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Numerical evaluation of blast resistance of RC slab strengthened with AFRP

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HIGHLIGHTS

- A FE model considering the dynamic interfacial behavior of FRP is developed.
- The AFRP changes the failure mode from spalling to be FRP rupture and debonding.
- The reinforcement effect of slab strengthened with AFRP is higher than with GFRP.
- The damage of the AFRP-strengthened slab decreases with the bond strength increases.

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ABSTRACT

In this study, in order to precisely evaluated the retrofitting effectiveness of the Aramid Fiber Reinforced Plastic (AFRP) sheet on the blast response of reinforced concrete (RC) slab, a refined non-linear finite element model is proposed for simulating of the structural response of RC slab strengthened with AFRP under blast loads. The complicated material models are applied in the simulation considering the high strain rate effects of the materials as well as the dynamic interfacial behavior between AFRP and concrete. Also, a appropriate erosion criterion technique is specially applied to capture the fracture and material separation process during the detonation of the explosive. At first, the numerical model of an actual laboratory sample of a conventional RC slab subjected to blast loads was simulated and verified using available experimental results. Then with the calibrated model, numerical simulations of RC slabs strengthened with AFRP to blast loadings are carried out. The numerical results of strengthened and non-strengthened RC slab (i.e., conventional slab) are compared to investigate the retrofitting effectiveness of AFRP on blast-resistant performance of RC slabs. In addition, a comprehensive investigation on the blast responses of FRP-strengthened RC slabs affected by these parameters, i.e. different AFRP layer, FRP type, strengthening mode, FRP bond strength and TNT mass, are also reported.

1. Introduction

Due to the increase of terrorist attack and accidental explosion in current society, the RC structure, which is the principle construction of civilian buildings and military construction, are tend to exposed to blast loadings [1–3]. The short-duration and high magnitude of blast loading can induce the severe damage to the RC structure. Generally, it's known that concrete has a relatively high capacity to resist the blast loads [4]. However, for some strategically important infrastructures such as government and defense buildings, in order to improve their resistance against impact or blast loads during their service life, reinforcement is required [5–7].

In recent decades, external bonding of fiber reinforced polymer (FRP) strips to improve the blast resistance has received great interests. The technique of external bonding FRP has many advantages, such as high strength, light weight, lower cost, excellent corrosion resistance, convenient construction, etc., and has now become more and more popular in field of concrete structure reinforcement. A few experimental studies have been conducted on evaluating the effectiveness of FRP reinforcement on the blast resistant performance of RC slabs. Lawver et al. [8] proposed an experimental research on the blast response of RC floor slabs strengthened with the carbon fiber reinforced polymer (CFRP). They reported that the CFRP-retrofitted slabs have higher stiff and could greatly decrease the deformation and damage of the RC floor slab. Tanapornraweekit et al. [9] experimentally studied the response of CFRP strengthened RC slabs undergoing multiple independent explosion testing. Their results showed that CFRP

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can improve the ductility of the RC slabs and prevent the occurrence of the concrete spall. Razaqpur et al. [10] performed a series of blast experiments on the RC slabs retrofitted with glass fiber reinforced polymer (GFRP) subjected to various explosive charge and found that the GFRP strengthened slabs had larger residual strength than the non-strengthened one under lower charge. In addition, the blast responses of RC panels retrofitted with hybrid CFRP-PU composite sheets were tested by Ha et al. [11].

In case of blast tests, it is difficult to quantitatively assess experimental results due to the differences of blast pressure and duration according to experimental and environmental conditions of each test case [12]. And it's also generally costly and time consuming. Therefore, Numerical study in retrofitting structures with FRP composites for blast protection is of great importance. Nowadays, with advanced computer hydrocode such as LS-DYNA, DIANA, and ABAQUS, etc., several numerical studies have been carried out to analyze the blast resistance of FRP retrofitted RC slabs. For example, Mosalam et al. [13] used the finite element platform DIANA to numerically analyze the blast response of the RC slabs retrofitted with CFRP under different blast loading duration. By using the FE software LS-DYNA, Nam et al. [14] simulated the blast response of the CFRP retrofitted RC slab with four different FRP models and ascertained the different behaviors of CFRP retrofitted concrete structures according to different FRP models. Similarly, Lin et al. [15] developed a FE model for numerical modeling of the blast responses of GFRP-strengthened RC slabs based on the software LS-DYNA. It' noticed that most of the numerical studies mentioned above haven't considered the dynamic interfacial behavior between FRP and concrete and just assumed a perfect bond between the FRP and concrete interface for simplicity of the FE models. Actually, debonding failure of the FRP has been reported to be a common phenomenon for the FRP retrofitted structures subjected to dynamic loads [8,11,12,15,16]. Therefore, debonding failure should be considered in the numerical model in order to more accurately model the responses of FRP-strengthened RC structures [12,16]. In recent years, Nam et al. [17] took into account the material characteristics and debonding failure mechanisms of FRP to perform a blast simulation of GFRP retrofitted RC slabs under the blast loading. Comparisons of simulation results with experimental data showed their FE model can effectively predict the debonding behavior of GFRP under blast loading. However, in their numerical results they only considered the debond failure of FRP without detailed analysed the damage mode of the slab before and after reinforcement, which is an important consideration in assessing the strengthening effect of FRP.

