Structural Robustness of RC Frames Under Blast Events

Marco Mennonna, Mattia Francioli, Francesco Petrini, and Franco Bontempi

Abstract This paper presents a numerical procedure for the robustness quantification of RC frames under blast-induced damage scenarios. The procedure is supported by a non-linear numerical analysis, by quantifying the structural response at the global level (i.e., response of the structural system/frame to the blast-induced damage) and by obtaining the so-called "robustness curves", representing the residual strength of the structure under increasing damage levels. The procedure is then applied to a 2D RC frame structure. The sensitivity of the robustness curves with respect to a set of analysis parameters is discussed.

Keywords RC structures · Structural robustness · Blast · Non-linear dynamics

1 Introduction

Although the events of progressive collapse have a very low probability of occurring, the consequences have usually a very high impact [1]. Progressive collapse can be triggered by many factors such as blast loading from explosives or gas leakage, design faults, vehicle impact, construction errors, debris impact, and other extreme loadings such as fire and high-magnitude earthquake. In many instances, a significant propagation of direct damage to key structural components throughout the structure have produced a progressive collapse of residential, iconic and public buildings,

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resulting in huge losses of life and property. The interest in the explosion and their potential of causing progressive collapse of structures began after an important event, which was the partial collapse of the Ronan Point tower in the UK in 1968 [2]. A comprehensive definition of structural robustness is reported in EN 1991-1-7 (2010) as "*the ability of a structure to resist events such as fires, explosions, impacts or the consequences of human error, without being damaged in a disproportionate way compared to the original cause*", that explicitly refers to the kind of actions that are relevant to the robustness. One of the most established procedures for robustness analyses in research is based on the so-called "damage-presumption approach", that is a non-linear analysis where a certain damage level is assumed for the structure (typically for a framed structure consisting in the removal of a column), and the residual strength of the structure is then evaluated. As for any structural collapse analysis, the results of the damage-presumption approach are very sensitive with respect to the various analysis parameters who play a certain role in the numerical solution: the two most important parameters are the time interval for column removal (which is representative of the blast explosion typology) and the value assumed by the structural damping.

In this paper, a sensitivity analysis is carried out on these two parameters in order to quantify the scattering of the numerical results coming out from the uncertainty/variability affecting the phenomena.

2 Global Robustness of Reinforced Concrete Frames

2.1 Structural Behavior Aspects

As reported in Starrosek [1], redundancy or compartmentation are the two main conceptual design strategies at global structural scale that can be pursued to satisfy robustness requirements, together with local ductility requirements. In this view, the good seismic design practice which has been established for modern reinforced concrete (RC) framed structures matches well with robustness requirements: they are highly hyper static structures; therefore, they allow to have alternative paths of different loads and to be able to suffer many local damages before a global collapse occurs, the sections of the elements are designed to be ductile and to have a bending behavior at failure. In general then, the criteria of seismic engineering have positive impact regarding the robustness of the building. Additional specific structural behaviors, like the membrane or catenary effects allow an over strength which can be well exploited in case of damage such as the removal of a key element like a column [3].

2.2 Numerical Analysis for Structural Robustness

Regarding the load resistance corresponding to the column removal scenario, a number of experimental studies have been conducted on the reduced scale specimens mostly in order to study the progressive collapse resistance in such scenario [4, 5]. The main drawback of the experimental studies is that the column removal and the successive load is usually applied quasi-statically, then not capturing the dynamic amplification effects, which can play a prominent role in this kind of problems. From the numerical analysis point of view, to capture the kind of effects listed in previous section, a material and geometric nonlinear Finite Element (FE) analysis must be put in place during the design and assessment phases of RC structures for robustness. The nonlinear dynamic procedure for progressive collapse is the most thorough method of analysis in which a primary load-bearing structural element (e.g., column) is removed dynamically and the structural material is allowed to experiment nonlinear behavior. This allows larger deformations and energy dissipation through material yielding, cracking, and fracture. The nonlinear dynamic procedure for RC frames consists in analyzing the frame dynamic response under the sudden removal of a number "n" of columns for the frame starting from the static equilibrium configuration reached by the structure under vertical loads (due to the seismic "permanent+0.3*variable" mass combination). The outcome of the nonlinear dynamic analysis can be of two typologies [6]: (a) after an initial damped transitory phase (fast dynamics), the structure reaches a static equilibrium condition; (b) the collapse occur. Regarding the collapse, it can be defined to occur when: (i) there is "run-away" behavior observed in the vertical displacement time history of the nodes around the removed column, or; (ii) the vertical relative drift (D_V) between the beam-column nodes located around the removed column reaches the value of 20–15% [7]. The latter is calculated starting from the vertical displacement of the node δ_V and the length of the beam to which the node belongs L_b

