Blind resistant design of structure to terrorist explosion

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ABSTRACT: The paper deals with the presentation of structure assessment, loaded by explosion of terrorist charge. 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. For structure response calculation the empirical formulas of the explosion load parameters were used. These formulas were derived by the authors for small charges. For determination of explosion effects and structure response were used 3-D analysis, based on detail modelling of the structure. This procedure entails two important uncertainties in the case of bent structures, i.e. a suitable choice of the ductility factor and the material strengthening factor. During very rapid reshaping of the structure, both factors are very important for structure analysis. The damage of these structure parts were therefore weighted accordingly with the angle of rotation of middle axis/surface and limit stress state/internal forces of selected structure. The own limit values of angles of failure determined experimentally upon explosion load of brick-layered, reinforced concrete and window glass are compared with results of other authors. The internal forces in the structure are considered as a part of the evaluation of the limit bearing capacity conditions, based on load combinations and reduction by the ductility factor q. The resulting internal forces are then evaluated on the basis of design standards for the appropriate structure material type, or as a variant, also according to its increased strength using factor k₁. An example of a specific building was used to discuss the explosion and the building safety hazard for a terrorist charge.

KEY WORDS: Explosion; Blast load; Dynamic analysis; Response; Failure assessment.

1 INTRODUCTION

When a blasting charge explodes in an open area, the action of the pressure of the shock wave on an obstruction 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 [₁, ₂]. 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 parameters of the explosive are also determined on the basis of mean values; the formulas that are used are empiric and operate with mean (probable) factor values. Thus the calculations of structures for shock wave effects are significantly influenced by these inaccuracies in the input quantities of the whole phenomenon.

In our specific case, the effects of an explosion are applied to an administrative building where an ordinary vehicle can be used to bring a terrorist charge on a road close to the building, and the charge can be initiated near the building.

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 [₅, ₇, ₈]. 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 [1, 2]:

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.) in a continuous and uniform 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 [2, 3, 10, 11] 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 \( \tau_+ \) are as follows:

\[
p_+ = \frac{1.07}{R} - 0.1 \text{ [MPa]} \quad \text{for} \quad R \leq 1 \text{ m/kg}^{1/3} \quad (1a)
\]

\[
p_+ = \frac{0.0932}{R} - \frac{0.383}{R^2} + \frac{1.275}{R^3} \text{ [MPa]}
\]

for \( 1 < R \leq 15 \text{ m/kg}^{1/3} \quad (1b) \)

\[
p_+ = \frac{0.035}{R} \text{ [MPa]} \quad (2)
\]

\[
\tau_+ = 1.6 \cdot 10^{-3} \cdot \sqrt{C_w} \cdot \sqrt{R} \text{ [s]} \quad (3)
\]

\[
\tau_+ = 1.6 \cdot 10^{-2} \cdot \sqrt[3]{C_w} \text{ [s]} \quad (4)
\]

For reduced distance

\[
\overline{R} = \frac{R}{\sqrt[3]{C_w}} \text{ [m/kg}^{1/3}] \quad (5)
\]

where \( \overline{R} \) 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 surface explosion (at the contact point 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 [2, 10, 11]. For a surface explosion, this effect can as a rule 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

\[
C_w = (1 \text{ to } 2) C \quad (6)
\]

When there is a normal (perpendicular) impact of the explosion wave against a solid barrier, a reflected wave is formed with the reflection overpressure \( p_{ref+} \), 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 \( t_0 \) is about the same as the duration of shock wave \( \tau_+ \).

\[
p_{ref+} \approx 2 p_+ \quad (7)
\]

\[
t_0 \approx \tau_+ \quad (8)
\]

4 PRINCIPLES OF RESPONSE ANALYSIS

The structure response is generally calculated and assessed in accordance with design standards for the given type of structure material. In our case, Eurocodes [4] are used. The dynamic response to the effects of the load due to an explosion must be superimposed on the effects due to static loads. 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 due to the formation of plastic joints and cracks. In this case, 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.

When a structure is loaded by an explosion, the formation of cracks not leading to a collapse is as a rule permitted. Thus ductility factor \( q \) may be used to reduce the magnitude of the explosion load. This is a highly efficient way of taking inelastic manifestations of the dynamic load into account.

\[
q = x_m / x_{el} \quad (9)
\]

where \( x_m \) is the maximum elastic-plastic displacement of the structure, and \( x_{el} \) is the elastic part of the displacement.

The applicable ductility factor is usually \( q < 3 \) for reinforced concrete structures. On the basis of a more detailed analysis of the structure, higher ductility factor values may be used, for example, on the basis of seismic standard EN 1998-1 [4].