The above studies show that some progress has been made in the dynamic response of FRP-strengthened RC slabs subjected to blast loading. However, because of the complexity caused by the short duration and high amplitude of blast loads involving in the dynamic response of RC structures, the numerical developments are still far from ideal in terms of accuracy and efficiency. In addition, for the FRP retrofitted material, most of the previous studies are mainly focused on considering the retrofitting effectiveness of CFRP and GFRP. Aramid Fiber Reinforced Plastic (AFRP) is a relative newcomer to FRP composites, compared with CFRP and GFRP. Although besides the common properties of all the FRP materials, it has some other unique features such as superior dielectric properties, high heat and flame resistance, better corrosion, impact and fatigue resistance, short curing time, etc. [18], its performance in strengthening the RC structure under blast loads has been less studied. Moreover, a comprehensive study on the effects of different influence factors, especially the different FRP strengthening sizes, different FRP materials, different FRP strengthening modes, different FRP bond strength, etc., on the blast response of FRP-strengthened RC slabs are rarely reported.

In the present paper, a numerical analysis is proposed to quantitatively assess the retrofitting effectiveness of AFRP on the blast response of the RC slabs. The complicated material models are applied in the simulation considering the high strain rate effects of the materials as well as the dynamic interfacial behavior between AFRP and concrete. Also, a appropriate erosion criterion technique is specially applied to capture the fracture and material separation process during the detonation of the explosive. At first, the numerical models are verified through comparing the simulation results of a conventional RC slab (i.e., non-strengthened RC slab) under blast loads with test data. With the calibrated model, numerical simulations of RC slabs strengthened with AFRP subjected to blast loads are then carried out. The numerical results in terms of the damage process, failure modes, time histories of displacement and reinforcing steel stress are compared for the non-strengthened and strengthened slabs to quantitatively evaluate the strengthening effect of the AFRP sheets. In addition, a comprehensive investigation of the blast responses of AFRP-strengthened RC slabs affected by various parameters (e.g., AFRP thickness, FRP types, FRP strengthening mode, FRP bond strength and TNT masses) are further considered.

2. Modelling the blast response of a conventional RC slab

In the present study, a general-purpose finite element program, ANSYS/LS-DYNA, is used to conduct the numerical simulation. Three dimensional nonlinear finite-element analysis of a conventional RC slab are firstly conducted to predict the blast response of the slab without strengthening, including experimental validation. The modeling approaches are summarized as the following.

2.1. Experiment setup

Fig. 1 shows the details of the experimental RC slabs from the literature of Sun [19], which formed a basis of the present study. The RC slab in the experiment has the dimension of 1000 mm, 1300 mm and 120 mm in width, length and height respectively. The concrete has the compressive strength of 48 MPa and Young's modulus of 48 GPa. The reinforcing steel bars has the yield strength of 560 MPa and Young's modulus of 230 GPa. The diameter of the reinforcing steel bars of the specimen are 10 mm. The center-to-center spacing of these steel bars is 100 mm in longitudinal direction and 200 mm in transverse direction. In the experiment, the RC slab is subjected to the blast pressure from 2.09 kg equivalent TNT with the standoff distance (i.e., distance between explosion source and slab) of 0.6 m. Further details about the experiment can be found in Ref. [19].

2.2. Material model

2.2.1. Material model for concrete

Table 1 shows the material property parameters of concrete and steel reinforcement. The dynamic behavior of concrete is modeled using the plasticity-based model CONCRETE DAMAGE REL3 (MAT72 R3). It's a plasticity-based model and well suited for analyzing the high strain rate behavior of concrete under blast loading [15,18,20]. The EOS_TABULATED_COMPACTION (EOS 8) is synchronously used with the MAT72 R3 to describe the behavior of concrete in compression or tension.

The pressure p is defined as [19]: $p = C(\varepsilon_v) + \lambda T(\varepsilon_v)E$, where the volume strain $\varepsilon_v = \ln v$, C and T are coefficients given as the functions of ε_v, E and λ are the internal energy and ratio of specific heats, respectively.

In order to get the reliable simulation of RC slab under blast loads, for concrete, the high strain rate effect is considered by