

Resilience of High-Rise RC Buildings to Dynamic Impacts

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Abstract. During the design of a high-rise building it is crucial to adopt appropriate constructive solutions to provide a building resilience to dynamic loadings including explosions. Here we demonstrate a general approach to the investigation of high-rise building resilience using an example of a real-life fifty-two-storied reinforce concrete tower Iset' located in Yekaterinburg, Russia. Several failure criteria for the load bearing elements and reinforced concrete in general are discussed. The LS-DYNA numerical simulations of a realistic explosive loading scenario of the tower confirming its resilience to such type of impacts are presented.

1. Introduction

Urbanization and rapid growth of megalopolises naturally leads to modern town-planning tendencies of increasing building density and substantial increase of high-rise buildings number [1]. During past several decades all over the world including Russian Federation a lot of incidents with explosions of civilian building had taken place. As targets for bombing attacks organizers usually choose objects to cause the highest possible people casualties, moral harm and economic damage. For these reasons high-rise buildings in dense city planning with a lot of civilians in them are attractive aims for terrorist attacks. Therefore, during the design of a high-rise building one needs to investigate a resilience of the building to extreme loadings including explosions. Safety of civilians in the events of extreme loading including blast wave loading should be provided for not only by comprehensive surveillance and security measures in order to prevent such events but also by adaptation of special constructive solutions. These constructive solutions should be drawn during the design and prevent possible progressive collapse of the high-rise building under the effects of blast wave loadings.

A distinctive characteristic of explosive loadings that differs them from for example earthquakes and wind loadings is their local impact nature. However, a blast wave produced by an explosion can cause stresses and deformations many times exceeding design values. Moreover, during the blast wave loadings the structure strength elements may experience short-time untypical loadings. High capacity explosions can cause substantial nonlocal damages due to produced high amplitude air blast wave. However, even in the case of relatively weak explosions it is possible that the blast wave harms key



structural elements that may lead to a progressive collapse of the building. Due to a wide variety of possible explosive loading scenarios, natural variations in the properties of used construction materials, variety of structure strength elements, quality of the construction and so on one can perform systematic study of the effects of explosive loadings on a particular building design only in the frames of probabilistic approach. In such approach one should reveal critical parameters and key strength elements of the building determining its resilience to such extreme loading events.

It is impossible to perform a full-scale experimental investigation of a high-rise building resilience to explosive loadings. Experimental foundation of such investigation is limited and may be established based on experiments studying blast wave effects on particular characteristic elements but not the entire building. Thus, efficient design of resilient to explosive loadings buildings is inconceivable without comprehensive computational basing and numerical modeling of different aspects of the design with the use of state-of-the-art finite element analysis codes and high performance computing.

In the present work we study a resilience of a high-rise building to explosive loading by an example of real-life fifty-two-storied reinforced concrete (RC) tower Iset' located in Yekaterinburg, Russia. Finite element model of the tower was kindly provided to the authors by researchers from Institute of Civil Engineering of Ural Federal University [2-3] (see figure 1). Numerical simulations were performed in LS-DYNA code [4-5] as one of the most efficient finite element analysis codes that provides capability to model various dynamic loading phenomena including explosive loading effects. The use of real building model is dictated by our desire to obtain easy to interpret relevant to real life calculation results with practical implications.

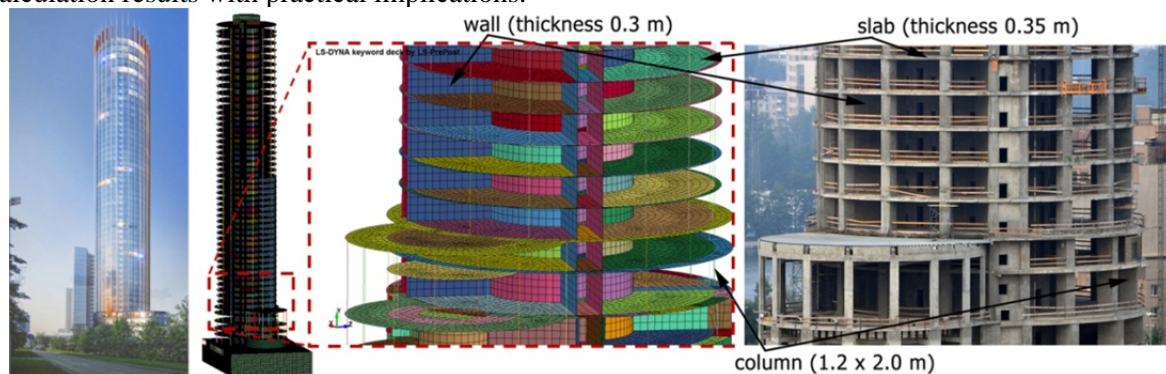


Figure 1. Photo of the fifty-two-storied RC tower Iset' with multilevel underground parking lot and its finite element model. Key structure elements of the tower like walls and slabs are modelled using two-dimensional shell finite elements while bearing columns are modelled by one-dimensional beam finite elements. The use of shells and beams instead of solid finite elements allows us to lower considerably the computational costs of the simulations. The finite element model consists of ~ 5.5 thousands of beam and ~ 165 thousands of shell finite elements.

