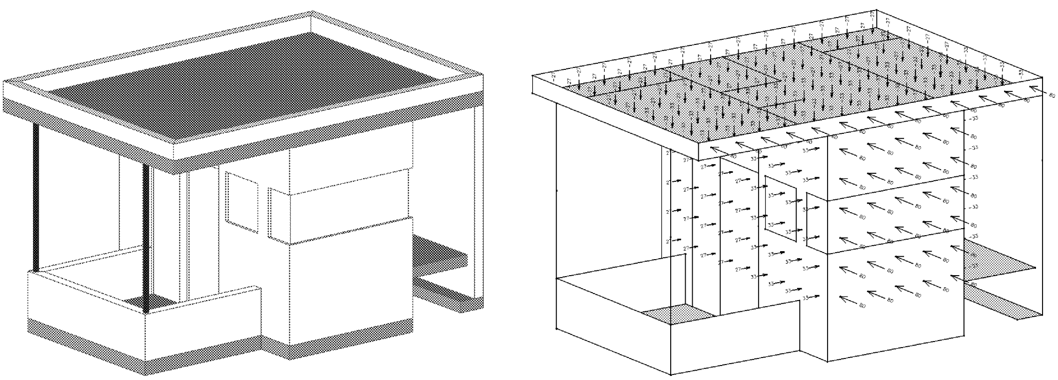

Fig.1: Calculation model of the whole structure (North-West view) and dynamic forces in selected points of above-ground parts

usually neglected in the simplified analysis. In our case, only simplified flow [2, 3] around the building was considered. Explosion load parameters were determined based on average values; the formulas used to calculate the load are empirical and operate with mean (probable) values of the coefficients. Thus the structure calculations for the impact wave effects are burdened significantly by these inaccuracies of input quantities of the whole phenomenon, as well [6].

The incident shock wave ($p_+ = 160\,\mathrm{kPa}$, $t_+ = 14\,\mathrm{ms}$) exerted on circumferential wall surfaces and on ceiling structures was considered as uniform, effected simplified step by step in three zones in terms of intensity as well as the initial moment of action of the reflective overpressure – dynamic load, as a function of the velocity of impact wave propagation:

– Zone 1, the whole west frontal wall (start of dynamic load on structure face $t^* = 0\,\mathrm{ms}$);
– Zone 2, perpendicular to the blast wave propagation, frontal parts of the north and south walls, frontal part of the roof ($t^* = +4\,\mathrm{ms}$);
– Zone 3, perpendicular to the blast wave propagation, rear parts of the north and south walls, rear part of the roof ($t^* = +9\,\mathrm{ms}$).