$$D_V = \tan^{-1}(\delta_V/L_b) \tag{1}$$

If the outcome of the non-linear dynamic analysis is not the collapse, an incremental static nonlinear analysis of the structure is carried out under horizontal forces (pushover) in order to evaluate the residual capacity of the damaged structure. In this way, each number of simultaneously removed column "n" is associated to a residual lateral force capacity (λ_u) as evaluated by the pushover, and expressed as percentage (λ_u/λ %) of the force capacity (λ) of the non-damaged structure, evaluated by a pushover analysis on the undamaged structure.

It is worth noting, that the response to the initial dynamic analysis (typically represented by the time history of the vertical displacement of the node) is strongly influenced by some parameters regarding the analysis procedure or the structural model. One of these parameters is the removal time interval (Δt_d) for the column: the less is Δt_d for the complete removal of the columns, the more impulsive is the response, the larger is the structural response, the larger is the damage (e.g., formation of plastic hinges) suffered by the rest of the structure. In this view, the identification or setting of the column removal time interval Δt_d for a certain "n" would be of value.

2.3 Robustness Curves

As a result of the above-mentioned numerical outcome, the robustness of the structure can be quantified and efficiently represented by the so-called "robustness curves" (RCs) as introduced by Olmati et al. [6]. RC are represented on a Cartesian plane in which the x-axis reposts the damage level suffered by the structure ("n" in the previous section), while the y-axis reports the corresponding residual force capacity percentage (λ_u/λ % in the previous section), see for example the qualitative representation of robustness curves represented in Fig. 1. The less is the steepness of the robustness curve, the more is the robustness of the structure under the considered damage.

The procedure for the evaluation of the robustness curves in Fig. 1, is depicted in the flowchart reported in Fig. 2: the non-linear dynamic analysis (NDA in the flowchart) consisting in the column sudden removal is conducted for a number of different locations (N_L) in the structure, and for an increasing damage level "D-scenario (i, j)" (where "i" indicates the location and "j" the presumed damage level). After each NDA, if the collapse does not occur, the pushover non-linear analysis under lateral load is carried out to determine one point (λ_u/λ %) of the robustness curve. The procedure is repeated for different locations and damage levels in order to obtain a set of robustness curves under blast presumed damage.