2. Finite element analysis model

LS-DYNA [4] provides for capability to model various processes of dynamical loadings of complex structures including blast loadings of buildings. Recent releases include a wide variety of numerical analysis tools to study dynamics and statics of high-rise buildings. The choice of simulation parameters, the degree of the model detailed elaboration and the use of various material models allows us to simulate the dynamical loadings within different levels of the event description. Therefore one can single out several general approaches to study the problem of a high-rise building resilience to dynamical loadings caused by explosions.

The first approach is focused on the response of characteristic key structure strength elements like columns, slabs, and bearing walls to the explosions. In this approach for example a RC column is modeled using solid finite elements representing concrete with embedded beam finite elements which mimic steel reinforcement bars. Such approach provides for capability to study in details the effects of

the blast wave loading on the key structure elements taking into account their features including anisotropy and heterogeneity. Based on the results of such modeling one can work out criteria for the fatal failure of the key structure elements under the explosive loadings [6-8].

In the second approach it is supposed to model the entire full-scale structure of a building using a combination of solid finite elements representing concrete with the embedded beam finite elements representing steel reinforcement bars. Although this approach is the most physically well-founded, in practice the modeling of high-rise buildings or extensive structures within this approach requires so high number of finite elements that the calculation times become unacceptable.

In the third approach the structure is modeled as in the second as the entire full-scale model but in a simplified manner. The number of finite elements and therefore the computational costs within this approach are decreased using shell and beam elements instead of solid elements (see figure 1). In this case specific properties of RC including steel reinforcement in the structure elements (bearing walls, columns and slabs) are accounted for indirectly using specially developed material models. There are several RC material models in recent LS-DYNA [4–5] releases that are developed for beam and shell finite elements and capable to model effectively various degree of reinforcement in concrete. One more peculiarity that requires special attention in this case is that the beam finite elements representing bearing columns have no surface which would perceive the blast wave pressure during the simulation. Thus, one needs to keep track of failure criteria overcoming by the beam finite elements and delete them from the simulations “by hands”.

2.1. Material properties model

Iset' tower is a fifty-two-storied solid RC tower with underground multi-level parking lot. There are many different material models for modeling RC developed for simulations of concrete structures in various environments and loading conditions in LS-DYNA [4]. For the purpose of present study we have chosen material model *MAT_CONCRETE_EC2 [5]. The parameterization of this material model was developed to implement in LS-DYNA capability to introduce materials based on European concrete structure design standard “Eurocode 2: Design of Concrete Structures” [9-10].

Usually the construction procedures and used materials including concrete compositions and reinforcement structures are developed for a particular building based on distinctive properties of the building and regional features [11]. Thus, the formulas of concrete compositions and reinforcement structures usually (including Iset' tower) are commercial secrets of the developers. In the present study based on general requirements we used the following characteristics of the concrete. B45 concrete class is used for load bearing columns and B25 concrete class is used for the slabs. Constitutive parameters of the RC including the fraction of steel reinforcement are presented in table 1. In addition to the constitutive parameters for the material model in our simulations we adopted *MAT_ADD_EROSION method [5] to account for RC irretrievable fatal failure. This model of the material failure is based on the concept that the structural elements are eliminated from the simulations when deformation and/or stresses in them exceed some critical values.

Table 1. Constitutive material parameters for reinforced concrete.

Concrete class (elements)	Density (kg/m ³)	Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus of reinforcement (MPa)	Yield strength of reinforcement (MPa)	Fraction of reinforcement	
						x-axis (%)	y-axis (%)
B25 (slabs)	2.15×10 ³	32.7	1.6	2×10 ⁵	450	1.5	1.6
B45 (columns and beams)	2.00×10 ³	58.9	2.2	2×10 ⁵	450	1.5	1.6

