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FE dynamics and damage modeling of a masonry arch bridge subjected to close-range explosions in controlled demolition scenarios.

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Abstract

This study investigates the structural response and the explosion- induced damage for masonry arch bridges under blast loading, with the goal of optimizing explosive charge placement in controlled demolitions. Due to their structural redundancy, masonry arch bridges exhibit nonlinear behavior under extreme dynamic loads, leading to unpredictable responses. Consequently, explosive demolition presents safety risks, including uncontrolled debris projection and incomplete collapse mechanisms, which may require hazardous post-blast dismantling. A comprehensive numerical analysis is performed using the San Marcello Pistoiese bridge (Italy) as a case study, with detailed geometric and mechanical data available in the literature. A three-dimensional finite element model was developed in Abaqus, in which masonry and infill material are modeled as homogeneous, isotropic solids. The Concrete Damage Plasticity (CDP) formulation is employed to describe the post-elastic behavior, including stiffness degradation and damage. Blast loading was simulated using the CONWEP approach, based on the empirical relations by Kingery and Bulmash (1984). Different demolition scenarios are examined, by varying the mass and position of the explosive charges. The numerical results have provided insights into damage evolution, collapse mechanisms, and effectiveness of alternative blasting configurations, facilitating the optimization of demolition strategies while accounting for the structural characteristics and uncertainties inherent in masonry arch bridges.

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1. Introduction

Masonry arch bridges are complex structures made of heterogeneous materials. The structural elements, such as piers, arches and abutments, are typically constructed from stone masonry, while the infill consists of loose or weakly cemented geomaterials. These bridges may require controlled demolition for many reasons, including replacement with new structures, functional obsolescence, economic disadvantage of retrofitting interventions, or environmental and urban planning constraints (Baker et al., 2017). As a result, it is crucial to understand their structural response under close-range explosions (Wu et al., 2024), since the high degree of structural redundancy in masonry arch bridges coupled with material heterogeneity leads to complex and uncertain demolition processes (Barsottelli & Avci, 2013). Inadequate demolition design, particularly concerning the quantity and placement of explosive charges, can result in ineffective blasting and incomplete collapse, requiring hazardous post-demolition manual dismantling. These risks can be minimized by conducting adequate preliminary studies using advanced numerical modeling techniques capable of describing the nonlinear mechanical behavior under extreme dynamic loads of both masonry and fill geomaterials, thus enabling safer and more efficient demolition strategies. Within this context, the manuscript presents some significant results obtained through Finite Element simulations (FE) of close-range explosions acting on a real masonry arch bridge, the San Marcello Pistoiese bridge, selected as a reference case study from the literature. A hypothetical controlled demolition scenario is investigated and a sensitivity analysis is performed to assess the influence of the position and mass of spherical TNT charges on demolition effectiveness. A detailed FE macro-scale model was developed in Abaqus (Dassault Systèmes Simulia Corporation, 2011), and the blast effects were evaluated in terms of internal forces and structural displacements. The resulting damage was subsequently examined both qualitatively, through damage maps, and quantitatively, using a post-processing tool implemented in Python. The manuscript is organized as follows: Section 2 describes the proposed methodology; Section 3 introduces the selected case study; Section 4 presents the FE model implemented; Section 5 discusses the numerical results; Section 6 presents final remarks and perspectives for future investigation.

2. Explosions: how to evaluate their effects on existing structures and infrastructures?

2.1. The CONWEP approach for modeling explosions effects in FE models

The CONWEP (Conventional Weapons Effects Program) approach is an empirical tool developed for simulating explosions of spherical charges detonated in free air (Hyde, 1988). It is based on the experimental results obtained by (Kingery & Bulmash, 1984) and allows the estimation of peak overpressure, pulse duration and shock wave distribution as a function of the charge's mass and of the distance from the detonation point. This approach has been implemented in Abaqus environment, that, after defining the type of blast, the equivalent mass of TNT and the detonation point, allows the numerical simulation of explosion-structure interaction.