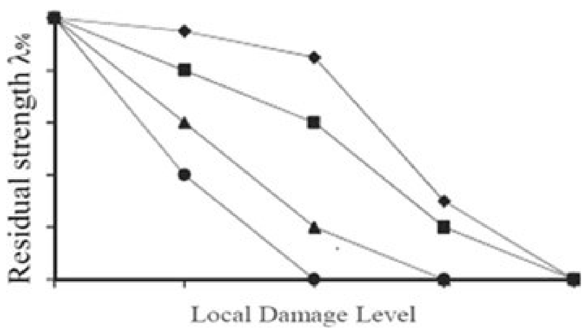


Fig. 1 Typical robustness curves

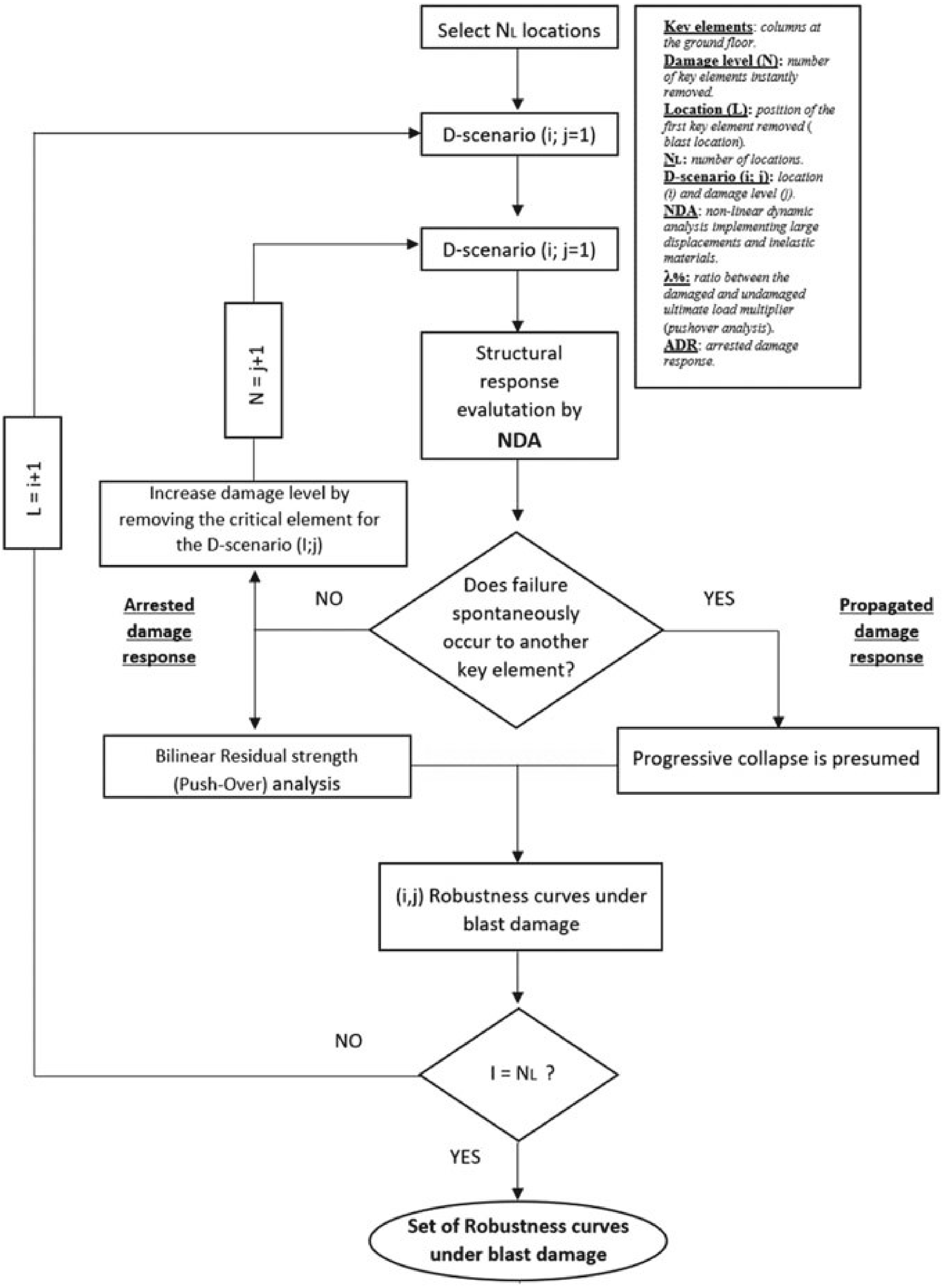


Fig. 2 Flowchart of the procedure to evaluate the structural robustness against blast damage [6]

3 Application to an Existing Structure

3.1 Case Study Structure and FEM Model

In order to develop the full procedure for the robustness quantification of RC frames under blast load scenarios, a 2D RC frame structure is considered (Fig. 3). The building to which the 2D frame belongs is a part of a very complex hospital system completed in the early 2000s. It is a RC structure made of concrete C28/35 and steel B450C. The structure is modeled using SAP 2000® commercial structural code, with a Finite Element modeling that allows the possibility to define the nonlinear properties of the materials: the nonlinear behavior is implemented using the approximation of plastic hinges, which are obtained from the Moment-rotation relationship (M-θ) evaluated from the equations provided by the Italian Standards NTC2018 [8]. Moreover, geometric nonlinearity is taken into account with large displacement and P-Δ options. As stated before, the 2D frame is extrapolated form a complex structure: in order to simulate the membrane effect that occurs in a 3D structure due to the connection of the different beams with the floor slab, a dedicated non-linear beam finite element is added. In particular, this latter element has been modeled on the basis of the behavior of the floor slab: a fiber-based model with diffusive plasticity has been used in order to identify its exact axial and bending behavior; thus, a simplified model with the approximation of plastic hinges has been created and connected to the columns of the 2D frame in such a way that the so-called membrane (catenary effect in 2D) effect can be taken into account in the 2D plane.