Strength of RC structural elements under dynamic/static loadings is determined by large number of factors. From the construction point of view the RC strength depends on the properties of the

reinforcement, concrete composition and solidification conditions. From the loading condition variations the strength of the RC is determined by the character of the loading (bending, compression, tensile loading) and characteristic times of loadings. It is known that in long-time (hours, days, months) compressive testing the RC strength might be 10 – 15 % lower than that in quasi-static loading conditions with the deformation rates in the range $10^{-3} - 10^{-1} \text{ s}^{-1}$. In dynamic loading with high deformations rates, exceeding 10^3 s^{-1} , the strength of the concrete increases substantially. Critical values of deformations when the concrete experience irreversible structural destruction are quite different upon compression and tensile loadings. Thus, it is practical standard to distinguish critical compressive and tensile deformations. There are a lot of studies focused on elaborating critical deformation patterns for various RC compositions and loading conditions. It was found that critical tensile deformation of a RC in quasi-static conditions is $\sim 2 \times 10^{-4}$. The full strength loss happens for approximately five times higher deformations $\sim 1 \times 10^{-3}$. While in dynamic loading experiments under explosive loadings with the deformation rates $10^2 - 10^4 \text{ s}^{-1}$ the critical tensile deformation reaches $\sim 1 \times 10^{-2}$ [12-14].

2.2. Load bearing column strength

The elaboration of the critical failure criteria for the bearing columns of solid RC buildings is accessible by experiments with the following numerical verifications [15], by finite element analysis simulations taking into account real geometry and reinforcement structure [16-17], and analytically. One of the rather effective means to protect a building from unacceptable explosive loading is organization around the building a protective perimeter preventing different high explosive carriers from bringing the explosives closer than potentially dangerous distance. In this approach it is supposed to choose safe distances for detonations of explosive charges of different TNT equivalent masses which would not cause critical failures of load bearing structure elements like columns. Based on numerous experiments and numerical simulations a dependence of safe distance on the explosive charge mass for typical carriers like pedestrians, cars and trucks was elaborated [18-19] (see table 2).

Table 2. Safe distance on the explosive charge mass for carriers like pedestrians, cars and trucks was elaborated in [18-19].

Explosive carriers			
Equivalent TNT charge mass (kg)	30	600	2000
Safe distance (m)	3	8	20

In the case of Iset' tower there is multi-level underground parking lot with its entrance near a bearing column (see figure 2). Consider the bearing column with the size $1.2 \times 2 \text{ m}$ under a spherical blast wave loading caused by a point charge explosion. Complete destruction of RC element (i.e. knocking-out all concrete and rapture of all steel reinforcement bars) of such cross section is difficult to realize. However, this is not required in order to make the column to lose its bearing purpose. It turns out that it is sufficient to knock-out the concrete from the reinforcement bars and uncover the reinforcement steel bars at some section of the column. Then the steel reinforcement framework loses its stability and the column loses its bearing properties under the loading of the structure weight P .

According to the Euler theory of stability one can determine the minimal length l_b knocked-out from the column concrete required for the reinforcement framework to lose its stability (see figure 3)

$$l_b = \frac{\pi d}{2} \sqrt{\frac{E_r \mu_r}{\sigma}}, \quad (1)$$

where E_r is elastic modulus of the reinforcement bars, d is their typical diameter, μ_r is the reinforcement fraction, and σ is static stress in the column under the structure weight before the explosive loading. Knowing critical length of knocked-out from the column concrete depending on distance from the explosion one can evaluate required equivalent mass of point explosive charge [20]

$$m = (1 + 2.6\mu_r) \sqrt{1 + 50\sqrt{\mu_r}} \frac{\sigma_{pr}}{A_0 \sqrt{E/\rho}} \frac{ha^2}{\cos^4 \alpha}, \quad (2)$$

where E and ρ are elastic modulus and density of the concrete, $A_0 = 410 \text{ m/s}$ is typical air blast wave speed, $h = 1.2 \text{ m}$ is the width of the column, and σ_{pr} is its ultimate compression strength. Using equations (1) and (2) one finds the dependence of point explosion charge equivalent mass required for the concrete knocking-out at length l_b on the distance from the explosion point a . In our case the closest point to the bearing columns where a truck can bring an explosive charge is about 3.8 m. Then the fatal column failure is possible by the charge mass of 1600 kg. For that charge and position of the explosion there are two columns which will lose their bearing capability under the blast wave loading (see figure. 2). To account for that we eliminate the beam finite elements representing these two columns while modeling the interaction of the blast wave with the structure.

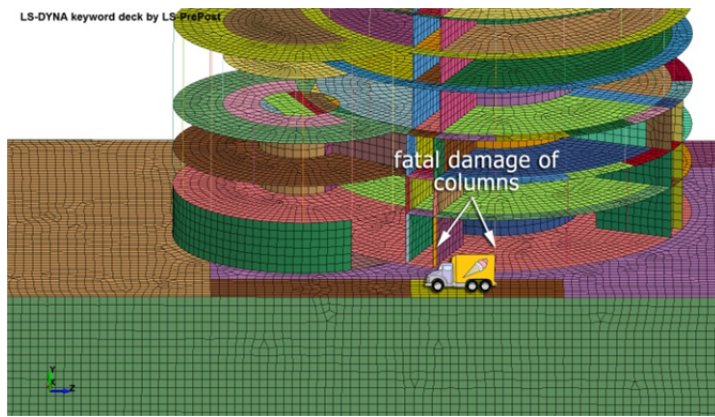


Figure 2. The entrance of the underground parking lot is the position where a truck carrying explosive charge can get. For this spot of 1600 kg TNT charge explosion two load bearing columns will receive fatal damage and lose their stability.