The main parameter defined in the CONWEP approach is the Hopkinson-Cranz scaled distance Z_{HC} (Hopkinson, 1915; Cranz, 1926), that depends by the standoff distance R and the charge's mass W, according to Equation 1.

$$Z_{HC} = \frac{R}{\sqrt[3]{W}} \tag{1}$$

For $Z_{HC} < 0.100\ m/\sqrt[3]{kg}$, the use of the CONWEP approach is not recommended (Shin et al., 2015), despite it remains useful as a first-order approach (Rigby et al., 2015; Kristoffersen et al., 2019). In this study, we have adopted it anyway for modelling close-range explosions, demonstrating that it can provide significant qualitative results and direct future research.

2.2. Sensitivity analysis for appraising the behavior of masonry arch bridges subjected to close-range explosions

We have implemented a sensitivity-analysis-based procedure to assess the damage caused to a masonry arch bridge by the detonation of point-source explosive charges. Position and mass of the explosive charges are the two factors that influence the effectiveness of demolition operations, and therefore, attention is focused over them, in order to understand how they can be optimized to achieve the collapse, minimizing the residual strength and the TNT's costs.

The procedure implemented consists of three steps. First, a three-dimensional FE model of the case study is implemented in Abaqus (Dassault Systemes Simulia Corporation, 2011), accurately representing its geometry. The mechanical behavior of the materials is modelled using Concrete Damage Plasticity, to also consider the evolution of damage in the homogenized material. The second step involves the positioning of the charges according to different layouts, and the numerical analysis of the effects induced on the infrastructure by their detonation. The detonation of the charges is simulated by using the CONWEP approach. In the third step of the procedure, an explicit analysis with transient explosive action is carried out and the effectiveness of the detonation of the charges is determined through three different operations:

- Evaluation of the forces and displacements induced by the explosions.
- Classification of the mesh points based on the tensile damage level reached (using a specific Python code).
- Critical analysis of the damage maps obtained.

3. The case study: San Marcello Pistoiese Bridge

The case study considered for the presentation and validation of the proposed strategy is the San Marcello Pistoiese bridge, located in San Marcello Pistoiese (Tuscany, Italy). The geometrical and mechanical features of the bridge are available in the literature (Pelà et al., 2009; Pelà et al., 2013). The structure is symmetrical, composed of three arches (Figure 1) and is characterized by the presence of different masonry materials and of an infill consisting of waste geo-material (Table 1). The reader is addressed to the mentioned references for further information.

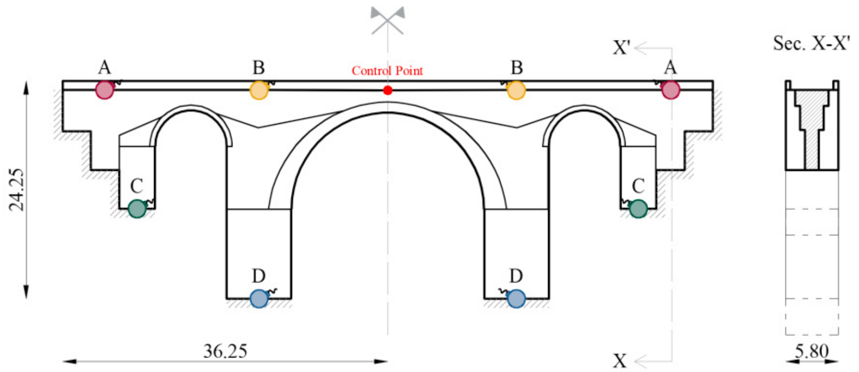

Fig. 1. Frontal view and transversal section of San Marcello Pistoiese Bridge and positions considered for TNT charges.

Table 1. The structural materials identified in the bridge, with indication of the position and label assigned.

Structural material	Position	Label
Stone and lime mortar masonry	Piers, spandrel walls, abutments, parapets	Masonry 1
Stone and concrete mortar masonry	Arch cornice	Masonry 2
Bricks and concrete mortar masonry	Vaults	Masonry 3
Waste soil-like material obtained from excavation of foundations	Infill above vaults and between spandrel walls	Infill

4. The continuum three-dimensional FE macro-model developed

4.1. Geometrical modeling of structural elements

A FE model of the San Marcello Pistoiese Bridge is implemented in Abaqus (Figure 2). The different parts of the structure are modelled as a three-dimensional solid elements and are placed in full contact. The reference system $\{O, x, y, z\}$ is such that the bridge extends longitudinally in the $\{x, y\}$ plane, with the z direction out of plane. A mesh composed of 32,692 quadratic tetrahedral elements of type C3D10M, with an approximate average size of 1.00 m, is adopted. The modified quadratic tetrahedral element C3D10M is robust for large-deformation and contact problems and exhibits minimal shear and volumetric locking.

