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Numerical simulation on dynamic behavior of reinforced concrete beam with initial cracks subjected to air blast loading

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ABSTRACT

Reinforced concrete (RC) structural members subjected to blast loading behave differently as compared to the same subjected to quasi-static loading. Numerical studies are conducted to study the influence of weights and positions of explosive charges, locations, widths and depths of initial cracks, and longitudinal reinforcement ratios on the dynamic behavior of simply supported RC beam with initial cracks (pre-cracked RC beam) under air blast loading. Results show that, compared with the perfect beams, the pre-cracked RC beams present themselves with an increase in the maximum deflection of mid-span, the maximum vertical velocity of mid-span node, effective stresses of concrete in compressive zone of the pre-cracked RC beam, and axial stresses of longitudinal reinforcement in tensile zone of the pre-cracked RC beam. Due to stress concentration of pre-cracked sections under air blast loading, the presence of initial cracks at the mid-span (or the end) of the pre-cracked RC beam could cause the failure of the pre-cracked RC beam prematurely at the cracked sections and where the blast loading begin to be loaded. Moreover, a crack on the surface of compression zone of the pre-cracked RC beam has a larger influence than that on the surface of tensile zone. The damage generated by blast loading effects is limited to a local area, and the dynamic behavior of the pre-cracked RC beam is not sensitive to the width and depth of initial cracks to some extent.

1. Introduction

Over recent decades, frequent occurrence of various terrorist attacks, industrial accidents has generated concern over a general vulnerability to blast seen in many conventionally designed structures, with localized blast damage causing global collapse in some cases [1–3]. Analysis of dynamic performances of reinforced concrete (RC) structures against air blast loading is a complex issue because the short duration of blast loading often exhibits spatial and time variations, which result in a varying strain rate for concrete material as well as steel reinforcement [4–6].

As one of the main bearing components of RC structures commonly used in protective design against potential blast loading conditions, analysis of dynamic behavior of RC beams has important significance in the design of anti-explosion structures. Current analysis methods for RC components subjected to blast loading consist of two major approaches: experimental and numerical studies. Many experimental studies are not feasible because the preparations and measurements in full-scale field experiments are complex and expensive, however. Fortunately, there are some remarkable exceptions. For instance, Zhang et al. [7] found that the decrease of the scaled distance could lead to the increase of spalling area according to the damage characters of RC beams under close-in blast loading. Ohtsu et al. [8] through experiment and analysis studied the dynamic failure of fiber-reinforced concrete slabs under blast loading. Wang et al. [9] investigated the explosion resistance of a one-way square RC slab subjected to closed-in blast loading and two major damage levels (moderate spallation, spallation with a few cracks) were identified in the tests. Magnusson and Hallgren [10,11] studied many RC beams made of normal or high strength concrete, with or without steel fibers, subjected to air blast loading. Chen and Yang [12] experimentally investigated the explosion-resistant capabilities of fifteen RC beams of three groups strengthened with carbon fiber reinforced polymer (CFRP) sheets under blast loading. Ohtsu et al. [13] experimentally and analytically investigated the dynamic failure of fiber-reinforced concrete (FRC) slabs, and it was observed that the averaged diameters and the volumes of the spall failure remarkably decreased with the increase in the flexural toughness of FRC concrete. Recently, Wang et al. [14] conducted experimental study on explosion resistance of a one-way square RC slab under closed-in blast loading. In order to evaluate the effectiveness of a numerical model to replicate the experimental damages of RC

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columns, Ambrosini et al. [15] experimentally investigated the damages of RC columns subjected to close-in blast loading. Numerical analysis also takes a very important role in studying the dynamic behaviors of RC structures under blast loading [16]. Zhou et al. [17] predicted the responses of high-strength steel fiber RC slabs and ordinary RC slabs under blast loading by proposing a dynamic plastic damage model for concrete material. Later, Zhou and Hao [18] modeled and analyzed the damage and fragmentation of concrete slab under contact detonation. Li and his coworkers [19] conducted experimental study on the dynamic performance of ultra-high-performance-concrete (UHPC) slab under contact charge explosion.

Mazurkiewicz et al. [20] developed the multistage numerical analyses procedure for a load carrying capacity assessment of a blast loaded I-column. Xu et al. [21] experimentally and analytically investigated the behavior of ultra high performance fiber reinforced concrete (UHPFRC) columns under blast loading. Mao et al. [22] investigated the dynamic performance of UHPFRC under blast loading using the explicit non-linear finite element program, LS-DYNA. Qu et al. [23] studied the influence of bearing types on the damage modes of RC beam under air blast loads by numerical simulation. General behavior of concrete plates subjected to air blast loading was investigated by Xu and Lu [24], they focused on the spall damage and proposed empirical spallation criteria considering the response of three-dimensional concrete. Utilizing Timoshenko Beam Theory, Dragos and Wu [25] investigated the interaction between direct shear and flexural responses for blast loaded one-way RC slabs using a finite element model.