Considering the 2D frame structure, a nonlinear static analysis has been made in order to evaluate the effectiveness of these new elements. After the removal of a certain column, vertical loads have been amplified using a λ multiplier. A pushdown analysis has been made on two models, which difference was the presence of the

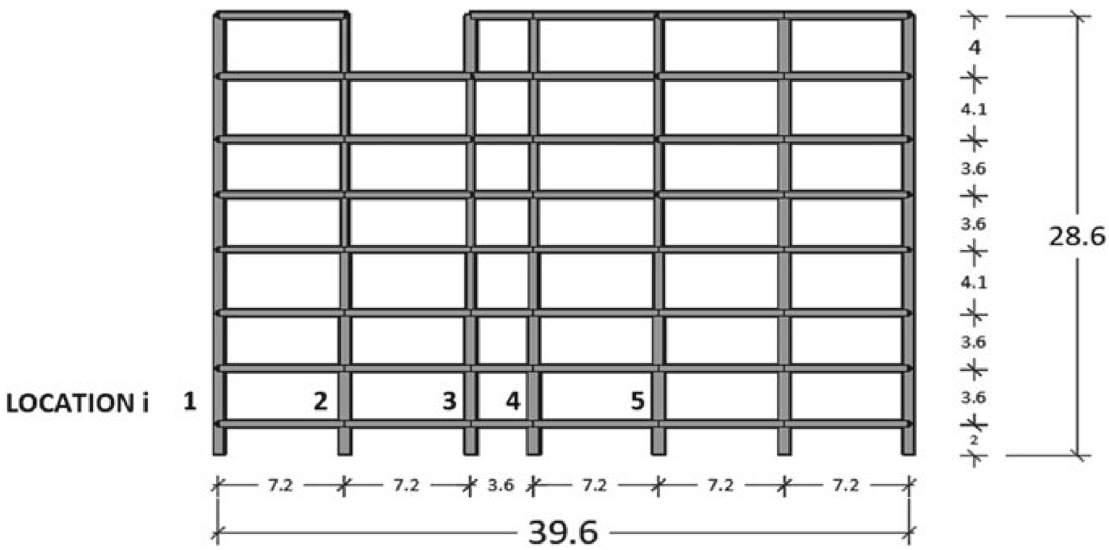


Fig. 3 2D RC frame structure and different locations assumed

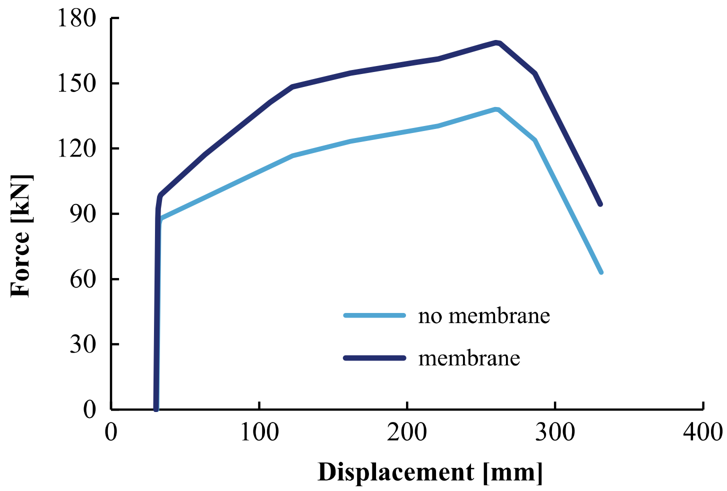


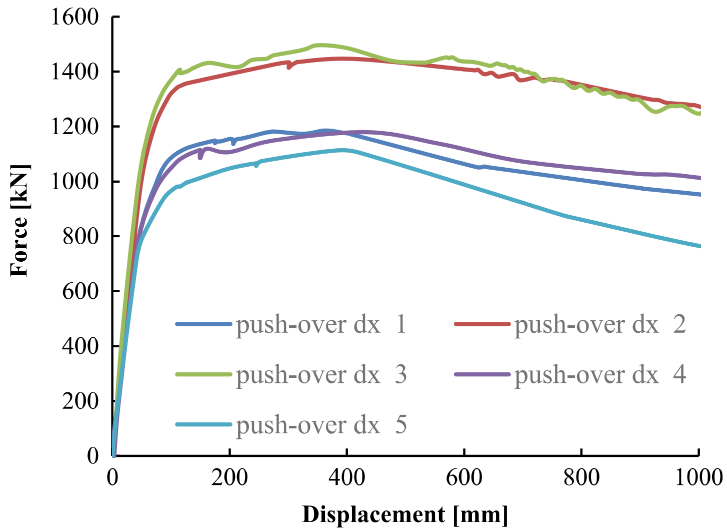
Fig. 4 Membrane forces in RC beam-column substructures under pushdown analysis

afore mentioned elements. During the analysis, the vertical displacement of the node at the top of the removed element was monitored, together with the resultant vertical forces. The outcome is shown in Fig. 4: the presence of the membrane/catenary effect allows an increase in strength without modifying the initial stiffness.

3.2 *Global Robustness Results*

The procedure for the robustness quantification of RC frames under blast load scenarios is conducted. The global analysis of the structure, using both nonlinear dynamic and nonlinear static analyses as depicted in the flowchart reported in Fig. 2, and its outcome is the evaluation of the global robustness. After having defined a certain number of location N_L (2, column 3 and column 5 of the 2D RC frame, see Fig. 3), each of which represents the position of the first key element removed -blast location, different analyses regarding each D(i, j)-scenarios (i = location, j = damage level) are developed; a particular location is considered and starting from a certain damage level (which corresponds to a number of elements removed), the structural response is evaluated by the non-linear dynamic analysis. At this point, if failure doesn't occur spontaneously to another key element, first the residual strength of the structure is identified using a nonlinear static analysis, then the damage level is increased (i.e., another element is removed) and again the structural response is evaluated. During the analysis that provides the evaluation of the residual strength of the structure (i.e., pushover analysis), the residual lateral