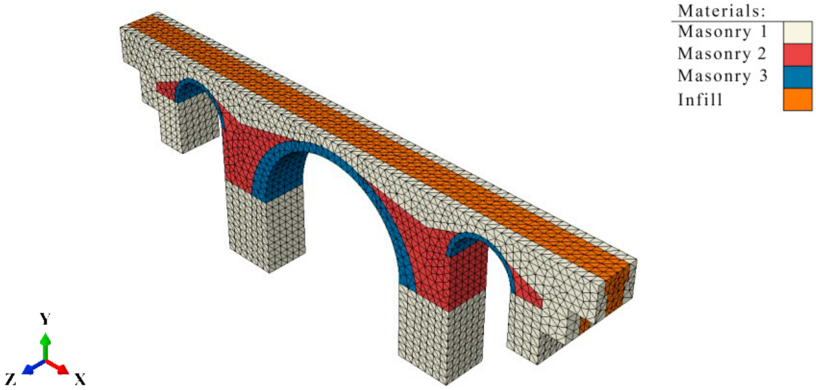

Fig. 2. FE Model implemented in Abaqus.

4.2. Mechanical modeling of homogenized materials

The structural elements and the materials constituting the bridge are modeled as homogeneous, isotropic, Cauchy continuum, with elastic and inertial parameters listed in Table 2. The post-elastic behavior of the materials is modeled by adopting the Concrete Damage Plasticity Material Model (hereafter CDP), a material model originally developed for modeling damage and cracking in concrete-like materials (Lubliner et al., 1989; Lee & Fenves, 1998). Due to its simplicity of use in Abaqus, it has become popular also for masonry structures, allowing efficient modeling both at the panel and at the building scale (Rainone et al., 2023; 2024). In this study, Masonry material 1, 2 and 3 have been modelled using CDP both for compressive and tensile behavior. For infill material, CDP was only used to model the compressive behavior, whereas the tensile response was described by a simple multi-linear stress-strain law, without defining a damage variable. A CDP-like yield function, anyway, has been assigned to the infill.

Table 2. Parameters adopted for the elastic response and the mass density of homogenized materials.

Material	Elastic Parameters			Mass density	Rayleigh Damping
	E $[MPa]$	υ	G $[MPa]$	ρ $\left[\frac{kg}{m^3}\right]$	ξ
Infill	1,000	0.20	416.67	1,800	0.05
Masonry 1	10,000	0.20	4,166.67	2,200	0.05
Masonry 2	12,000	0.20	5,000.00	2,200	0.05
Masonry 3	10,000	0.20	4,166.67	1,800	0.05

The CDP model requires the assignment of a set of parameters that define the yield surface, the flow-rule and the visco-plastic regularization (for further details about these aspects of the model, the reader is addressed to the Abaqus manual (Dassault Systemes Simulia Corporation, 2011). For all the materials, given the absence of specific experimental data, the following values have been assumed: $\psi = 10°$ for the dilancy angle; $\epsilon = 0.1$ for the eccentricity of the potential flow rule; $\sigma_{b0}/\sigma_{c0} = 1.16$ for the ratio between the equi-biaxial compressive initial yielding stress and the uniaxial compressive initial yielding stress; $K_c = 2/3$ for the parameter that modifies the Drucker-Prager yield function (Drucker & Prager, 1952); $\mu = 0.01$ for the viscosity parameter resulting from the use of a generalized Duvaut-Lions regularization (Duvaut & Lions, 1972). For modeling masonry's post-elastic behavior, the laws represented in Figure 4 are adopted.

