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Influence of seismic design criteria on blast resistance of RC framed buildings: A case study

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ABSTRACT

In the last decades iconic and public buildings in urban habitat have been subjected to terrorist attacks and many of them are located in earthquake-prone regions. This study is aimed at assessing the influence of seismic design criteria on blast resistance of RC framed structures. Two 3D models were developed and analysed for a case-study building: one was designed for earthquake resistance according to Eurocode 8 (EC8); the other was designed only for gravity loads according to codes and practice going back to the 1970s. Several blast scenarios were considered and a two-step analysis procedure was used. Local analysis was carried out to identify columns directly failing under blast scenarios, whereas global pushdown analysis was performed on each 3D damaged model to assess robustness. Dynamic increase factors at both material and structural levels were assumed. Flexural–shear interaction and limited strength of beam–column joints were also addressed in the case of EC8-nonconforming building. Local pressure–impulse analysis was carried out in addition to simplified static and dynamic analyses; the same numbers of collapsed columns were found for the EC8-conforming building, while static analysis was too conservative for the EC8-nonconforming building. Pressure–impulse diagrams let to predict residual load-carrying capacity of adjacent columns. Seismic design criteria provided sufficient robustness only against some blast scenarios. In the case of EC8-nonconforming building, inclined beams in the staircase induced higher robustness against explosions occurring there and global ductility reduced under increasing load-bearing capacity. The latter can enhance by increasing longitudinal rebar in a way to avoid flexural–shear interaction, and/or reducing stirrup spacing.

1. Introduction

Explosions are one of the most frequent sources of accidental and man-made catastrophes which induce relevant economic losses and fatalities [1]. Such low probability/high consequence events can involve both civil and industrial buildings as a result of uncontrolled gas releases, vehicle or aircraft impacts, and terrorist attacks. In the last decades, strategic and iconic structures located in urban habitat have been subjected to blast actions in many parts of the world, so large amounts of money have been invested to increase homeland security. Furthermore, many of such structures are located in earthquake-prone regions and some of them were designed according to current seismic codes. Thus, public authorities and stakeholders are considerably interested in assessing whether strategic and iconic structures are able to resist not only earthquake actions, but also deliberate explosions. If an earthquake-resistant structure is at least partially able to withstand gravity loads after an explosion (in the sense that a fraction of blast resistance is provided by seismic design criteria), then strengthening interventions are less expensive and the homeland security action is more effective because a major number of structures can be protected with limited funding. The matter is clearly that the structural response of a building under earthquake ground motion is rather different from that experienced under blast loading. Earthquake ground motion involves the entire foundation system so all structural components are involved. Conversely, blast loading induces direct damage to few elements and their failure or loss can be a critical condition for the remaining part of the structure. If redundancy is low, damage can propagate throughout the structure causing progressive collapse [2–5]. The latter is then induced by a chain reaction mechanism resulting in a pronounced disproportion in size between a relatively minor triggering event and resulting collapse, that is, between the initial amount of directly damaged elements and the final amount of failed elements [6]. A specific robustness assessment is then needed also for earthquake-resistant structures subjected to terrorist threats because the assumption that seismic design would be sufficient to mitigate the risk of progressive collapse must be viewed with scepticism [7]. Although detailed investigations have been performed for blast resistance of steel structures [8–12], some open issues still remain for reinforced concrete (RC) structures for which research has mainly focused on single components [13–16].

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This study aims at assessing the influence of seismic design on blast resistance of RC framed structures located in urban habitat. Numerical results by Bao and Li [14] revealed that seismic detailing can significantly increase residual strength of blast-damaged RC columns. The scope of this paper is to assess that outcome at the larger scale of RC framed structures. A typical multi-storey building structure was analysed in the following cases: (1) earthquake-resistant structure designed in compliance with Eurocode 8 (EC8) [17]; and (2) existing structure not designed for seismic actions. Several scenarios were considered to investigate nonlinear structural response under blast actions occurring inside and outside the building. Small distances of the blast centre from the structure (near field explosions) were addressed in order to simulate the case of iconic and public buildings in urban habitat with lacking or ineffective protective barriers. Flexural–shear interaction in members and the limited strength of beam–column joints were considered by proper capacity models and offline verifications, to assess their influence on blast resistance. According to recent investigations [18], in this study both longitudinal and transverse reinforcements were varied and strain rate effects were included in the capacity model. Conversely, the ultimate strain of concrete was not changed because it does not significantly affect progressive collapse resistance. Therefore, structural robustness is discussed by means of diagrams and different parameters.