force capacity (λ_u) considered is the one that corresponds to the event that occurs first between the "run-away" behavior observed in the vertical displacement time history of the nodes around the removed column or the presence of a vertical drift ratio ($D_{V,\,MAX}$) bigger than 15% (see paragraph 2.2). Obviously, if N_L is different from 1, all is repeated N_L times. Before starting to apply the procedure in order to identify the robustness of the structure under blast loads, various locations of hypothetical damage were assumed (Fig. 3). Depending on which column is removed, the results obtained are different

Fig. 5 Push-over curves of the 2D frame structure due to different locations of damage



(Fig. 5): the internal columns (n°3, n°4 and n°5) are characterized by a bigger area of influence and the hypothetical damage to one of them could cause a bigger reduction of the capacity.

The curves obtained, for simplicity of representation, are then bi-linearized: the real curve is replaced a with simplified curve which has at first a linear part and then a perfectly plastic plateau at the F_Y value for the force. The slope of the linear part is identified imposing the passage for the point $0.6F_{MAX}$ of the original capacity curve, while the value of F_Y is obtained by imposing the equality of the areas underpinned by the bilinear curve and by the capacity curve for the maximum displacement d_U.

Once established the locations, for each of them, some sensitivity analyses have been carried out varying different parameters: the damping ratio (ζ) and the removal time interval of column (Δt_d). Considering the first parameter, Fig. 6, shows the effects of the variation of the damping ratio ζ for location 1 when the removal interval Δt_d is set equal to 0.03 s. As the damping index increases, the maximum vertical displacement and the time necessary to dampen the free oscillations of the removed column node decreases. For successive analyses, the damping ratio is set equal to 4% since smallest values (e.g., 1% in the figure) do not determine a significative

Fig. 6 Displacement of the node at the top of column 3 (location 1): effect of variation of damping ratio