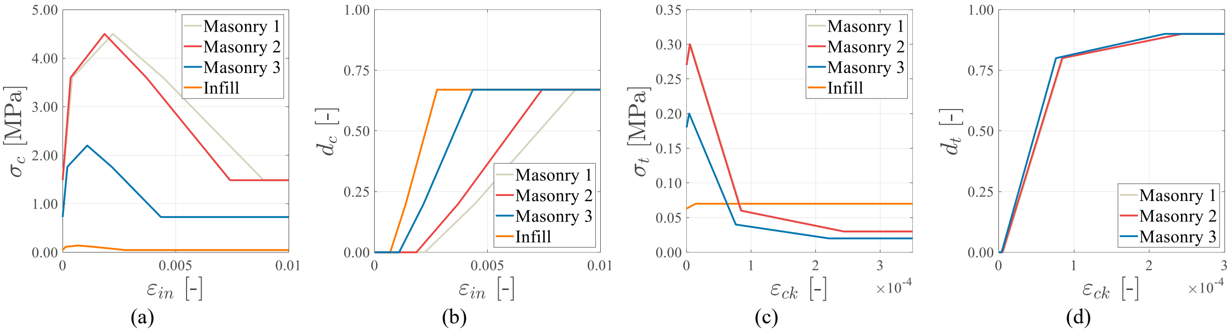

Fig. 3. Stress-strain and damage laws adopted for modeling the post-elastic behavior of homogenized masonry materials: (a) constitutive model in compression; (b) damage model in compression; (c) constitutive model in tension; (d) damage model in tension.

4.3. Controlled demolition scenarios considered

For the TNT charges, the four symmetrical positions shown in Figure 1 (A, B, C, D) are defined. The charges are applied to the façade with normal $+z$, symmetrically and eccentrically with respect to the vertical median plane of the bridge. For each of the charges, three different values of TNT equivalent mass are adopted: 100, 300 and 500 kg. Therefore, a total of 12 detonation scenarios is analyzed. For communication purposes, in the following, each demolition scenario is labelled using the identifiers of the points where the charges are placed. Moreover, the equivalent mass of TNT specified each time refers to the single charge applied.

5. Results obtained from non-linear analyses

This section presents the results obtained from numerical analyses, for each demolition scenario. Let us consider that the detonation of the charge occurs at time $t = 0$. A time interval of $0.50\ s$ is adopted for studying the structural response in the dynamic transient. The effects of explosions are first analyzed in terms of forces and displacements, reporting the horizontal reaction-force evolution in Figure 4 up and the displacement of the control point in Figure 4 down (both along Z).

The reaction-force numerically obtained has the typical trend of the overpressure wave generated by an explosion (Tetougueni et al., 2020). Therefore, the result is acceptable from a phenomenological point of view, demonstrating the effectiveness of the model. An increase in the mass of TNT always results in higher peaks of the base shear. Test A and D provide similar results in terms of forces and evolution of them during the time. Test B is characterized by a reversal of the sign of the base shear, leading to high force peaks also along the -Z direction. With a mass of 300 and 500 kg, Test C always maximises the force applied on the infrastructure. Test B always leads to the maximization of the control point displacement, promoting the plasticization of the system even for a reduced mass of TNT. An increase in the mass of the charges always produces a considerable increase in the displacement of the control point.

The damage caused in the different demolition scenarios is measured by comparing the ratio between the number of mesh elements where a certain d_t value is recorded and the total number of elements. The admissibility range for d_t is divided into 10 intervals of equal dimensions. The number of mesh elements falling within each interval is evaluated by adopting a specific code implemented in Python. It is necessary to highlight that for the infill the tensile damage model is not defined, so the mesh points of the infill are excluded from the classification.

The results obtained (Figure 5) demonstrate that for $W_{TNT} = 100\ kg$, Test D maximises the yielding (first interval) of the elements. However, it is evident that all the scenarios reach almost the same level of extensive damage (last interval). When the TNT weight is set at 300 kg, both Test B and Test D result in significant levels of damage. Conversely, when the TNT weight is increased to 500 kg, Test B emerges as the optimal choice for the controlled demolition of the infrastructure.