Table 1. Estimate of factor \( k_i \) in dependence on duration \( t_0 \).

<table>
<thead>
<tr>
<th>( t_0 ) [s]</th>
<th>( k_i )</th>
<th>( 10^{-1} )</th>
<th>( 10^{-2} )</th>
<th>( 10^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \geq 1.0 )</td>
<td>1.0</td>
<td>1.05</td>
<td>1.10</td>
<td>1.20</td>
</tr>
</tbody>
</table>
The strength characteristics of the structure material may also be increased in the calculation of the structure response. An estimate of this increase (material strengthening factor \( k_f \)) is shown in Table 1, in dependence on the duration of the explosion load effect \( t_0 \).

The magnitudes of the internal forces in the analysed 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 \( q \) \([4, 5, 6, 12]\). The resulting internal forces are then evaluated on the basis of design standards for the appropriate structure material type, or as a variant, also according to its increased strength using factor \( k_f \).

However, this procedure entails two important uncertainties in the case of bent structures, i.e. a suitable choice of the ductility factor, 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 displacements and rotations 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.

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

\[
\psi = \arctg \left( \frac{x_m}{0.5 h_{\text{span}}} \right)
\]

(10)

where \( x_m \) is the maximum achieved dynamic displacement caused by the explosion load and \( h_{\text{span}} \) 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.

In earlier publications, 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 \( \psi_{\text{max}} \) i.e. the angle where damage is caused to the structure by breaking.

Table 2. Limit failure angle \( \psi_{\text{max}} [^\circ] \) upon breaking of the material \([2, 3, 11]\).

<table>
<thead>
<tr>
<th>Type</th>
<th>Structure material</th>
<th>( \psi_{\text{max}} [^\circ] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Concrete C16/20 to C40/50</td>
<td>6.5</td>
</tr>
<tr>
<td>2</td>
<td>Masonry, full bricks 10, mortar 4 or mortar 10</td>
<td>5.0</td>
</tr>
<tr>
<td>3</td>
<td>Masonry, cement bricks, mortar 4</td>
<td>4.5</td>
</tr>
<tr>
<td>4</td>
<td>Masonry, cellular concrete or perforated precise blocks, mortar 4</td>
<td>4.0</td>
</tr>
<tr>
<td>5</td>
<td>Steel S235</td>
<td>10.5</td>
</tr>
<tr>
<td>6</td>
<td>Wood, hard and soft</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>Window glass, thickness 3 mm</td>
<td>6</td>
</tr>
</tbody>
</table>

The approximate failure angle value on reaching the rupture limit value is shown in Table 2. More conservative limit values of angle \( \psi \) were derived according to \([7, 8]\), which correspond to the chosen structure rupture risk. These values have been adapted and are shown in Table 3.

Table 3. Angle \( \psi [^\circ] \) of the expected damage to bent structural elements \([2, 7]\).

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

The mean occurrence of damage corresponds to the damage to reinforced concrete or masonry elements, e.g. spalling, or the occurrence of tiny cracks in the structure elements, which pose no threat to their stability and can be repaired, e.g. by grouting.

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 \( \psi_{\text{max}} \), see Table 2.

5 EXAMPLE OF ANALYSED STRUCTURE

The reinforced concrete wall structure of the building was made of concrete C25/30, base plate in thickness 300 mm, ceiling and floor slabs in thickness 250 mm, walls in thicknesses 200 to 250 mm, and it was sufficiently reinforced using classic reinforcement in both directions (crosswise) along both surfaces. Rectangle columns 500×500 mm, circular columns 500 mm and rectangle beams under floor plates 500×300 mm. 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 of the building is illustrated in Figure 1. The dimensions and distribution of individual structure parts were designed while respecting the structure geometry and its dimensions, in order to obtain the most precise model of the building’s mass and rigidity. Besides its dead load, the equivalent 50% of permanent component of the variable load were included in the structure mass \([11, 12]\).

The reinforced concrete wall/plate/beam structure of the building was designed to sustain the effects of a terrorist charge explosion characterized by the load \( P_{\text{ref}} = 320 \) kPa and
triangular pulse of the load 2200 kPa·ms, i.e. with overpressure in the shock wave of $p_+ = 160$ kPa and duration $t_+ = 14$ ms.

The first 100 natural frequencies up to 39 Hz have been considered. The natural modes descriptions of the first ten natural frequencies are in the Table 4.

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 time steps of 0.001 s.