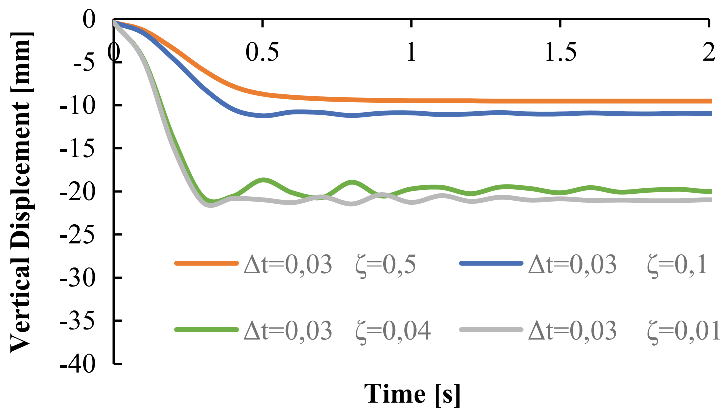
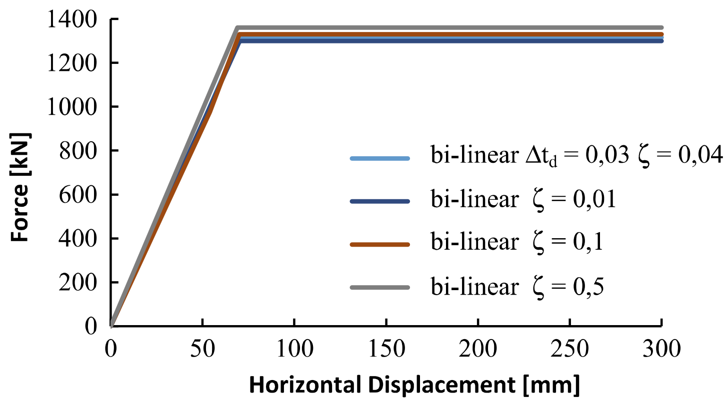


Fig. 7 Pushover curve of 2D RC frame structure – damage level 1: effect of variation of damping ratio



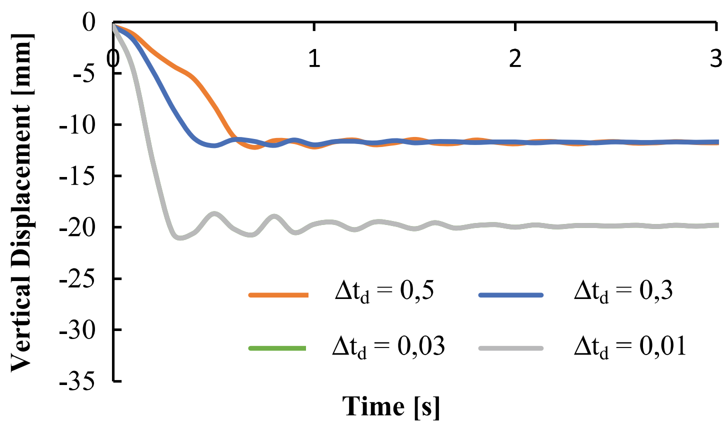
difference in terms of "damping" time. For sake of completeness, it has to say that a very large damping index, such as 0.5, leads to an almost absence of oscillation.

The bi-linear pushover curves in Fig. 7 show the case of damage 1, with instantaneous removal of column 3 and depict the influence of the damping index parameter at the same removal time interval Δt_d, set equal to 0.03 s. As the damping index decreases, the above-described dynamic amplification effect leads to a decreasing of both the stiffness and strength of the damaged frame (i.e., after the removal of the column) under lateral load.

Figures 8 and 9 show the effect of the variation of Δt_d for location 3. As it appears in Fig. 8, which shows the results of a nonlinear dynamic analysis that captures the effects of amplification in terms of displacement and in terms of geometric and material non-linearities, the displacement of the node at the top of the removed column increases as Δt_d decreases; there is a small difference between the cases with $\Delta t_d = 0.5$–0.3 and $\Delta t_d = 0.01$–0.03. It is also possible to note that the value of Δt_d has also a certain influence on the amplitude of the oscillations around the residual displacement and on the damping shown in the time histories.

Figure 9 shows the results of pushover analyses for location 1 with damage level equal to 1 (column 3 removed) and how the variation of Δt_d affects the capacity of the damaged structure: although there are just slight differences between the curves for the cases considered, as the Δt_d value decreases also the overall capacity decreases.