It is noticed from the above literature review, most of the previous studies are limited to uniform and perfect structures. However, cracks, notches or defects may be contained on the cross-sections of real structures. Defects influence in a negative way the service life of structures. Thus, the failure features of simple cracked (imperfect) structures have been a focal point of research. For instance, Hudson and Darwin [26] used explosives to damage several RC beams and strengthened some of them with CFRP. They examined if the repaired beams exhibited enhanced flexural capacity with respect to the unrepaired ones. Chondros and Dimarogonas [27] investigated an aluminum cantilever beam with a crack based on a number of experiments and concluded that both experiments and the mathematical formulae shared the same conclusion. Paik et al. [28] studied the behaviors of cracked plates and estimated the ultimate strength of cracked plates under compression and tension by proposing theoretical models. Alinia et al. [29] investigated the effect of relative crack length on buckling capacity of shear panels using the finite element method. Wu and Davies [30] developed a theoretical method to predict the loading capacity of a cracked FRP RC flexural beam.

In conclusion, most of the previous studies are limited to uniform and perfect RC structures under blast loading and the studies of pre-cracked RC beams are mainly focused on considering being subjected to static loading. Only limited research has been developed to study dynamic behavior of simply supported RC beams with initial cracks (pre-cracked RC beam) subjected to blast loading. Cracks influence in a negative way the service life of structures. The available methods for predicting the damage of RC beams subjected to blast loading might not be applicable to predict the damage of pre-cracked RC beams. In the present study, a numerical investigation is carried out to study the dynamic behavior of

Table 1
Material parameters of ordinary concrete [33].

Mass density, RO	2440 kg m^{-3}	Amount of plastic strain before fracture, EFMIN	0.01
Normalized cohesive strength, A	0.79	Crushing pressure, PC	0.016 GPa
Normalized pressure hardening, B	1.6	Crushing volumetric strain, UC	0.001
Pressure hardening exponent, N	0.6	Pressure constant, K_1	85 GPa
Strain rate coefficient, C	0.007	Pressure constant, K_2	−171 GPa
Quasi-static uniaxial compressive strength, FC	0.040 GPa [7]	Pressure constant, K_3	208 GPa
Normalized maximum strength, SFMAX	7.0	Locking pressure, PL	0.80 GPa
Damage constant, D_1	0.004	Locking volumetric strain, UL	0.10
Damage constant, D_2	1.0	Maximum tensile hydrostatic pressure, T	0.004 GPa

Table 2
Material parameters of steel reinforcement [37–38].

Mass density, RO	7800 kg m^{-3}
Young's modulus, E	2.0×10^5 MPa
Poisson's ratio, PR	0.3
Yield stress, SIGY	395 MPa [7]
Tangent modulus, ETAN	2.0×10^3 MPa
Hardening parameter, BETA	0
Strain rate parameter, SRC	40
Strain rate parameter, SRP	5
Failure strain for eroding elements, FS	0.12

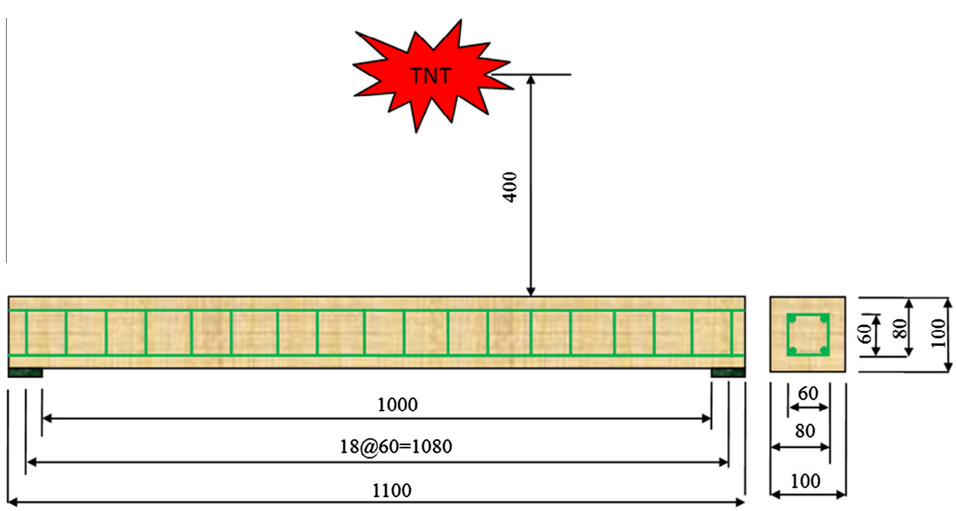

Fig. 1. Schematic diagram of TNT charge and RC beam in the test.