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Table 4 Natural frequencies and modes

<table>
<thead>
<tr>
<th>$i$</th>
<th>$\tilde{f}_{i0}$ [Hz]</th>
<th>Description of the natural mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.94</td>
<td>Whole structure - rotation on the subsoil around the longitudinal axis $y$</td>
</tr>
<tr>
<td>2</td>
<td>4.31</td>
<td>Whole structure - rotation on the subsoil around the transversal axis $x$</td>
</tr>
<tr>
<td>3</td>
<td>6.01</td>
<td>Whole structure - rotation on the subsoil around the vertical axis $z$</td>
</tr>
<tr>
<td>4</td>
<td>6.10</td>
<td>Vibration of corridor roof</td>
</tr>
<tr>
<td>5</td>
<td>6.62</td>
<td>Translation of the structure in direction $z$ and vibration of floor plates</td>
</tr>
<tr>
<td>6</td>
<td>8.35</td>
<td>Bending of the 2nd floor plates and south wall</td>
</tr>
<tr>
<td>7</td>
<td>8.54</td>
<td>Rotation of the structure round transversal axis $x$ and vibration of floor plates</td>
</tr>
<tr>
<td>8</td>
<td>9.64</td>
<td>Bending of all the floor plates and south wall</td>
</tr>
<tr>
<td>9</td>
<td>9.92</td>
<td>Rotation of the structure round longitudinal axis $y$ and vibration of floor plates</td>
</tr>
<tr>
<td>10</td>
<td>10.43</td>
<td>Bending of all the floor plates</td>
</tr>
</tbody>
</table>

Figure 2. Calculation model, selected nodes in the periphery of the northern wall for time history graphs.

Table 5. Characteristics of the explosion load areas of the front wall (see Figure 2).

<table>
<thead>
<tr>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
</tr>
<tr>
<td>Radius of the circle or annulus round the normal line of the shock wave impact [m]</td>
</tr>
<tr>
<td>Impacting wave pressure [kPa]</td>
</tr>
<tr>
<td>Duration of overpressure [ms]</td>
</tr>
<tr>
<td>Impact angle [°]</td>
</tr>
<tr>
<td>Start of action of the load from the time of the wave impact on the wall $t^*$ [ms]</td>
</tr>
<tr>
<td>Reflection overpressure [kPa]</td>
</tr>
</tbody>
</table>

To simplify the considerations, the explosion is deemed to load the front wall of the structure stepwise in parts [11, 12], continuous, in four zones (Figure 2) corresponding to the duration of action of the impacting aerial shock wave, with the reflection factor equal to approximately 2, according to equation (7).
The dissipative characteristics of the structure were taken into account by applying the ductility factor, set as equal to 2.5 for plate structures and horizontal beams, and equal to 1.5 for columns.

To provide an example of the nature of the rotation of median fibres of the face wall, Figure 3 and Figure 4 show isolines of the rotations in the front wall of the building (from the side of the explosion) around the z and y axes in the plus and minus directions.

The maximum rotation values of the front wall round the vertical z axis were from +0.40° to –0.43°, and round the horizontal longitudinal y axis the values were from +0.29° to –0.36°.

Calculated rotations 0.43° about z and 0.36° about y with shows clearly that the structure of the front wall is sufficiently safe against major damage. Its rotation values are lower than the limit failure angle $\psi_{\text{max}} = 2^\circ$, which corresponds to the mean damage to the structure. The formation of only tiny, predominantly capillary cracks can thus be expected in this external wall at the points where the partition walls connect to the external wall, in the staircase part.
The explosion load due to an outside emergency or a terrorist explosion is usually burdened with a number of uncertainties, related to determining the amount of explosive medium, its location in relation to the loaded structure, and the conditions in the surroundings. These load effects were derived by the authors based on the experimental results of small charge explosions. They may be used for an engineering estimation of the probable blast loads. This methodology enables us to determine with sufficient accuracy the time course of the impacting shock wave and its interaction with the structure itself.

The authors have used limit rotation values (angle of failure) determined experimentally on the basis of the explosion load of masonry, reinforced concrete and window glass plates and comparing their own results [2, 3, 9] with results published by other authors [1, 5, 6, 7, 8].

The analysed structure response was assessed on the basis of the results of a 3D dynamic calculation using the magnitudes of the internal forces and deflections and rotation of the central line of beam or plate sections of the structure. Evaluating a structure on the basis of the limit rotation is a methodology under development at present, and is in accordance with recent research trends for structure loaded by blast wave of explosion.

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 load are presented in parts, together with the principles for evaluating the structure according to the internal forces in this structure and according to the angle of failure corresponding to the given explosion load.

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