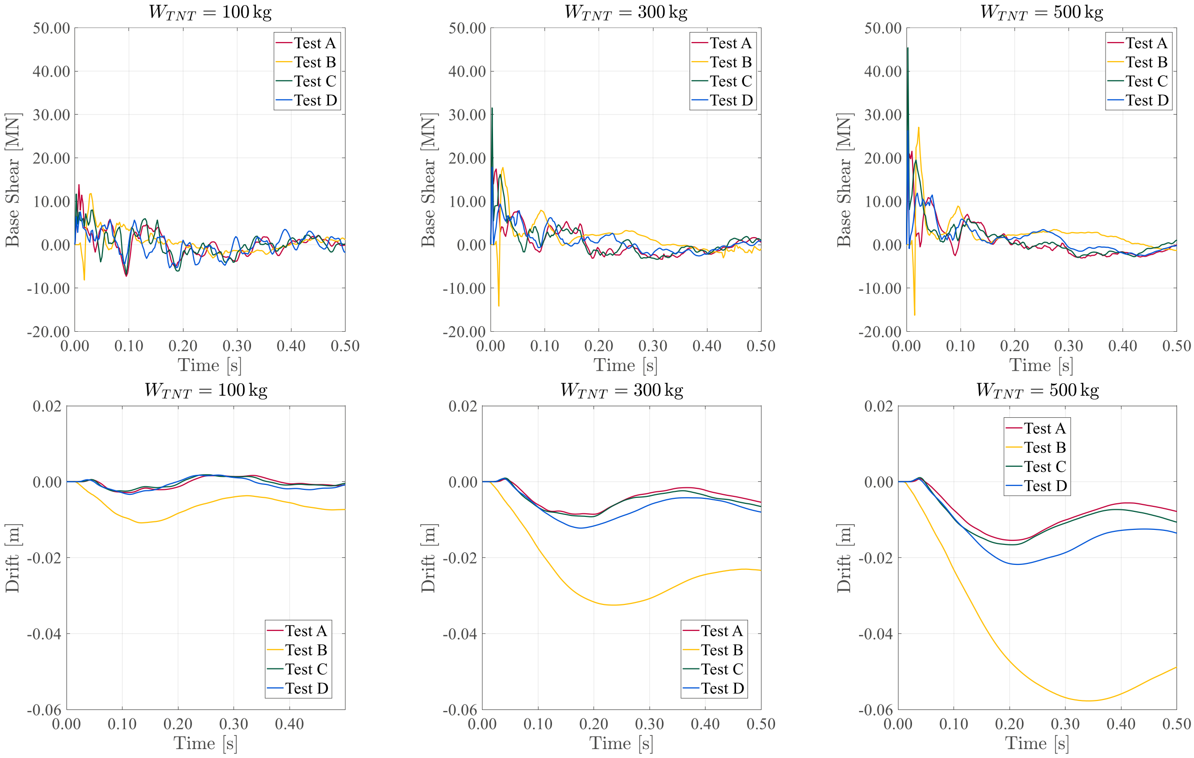

Fig. 4. Evolution of the Z-Reaction force and of the displacement of the control node during the time.

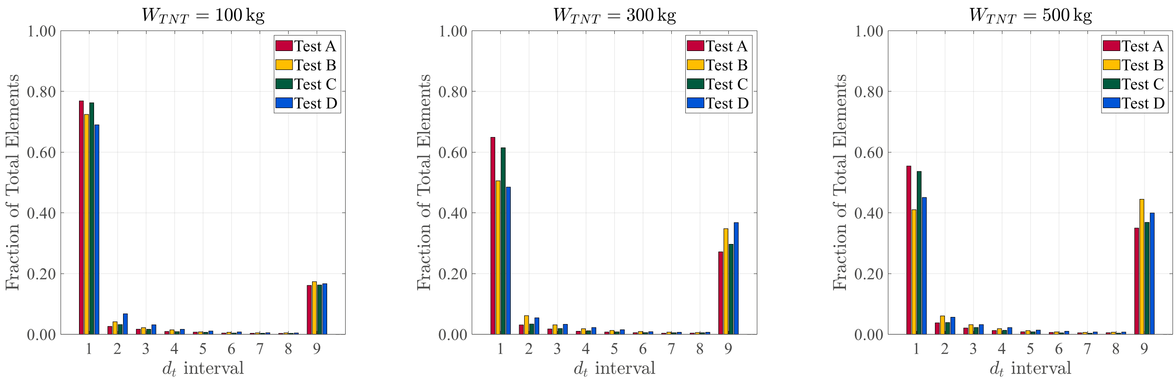

Fig. 5. Mesh element classification for the different demolition scenarios considered.

To qualitatively investigate the opportunity of increasing the TNT mass from 300 to 500 kg, the damage maps obtained for Test A have been analyzed by varying the charges' mass (Figure 6). This allowed us to observe how the placement of explosive charges at the level of the roadway and on the abutments affects damage in the abutments, arches and base of the piers. An increase in the mass of TNT from 100 to 300 kg results in an extension of the damage map to the abutments, to the keystone of the central arch and to the base of the piers. A further increase in the mass of TNT leads to an extension of damage to the sides of the central arch and to the pier shafts.