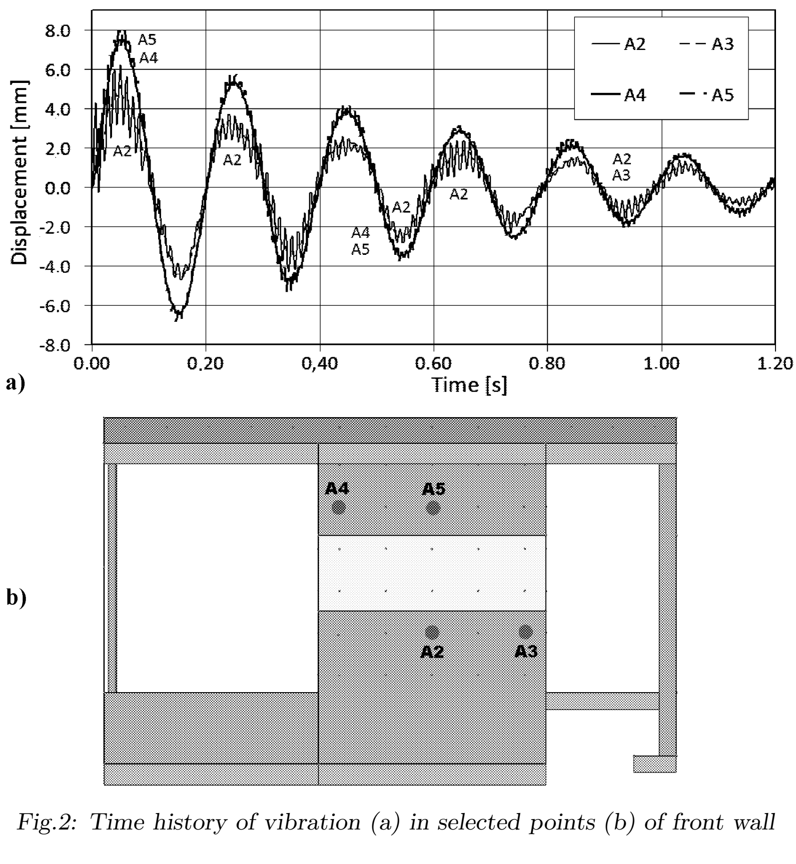

Fig.2: Time history of vibration (a) in selected points (b) of front wall

6. Forced vibration

The decomposition of dynamic load history to the natural modes of vibration is used for the forced vibration analysis by means of Scia Engineer program. The damping of the structure of the building has been set as a logarithmic decrement 0.314. For higher natural frequencies the damping is usually higher, but the computer program does not allow setting a different damping for higher frequencies. The calculation of forced vibration has been made with 300 time steps of 0.001 s and alternatively with 600 time steps of 0.002 s. The dynamic response is calculated respectively for each time step. The size of time step was chosen as a compromise [7] between the range of blast wave duration (14 ms) and dominant natural periods of vibration (from 0.2 s).

The calculated rotations (angles ψ) of the central line of structural elements were used for structure assessment. The maximal angle of rotation in the west wall was 0.24 degrees round vertical axis z and 0.17 degrees round horizontal axis x. In the north and south walls the maximal angle was 0.11 degrees round vertical axis z. Maximal rotation of the roof plate was 0.18 degrees round horizontal axis x. From all these rotations it is clear that the concrete values are smaller than the limit value 4 degrees. The concrete structure is therefore safe enough and responds to the structure hazard smaller then the moderate hazard.

7. Conclusion

The example of a specific building was used to address the problem of explosion and threatened safety of the building upon an explosion of a rather large explosion charge located in a car and detonated near the building, on circumferential roads. Considering uncertainties associated with the determining of all parameters of the explosion load, methodology derived by the authors [4, 5] based on the experimental results of small charge explosions has been used for an engineering estimate of the probable explosion load, especially the time course of the impacting shock wave and its interaction with the structure itself. This simplified methodology lends itself to determination of load characteristics and to assess the building structure dynamic response with the sufficient accuracy.

The structure response was assessed based on the results of a 3D dynamic computation according to the magnitude of internal forces and displacements, and partial rotation of the central line of beam or slab cross-sections of the structure. Currently, structure assessment methodology based on partial rotation of the cross-sections has been in the process of development; it corresponds to the most recent research trends. The authors used limit values determined experimentally upon explosion load of brick-layered, reinforced concrete and window glass boards based on comparing their own [4] and other published results [2, 7].

A reinforced concrete administrative building has been used as an example for determining and documenting the load due to a terrorist explosion. The results for the response of the building to this blast load are presented in parts, together with the principles for evaluating the structure according to the structure displacements an failure angles corresponding to the given explosion load.

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References

[1] ČSN EN 1998-1 Eurocode 8, Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings, ČNI 2006, Praha

[2] Henrych J.: The dynamics of explosion and its use, Academia 1979, Prague

[3] Koloušek V. a kol.: Stavebné konštrukcie namáhané dynamickými účinkami, SVTL 1967, Bratislava

[4] Makovička D., Janovský B.: Příručka protivýbuchové ochrany staveb, Česká technika – nakladatelství ČVUT v Praze, 2008

[5] Makovička D., Makovička D.: Simplified evaluation of a building impacted by a terrorist explosion, In: Jones N., Brebbia C.A. (Ed.): Structures Under Shock and Impact XI, WIT Press 2010, p. 93

[6] Makovička D., Makovička D.: Blast resistant design and limits of the response of a structure to an external explosion, In: Schleyer G., Brebbia C.A (Eds.): Structures Under Shock and Impact XII, WIT Press 2012, p. 229

[7] McCann D.M., Smith S.J.: Blast resistant design of reinforced concrete structures, STRUCTURE magazine, 2007, p. 22

[8] TM 5-1300: Structures to resist the effect of accidental explosions, U. S. Army Corps of Engineers: Washington, D.C., 1990, (Navy NAVFAC P-397 or Air Force AFR 88-22)

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