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Numerical analysis of prestressed reinforced concrete beam subjected to blast loading

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Prestressing technique has been widely used in civilian and military constructions. The prestressed reinforced concrete (RC) structural components such as beams and columns usually outperform the non-prestressed RC components because prestressing not only increases the structural stiffness and load carrying capacity, but also has higher crack resistance than non-prestressed component. As a result, it usually leads to light structures. The investigation of non-prestressed RC components subjected to blast loadings has been reported in the literature. However, the study on the blast-resistant capacity of prestressed RC components is very limited. In this study, the dynamic response of a simply-supported prestressed RC beam with rectangular section under blast loadings is numerically investigated by using finite element codes LS-DYNA. The prestress is pre-applied on the RC beam in an analytical approach. The reliability of the numerical model is calibrated with testing results available in the literature. With the calibrated model, numerical simulations on four groups of prestressed RC beams to blast loadings are carried out to investigate the influences of prestressing level and concreted compressive strength on beam blast loading resistance capacity. The structural responses such as mid-span maximum deflection, residual deflection, cracking, stress of rebars and shear stress of concrete near the supports are extracted from the numerical results. The effectiveness of prestressing on blast-resistant capacity of RC beam is demonstrated through comparing the results with the bench marking non-prestressed RC beam under the same blast loadings.

1. Introduction

Blast loadings due to terrorist bombing or accidental gas explosion may cause significant structural damage, casualty and economic loss. Reinforced concrete is commonly used in the building industry. Conventional RC column, beam and panel, as major load carrying components, are often damaged when subjected to blast loading, which might lead to partial or total collapse of building structures. In 1968, an internal gas explosion seriously damaged the Ronan Point residential apartment building in the UK, owing to the failure of some structural components that triggered progressive collapse [1]. Engineering solutions for structure protection need to be developed and improved to ensure the safety of structures. To overcome concrete's natural weakness in tension and the growth of cracks, prestressed technique is employed in both civilian and military constructions. Prestressing concrete may increase structural stiffness and crack-control performance. As a result it reduces structural member size, self-weight and construction cost. Prestressing can be achieved in three ways, i.e., pretension, bonded post-tension and unbonded post-tension by using tendons [2]. Prestressed tendons are made of high tensile steel cables or rods, which provide compressive stress on concrete. The compressive stress balances the tensile stress of concrete when subjected to external loads. Consequently, the appearance and growth of cracks in concrete might be reduced and delayed in the tension zone of concrete, as shown in Fig. 1. Various standards [3,4] provide guides on designing the prestressed RC beams to resist static loads, but the effects of prestressing concrete on RC structures blast loading resistance capacities are relatively less studied.

The research on the non-prestressed concrete components subjected to blast and impact loadings has attracted intensive attentions over the years. The flexural damage is usually observed in the RC structures under the blast loadings. Fang and Wu [5] found that the flexural damage transferred to the brittle shearing damage with increasing the loading rate, height of cross section,

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longitudinal reinforcement ratio or decreasing the strength of concrete. Lin et al. [6] numerically investigated the response of reinforced concrete panels under blast loadings by using LS-DYNA. The effect of blast intensity and panel specification on the panel's blast resistance performance was studied. Magnusson and Hallgren [7] carried out the tests on the high strength reinforced concrete beams to air blast loading, and observed that the failure modes of beams were different when subjected to static and dynamic loads. All beams subjected to static loading failed in flexure mode and some of the beams subjected to air blast loadings failed in shear mode. The concrete beams showed an increased load carrying capacity when subjected to blast loadings compared to static loading. Jiang et al. [8] numerically investigated reinforced concrete beams subjected to impact loadings by using LS-DYNA. The elasto-plastic damage cap (EPDC) model for the concrete and the elasto-plastic model for the reinforcement are incorporated into the numerical model. Fang et al. [9] reported that strain rate effect has a significant effect on blast-resistant capacities of reinforced concrete beam. Yi et al. [10] experimentally investigated the blast-resistant capacities of ultra-high performance concrete and reactive powder concrete in concrete structures, which have been proved having better blast-resistant capacity than normal strength concrete structure.