Fig. 8 Displacement of the node at the top of column 3: effect of variation of ΔT_d (removal time of the column)



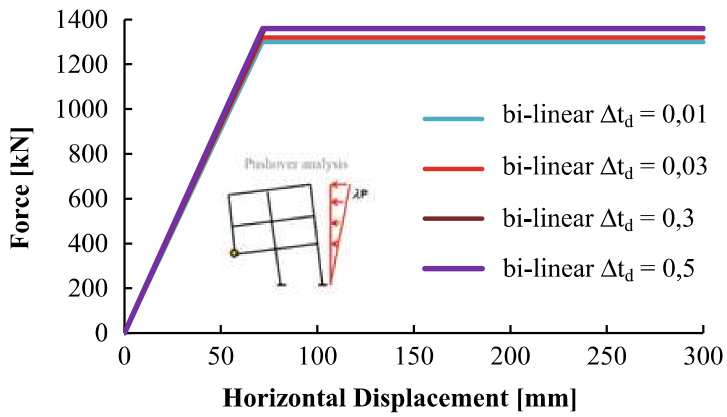


Fig. 9 Pushover curve of 2D RC frame structure – damage level 1: effect of variation of ΔT_d (removal time of the column)

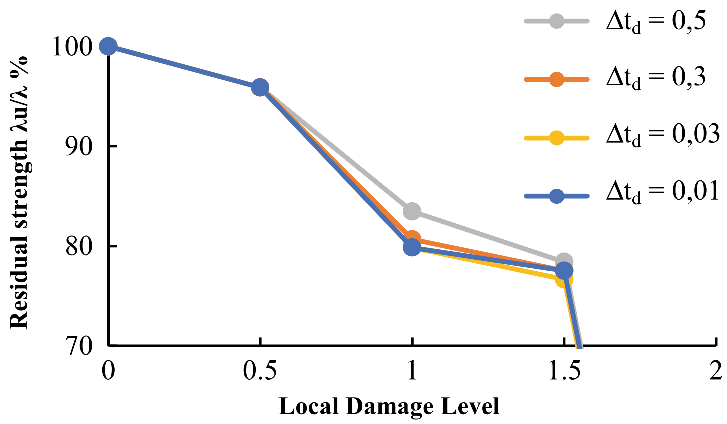


Fig. 10 Robustness curves for 2D RC frame structure for location 1: effect of variation of Δt_d (removal time of the column)

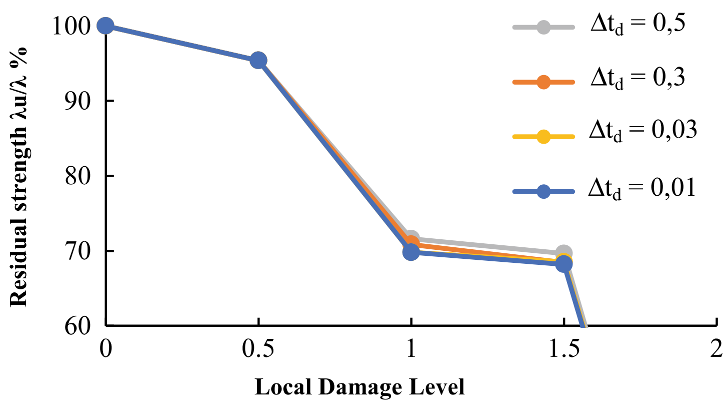


Fig. 11 Robustness curves for 2D RC frame structure for location 2: effect of variation of Δt_d (removal time of the column)

It is important to understand the effect that different values of Δt_d have in terms of decreasing the capacity of the structure because this parameter can be used to simulate the damage induced by different blast scenarios: the time interval of column removal Δt_d can be considered as the time during which the damage propagates and affects the element structural element under blast-load effects, and it is possible to assume that it depends on the different properties/intensity measures of the explosion, like stand-off distance from the ignition and equivalent kilograms of TNT.