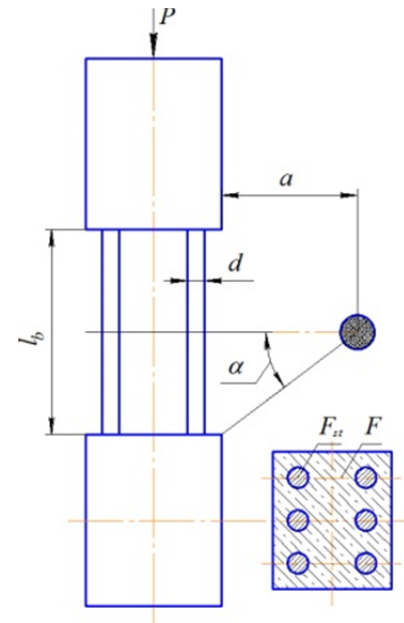


Figure 3. After an air blast wave loading concrete is knocked-out from a column bearing weight P at length l_b . If l_b exceeds some critical value the steel reinforcement bars lose their stability.

2.3. Static loading model

It is well known that RC structures experience appreciable shrinkage during construction process and exploitation. The presence of such deformations needs to be accounted for in the following investigation. The finite element model of Iset' is subjected to the loading by its own weight under gravitation. The simulation of the static loading was performed using implicit LS-DYNA solver. Due to the gravitational loading of the building the top stories of the tower displaced $\sim 4 \text{ cm}$ downward.

2.4. Dynamic loading model

After the gravitation loading within implicit solver simulations we change the solver to an explicit one. In the vicinity of the two first-floor load bearing columns shown in figure 2 we apply explosive loading. The point charge explosion is modeled using *LOAD_BLAST_ENHANCED method [5]. As the explosion parameters for the *LOAD_BLAST_ENHANCED card we use coordinates of charge center near the columns and one meter above the ground level, equivalent mass of TNT charge 1600

kg, and as type of blast source we use “spherical free-air blast”. In the simulations of such event it was found that the air blast wave of such position and TNT equivalent destroyed two load bearing columns and partially damaged a wall of stair flight and zero- and first-floor slabs (see figure 4).

After the dynamic loading of the model we again change the solver to the implicit one and continue the simulation of the damaged structure behavior under static gravitational loading for ten minutes. The result of this simulation evidence that eventhough the explosion destroyed two load bearing columns there is no tendency of progressive collapse of the tower in ten minutes timescale after such explosion. Thus, one can conclude that Iset’ tower is resilient to that kind of event.

3. Conclusion

It is impossible to overestimate the importance of elaboration and adoption of the correct constructive decisions to provide resilience of high-rise buildings to dynamic loadings including possible explosions. Development of the constructive decisions and security measures to prevent undesirable consequences and possible progressive collapse of the building in the case of explosions is necessary. In the present work we demonstrate a general approach to the investigation of a resilience of high-rise solid RC building using an example of real-life RC tower Iset’ located in Yekaterinburg, Russia. Possible ways of the choice of criteria for the destruction of load bearing elements of a structure and RC material in general are discussed. The calculations of the realistic explosive loading scenario of the Iset’ tower confirming its resilience to such type of impact is presented. In further works it is planned to study influence of explosive loadings on behavior of the reinforced concrete core of the building under dynamic impacts.

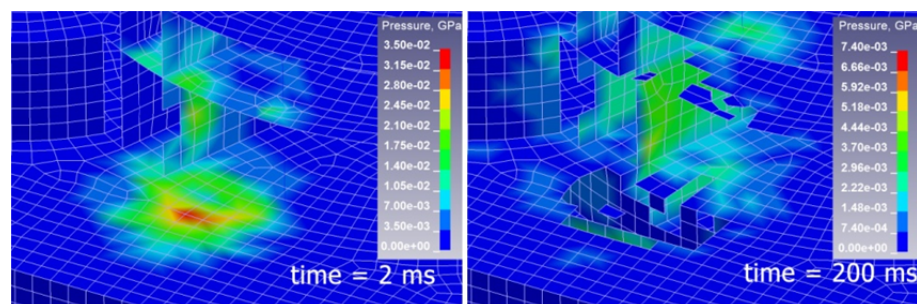


Figure 4. Profiles of the pressure on the surface of the structure for two instances of time (at 2 ms and 200 ms after the explosion).

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