Most of the previous studies on high-rate dynamic structural responses of the prestressed RC components are subjected to impact loadings. Very limited study on the blast-resistant capacity of prestressed RC components has been found in the literature. Li et al. [11] tested three partially-prestressed concrete (PPC) beams by using drop hammer. The impact-resistant performances of the PPC beams were demonstrated in the study. Ishikawa et al. [12,13] experimentally and analytically investigated the performance of bonded and unbonded prestressed concrete beams subjected to impact loadings. It was found that the prestressed tendon was more vulnerable to break under higher loading rate. Iskhakov and Ribakov [14] proposed a design method for two-layered bending prestressed beams which consist of steel fibered high strength concrete in compressed zone and normal strength concrete in tensile. Cramsey and Naito [15] reported the performance of a 30-ft partially prestressed concrete panel subjected to different blast loadings. It was found that the panel could sustain rotation of 2.7° without failure under the highest blast load considered in the study. Three ultra-high strength concrete panels prestressed by using high-strength steel tendons were tested to investigate the blast-resistant performance under blast loadings. The results demonstrated the good performances of these panels, which all survived the blast tests with only minor cracks even with considerable deflections [16]. An analytical approach of finite layered section combing with rate-sensitive model was proposed to investigate the dynamic responses of the partially prestressed concrete beams subjected to blast loadings [17]. Cofer et al. [18] validated numerical model of prestressed concrete girder with bulb-tee section subjected to explosions above and below the girder. A simple-span bridge with prestressed girder and slab was also modeled to examine the damage when subjected to different blast scenarios. Unfortunately, the above studies only reported limited test data and general observations. Some important information such as detonation weight is not revealed. Therefore they cannot be used to quantitatively assess the effectiveness of prestressing concrete structures on their blast load-carrying capacities.

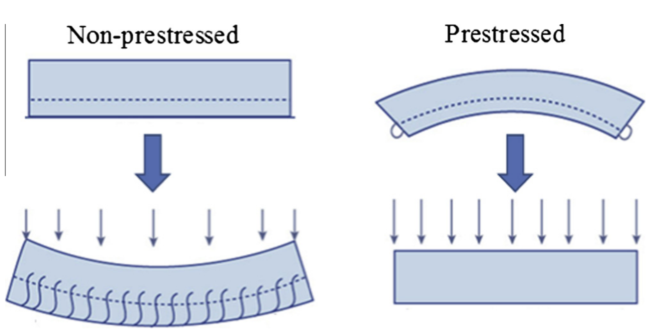

Fig. 1. Schematic diagrams of non-prestressed and prestressed beams.

All the above studies indicated the effectiveness of prestressing concrete in increasing RC structures blast-load or impact-load carrying capacities. Those studies concentrate on analyzing the particular tested structural components and verifying the specific numerical models. There is no systematic study in the literature that devotes to examining the effectiveness of prestressing levels on enhancing the blast-load carrying capacities of RC beams. In the present paper, the dynamic response of simply-supported prestressed RC beams subjected to blast loadings is numerically investigated. The reliability of the numerical model is calibrated with some testing results available in the literature. With the calibrated model, numerical simulations of prestressed RC beams to blast loadings are carried out by considering varied prestressing levels, different concreted compressive strengths and blast intensities. The mid-span maximum deflection, residual deflection, shear stress and cracking of RC beams without prestressing or with different levels of prestressing are extracted from numerical simulations. The numerical results of prestressed and non-prestressed RC beams are compared to investigate the effectiveness of prestressing on blast-resistant performance of RC beams.

2. Numerical model calibrations

The numerical simulation is carried out by using commercial software LS-DYNA 971 [19]. LS-DYNA is based on explicit numerical methods and has been widely employed to analyze the problems associated with large deformation structure response to high velocity impact and blast load, and high strain rate behavior of materials. It has been proven yielding reliable numerical predictions of structural response and damage to blast loadings.

2.1. Experimental descriptions

To verify the accuracy and reliability of the finite element model, numerical model is calibrated with the experimental and numerical results available in the literature. It should be noted that no blasting test on prestressed RC structures with sufficient information such as charge weight, dimension, and prestressing level, etc. can be found in the open literature. Therefore, in the present study, testing data conducted on RC structures without prestressing is adopted to verify the numerical model. It is believed that the numerical model calibrated is applicable to simulating blast responses of prestressed RC beams because, as will be described later, the simulation of the responses of the prestressed RC beam to blast loads is performed in two steps, i.e., applying the static prestressing in the first step, and applying the blast loading in the second step, and the two steps are not coupled. Prestressing only affects the initial conditions of the RC beam when blast load is applied.

A 1/4-scale RC frame model was tested by Baylot and Bevins [20] to study the dynamic response of the central column of a two-storey RC structure. A 7.1 kg C4 high explosive of hemisphere shape (with equivalent TNT weight of 8 kg) at a standoff distance of 1.07 m was detonated in the test. The experimental setup and results are shown in Fig. 2.