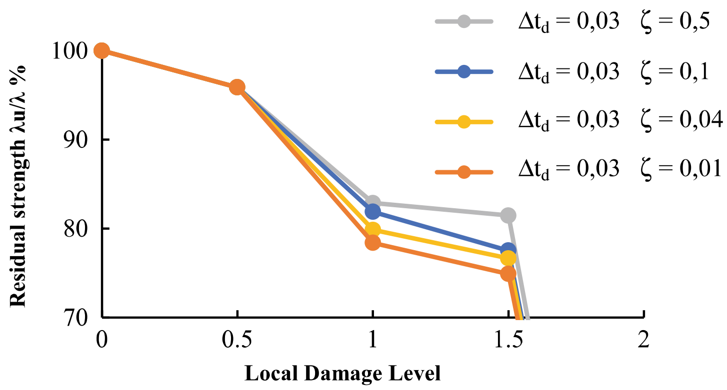


Fig. 12 Robustness curves for 2D RC frame structure for location 1: effect of variation of damping ratio

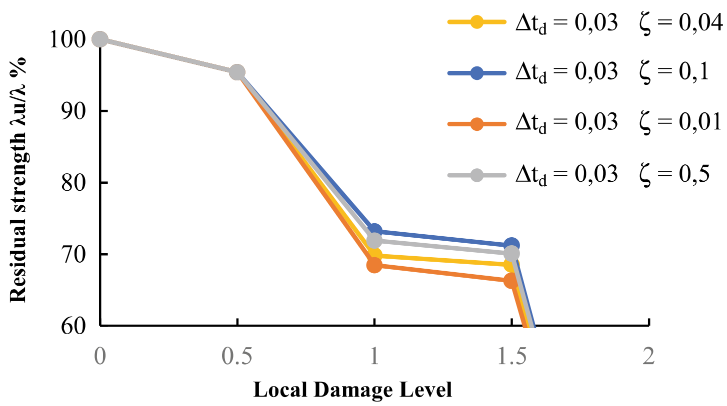


Fig. 13 Robustness curves for 2D RC frame structure for location 2: effect of variation of damping ratio

Figures 10, 11, 12 and 13 shows the results of the discussed analyses in terms of robustness curves, obtained as described in paragraph 2.3. Using the terminology presented in the flowchart of Fig. 2, two locations are considered ($N_L = 2$): location 1 implies that the first element removed is column 3, while for location 2 the first element removed is column 5. In both cases, damage level 2 corresponds to the complete failure of the column adjacent to the first element removed (column 2 for L1 and column 4 for L2). Damage level 0.5, instead, corresponds to the loss of the 50% of the transversal section; this means that the explosion results in a loss of element stiffness and capacity, but not in a collapse. The damaged element continues to carry the axial load but there are no dynamic effects due to the loss of the column. It should be noted that for the damage level 1.5, considerations are fully similar to those reported for the damage level 0.5: in this case, one column is completely removed, and the loss of 50% of the second column's section is considered. For example, in Figs. 10 and 11 it is possible to notice the effect of the variation of Δt_d: coherently to Fig. 9, where the pushover curves for damage level 1 are reported, the decrease of Δt_d determines a decrease of the residual capacity for both locations. Damage level 2 always determines the progressive collapse of the structure, while damage level 1 causes a drop in initial capacity of about 20% for L1 and about 30% for L2. Similarly, Figs. 12 and 13 shows the effect of the variation of the other parameter investigated, the damping ratio, with the same removal time of the column ($\Delta t_d = 0.03$ s). The issue related to capacity losses remains the same as previously discussed:

if the damping index increases, there is an increase in the capacity of the RC frame compared to cases with a smaller damping value. Even in this case, damage level 2 causes the collapse of the structure and damage level 1 determines a reduction of the structure's capacity.

4 Conclusions

In this paper, a procedure for the robustness quantification of RC frames under blast induced damage has been presented, connected to a global assessment of the structure and based on nonlinear dynamic analysis in order to evaluate the behavior of the damaged structure and a nonlinear static analysis in order to find a characteristic value of the residual capacity. The influence of parameters regarding the structural aspects (damping index) and explosions typology (removal time interval of the element) has been evaluated and described. As a general conclusion, it has to be highlighted that, due to the high sensitivity of the analyses to the removal time interval of the element, the connection of the explosion typology (e.g., stand-off distance and intensity) to this parameter it is necessary for an exhaustive association of the robustness performances to the blast load. Further researches are under development on this side by the authors.

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