2. Blast loading

An explosion is a chemical process which causes a very fast and considerable pressure increase in the medium where it occurs (that is, air or water), as well as high temperatures. The shock wave propagates with a given speed, magnitude, and duration; the latter does not exceed 10^{-2} s. The properties of gas explosions depend on the fuel-oxygen cloud concentration, the characteristics of the confining space (size, shape, rigidity and degree of aeration), and the type of ignition source (e.g., hot surfaces, open flames or hot gasses, mechanical friction or sparks, electric equipment, electric or electrostatic discharges). The properties of bomb explosions are mainly affected by the exploding mass, its distance from the target structure, and the confinement provided by reflecting surfaces which can increase overpressures. An explosion in air can produce deflagration, namely low-velocity flames and pressures ($v < 10^3$ m/s), or detonation, namely high-velocity flames and pressures ($v > 10^3$ m/s). Detonation causes flying debris, and hence more destructive effects. The present study deals with the effects of bomb detonations in terms of overpressures on structural components, whereas flames and flying debris are neglected. Effects of flame propagation and acceleration mechanisms caused by the presence of non-structural components and contents are indeed out of the scope of this paper, because their computation requires advanced computational fluid dynamics tools.

The explosive yield of trinitrotoluene (TNT) is considered to be the standard strength measure of bombs and other explosives. The overpressure time history after a bomb explosion is characterised by two phases: the former is positive, very quick and strong; the latter is negative, longer and less intense (Fig. 1). Assuming an infinite target size, the pressure time history after an explosion can be simulated through the modified Friedlander equation [19]:

$$p(t) = p_0 + p_{\max}\left(1 - \frac{t'}{t_d}\right)\exp\left(-\frac{bt'}{t_d}\right) \quad (1)$$

where t' is the time measured from the arrival time t_a of the blast wave to the target (i.e., $t' = t - t_a$), p_0 is the reference ambient pressure, $p_{\max}$ is the peak overpressure (i.e., $p_{\max} = \Delta p(t_a) = p(t_a) - p_0$), t_d is the duration of the positive pressure phase, and b is a waveform parameter [20]. The first phase of overpressure time history can be approximated as a triangular impulse with instantaneous rise time and linear decay up to t_d. Therefore, assuming the origin time equal to t_a and $t \leqslant t_d$, Eq. (1) can be replaced by:

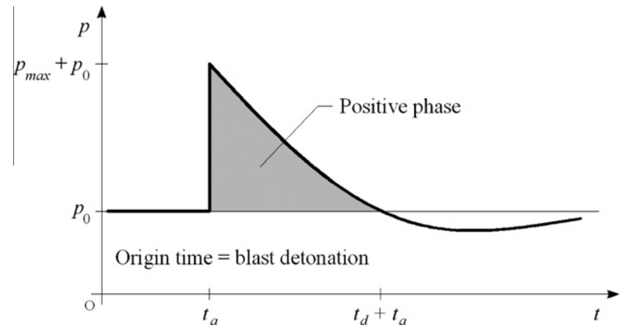

Fig. 1. Blast-induced pressure time history.

$$p(t) = p_0 + p_{\max}\left(1 - \frac{t}{t_d}\right) \quad (2)$$

Both b and $p_{\max}$ are blast parameters which depend on the reduced distance $Z = R/W^{1/3}$, where R is the distance of the blast detonation point from the target element (in m) and W is the explosive charge mass (in kg of equivalent TNT) [21]. Bomb detonations with different charge weight and distance produce equal peak pressures if their reduced distance is the same. It is underlined that the equivalent mass of TNT for any explosive type can be defined as:

$$W = \frac{H_e}{H_{TNT}} W_e \quad (3)$$

where W_e and H_e are the mass and heat of combustion of the explosive charge, and H_{TNT} is the heat of combustion of TNT. The peak overpressure (in kg_f/cm^2) can be predicted as follows [21]:

$$\begin{aligned} p_{\max} &= \frac{14.0717}{Z} + \frac{5.5397}{Z^2} - \frac{0.3572}{Z^3} + \frac{0.00625}{Z^4} \quad \text{if } Z \in [0.05, 0.3] \\ p_{\max} &= \frac{6.1938}{Z} - \frac{0.3262}{Z^2} + \frac{2.1324}{Z^3} \quad \text{if } Z \in [0.3, 1] \\ p_{\max} &= \frac{0.662}{Z} + \frac{4.05}{Z^2} + \frac{3.288}{Z^3} \quad \text{if } Z \in [1, 10] \end{aligned} \quad (4)$$

The positive phase duration of overpressure time history (in s) can be predicted as follows [22]:

$$t_d = 10^{-3} k \sqrt[6]{W} \sqrt{R} \quad (5)$$

where k is a constant usually set to 1.3.

3. Assessment methodology

Structural robustness of the building under study was investigated by means of a two-step procedure falling in the class of direct assessment approaches [23,24]. In a direct approach progressive collapse scenarios are explicitly analysed, whereas in an indirect approach structural robustness is guaranteed through minimum levels of overstrength, redundancy and ductility [25]. Direct approaches include alternate path analysis which involves removal of members from the structure to determine if the damaged structure can tolerate load redistributions.

The first step of the methodology used in this study was the analysis of single structural components under blast loading. This step was aimed at identifying critical blast scenarios where each scenario was defined by the quantity of explosive and location of blast centre within or close to the structure. In particular, W was