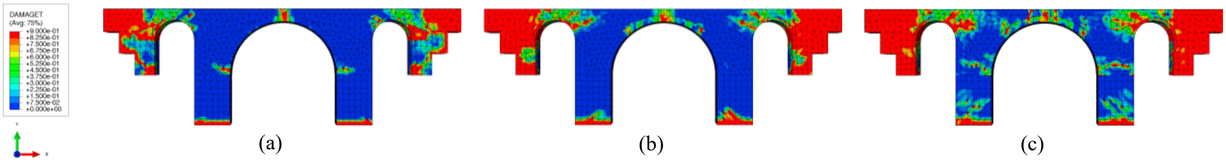

Fig. 6. Damage Maps obtained for Test A by adopting: (a) 100 kg of TNT; (b) 300 kg of TNT; (c) 500 kg of TNT.

By varying the position of the charges and maintaining a constant mass of TNT equal to 300 kg (Figure 8), it can be observed that position D, which could be considered optimal for the progressive collapse of the central part of the structure, does not lead to significant damage to the abutments, which could subsequently require manual dismantling. On the other hand, position B leads to significant damage to the abutments and to the base of the piers (because of the overpressure wave), nevertheless favoring progressive collapse mechanisms and reducing the subsequent demolition operations of the remaining components.

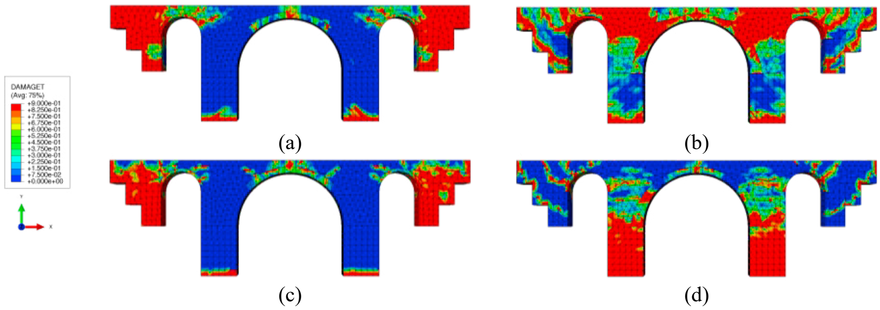

Fig. 7. Damage Maps obtained by adopting 300 kg of TNT for the configuration: (a) Test A; (b) Test B; (c) Test C; (d) Test D.

6. Final remarks and future developments of the research

We have implemented advanced FE models integrated with Python codes for evaluating the effects induced by the detonation of spherical TNT charges on masonry arch bridges, performing sensitivity analyses. These structures are structurally redundant and made of heterogeneous and loose materials, which react unpredictably to explosive forces. Therefore, it is necessary to develop appropriate numerical tools for the design of demolition operations.

To this end, a specific procedure has been proposed and applied to the case study of San Marcello Pistoiese Bridge. A FE model of the bridge has been implemented in Abaqus. The mechanical behavior of the materials has been modelled using CDP, while the detonation of the explosive charges has been modelled using the CONWEP approach. The position and mass of the charges have been varied and, for each case, the horizontal reaction-force, the displacement of a control node and the damage induced have been evaluated.

The results obtained have shown that, in the case study, the positioning of TNT charges on the sides of the central arch maximizes the effects of the explosion by increasing the horizontal reaction-force and the induced displacement, promoting the damage and the progressive collapse of the structure. An increase in the mass of TNT from 100 kg to 300 kg always leads to greater demolition effectiveness, also in terms of damage. A further increase in the mass of TNT from 300 kg to 500 kg, however, may not be structurally and economically viable.

The procedure adopted demonstrated to be effective for the assessment of the effects caused by the detonation of spherical TNT charges on existing infrastructure. Despite some limitations encountered in relation to both the use of FE models (which is intrinsically unable to model the progressive collapse of the structure along time) and the use of the CONWEP approach (based on empirical data rather than an actual fluid-structure interaction modelling), the strategy developed is promising also for a generalization to all types of infrastructure. Future developments include the use of discrete modelling strategies and more advanced approaches from a theoretical and numerical point of view for simulating the effects of close-range explosions.

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