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Spalling in concrete arches subjected to shock wave and CFRP strengthening effect

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ABSTRACT

The purpose of the present study is to put forward an innovative method to improve dynamic response behaviors of protective concrete arches subjected to blast load. To achieve this goal eight arches were made, of which six were strengthened with carbon fiber reinforced polymers (CFRPs) on the intrados. Field explosion experiments were designed and carried out to reveal the strengthening effects of different CFRP strengthening schemes. The dynamic structural responses of the tested arches were recorded through linear variable differential transformers (LVDTs) and pressure sensors. The results of the experiments, such as the distribution of concrete cracks and the debonding length of the CFRP strips, indicate that CFRPs are effective in reducing concrete cracking and spalling of the protective arches, and that the fully-bonding method is significantly more effective than the partially-bonding method. Meanwhile, when the scaled standoff distance decreases, the strengthened arches experience failures ranging from ductile cracking to dynamic spalling. Simplified analysis models are proposed to estimate the equivalent static load and to reveal the protective mechanism of the CFRP strengthening. The research confirms that by using the CFRP bonding technique, an efficiently protective concrete arch structure with excellent anti-explosion performance could be constructed.

1. Introduction

In recent years, intentional terrorist activities and potential military attacks have highlighted the need for studying the dynamic responses of concrete structures under explosion conditions. Protecting civilian, industrial structures from explosions is of paramount importance (Pham and Hao, 2017; Aoude et al., 2015; Mussa et al., 2017). Numerous studies (Xia et al., 2016; Qasrawi et al., 2014; Huang et al., 2017; Chen et al., 2015) have been conducted on various related techniques, and some design guidance has been developed to increase the resistance of structures against blast loading.

During an explosion, a rapid chemical reaction takes place, resulting in a sudden release of a large amount of energy. The design rule for blast-loaded structures is to improve the energy absorption ability of the structure, which can be achieved by increasing the structure's strength, ductility, or mass (Alhadidmm et al., 2014). However, adding additional mass to an existing building is undesirable because it increases its self-weight (Chen and Hao, 2014). Thus, the fiber-reinforced polymer (FRP) strengthening method has been used to increase structural strength and ductility (Razaqpur et al., 2009). FRP has the advantages of high strength-weight ratio, short installation period, minimal intervention upon the concrete structure, and adaptability to curved surfaces (Sun et al., 2017; P. Wang et al., 2016).

As a vital component in underground engineering, concrete arches have a wide range of applications in underground construction (Karnovsky, 2011 Dec 29). Sadaghiani and Dadizadeh (2010) introduced a new Concrete Arch Pre-supporting System (CAPS) for construction of large underground spaces. This method is a quick and generally economical approach to increase the stability of the large span underground excavations in shallow and weak ground. Q. Wang et al. (2016) developed a new 3D U-type confined concrete arch system from the conventional U-type steel arch centering, to solve the support problems of high stress roadways in deep mines. All these concrete arches should be pre-fabricated. To reinforce an existed underground concrete arch, the anchor system can be used (F.T. Wang et al., 2016), but the construction period is long.

It has been proved that the FRP reinforcement is effective in improving load-carrying capacity, decreasing structural deformation and improving structural stability of concrete arches (Buchan and Chen, 2007; Bertolesi et al., 2016). Numerous theoretical and experimental

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studies have been carried out on the use of FRP to strengthen concrete and masonry arch structures in the last 20 years (Tao et al., 2011; Corradi et al., 2015; Biscaia et al., 2017; Pintucchi and Zani, 2016). This strengthening mechanism aims to improve the ability to withstand the tensile stress ordinary arches cannot bear. When FRP is adhesively bonded to the surface of the arch structures, it can improve tensile capacity and restrain the development of cracks. Hamed et al. (2014) revealed that applying FRP leads to a stable debonding mechanism in the strengthened concrete arch, which differs from that in FRP-strengthened beams and slabs, where FRP debonding rapidly propagates from the edge toward mid-span in an unstable manner. Caporale et al. (2013, 2014) proposed a numerical procedure to estimate the ultimate load of masonry multi-span arch structures strengthened with externally bonded FRP reinforcement. It is found that the effectiveness of strengthening depends on the configuration of FRP. In fact, some configurations of FRP greatly increase the load-carrying capacity of the structure, while others are ineffective. Therefore, it is essential to appropriately design the strengthening layout to avoid the waste of materials or even the enhancement of the blast effect on strengthened members. Dagher et al. (2012) designed a concrete-filled tubular FRP arch structure for bridge construction. The novel composite arch structure without steel reinforcements exhibits excellent structural performance when loaded quasi-statically, but the fabrication of this composite arch structure is too difficult. In previous studies conducted by the author (Zhang et al., 2015; Wang et al., 2017), the performance of CFRP-strengthened RC arches was studied through quasi-static compressive experiments. It was found that the effects of CFRPs in strengthening arches depend on the construction material, the strengthening scheme, and the rise-to-span ratio of the arch.

Concrete structural members subjected to blast loading behave differently compared to quasi-static loaded members (Qu et al., 2016; Zhang and Li, 2015). Under blast loading, concrete members show a unique behavior known as “spalling”, which endangers personal safety (Alhadidmm et al., 2014), as shown in Fig. 1 (Xie et al., 2014). Apart from spalling, tensile cracks and shear failures of the concrete are the main failure modes of blast-loaded RC structures (Chen et al., 2014; Ma et al., 2010). Nevertheless, research results (Xie et al., 2014) have shown that externally bonded CFRP sheets play an important role in controlling the development of tensile cracks in concrete, and restricting the concrete spalling induced by reflective tensile waves. The CFRP strengthening mechanism can also increase the stretching area and let more concrete in compression state, which effectively restricts the structural failure and increases the bending rigidity and load carrying capacity of the arch. However, the effects of the CFRP strengthening mechanism during an explosion have not been investigated thoroughly.

In this study, eight concrete arches were fabricated, with six strengthened with CFRP sheets using different strengthening schemes.

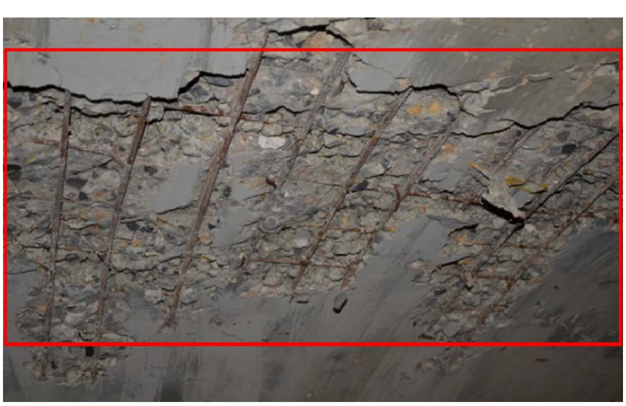

Fig. 1. Dynamic tensile stress-induced concrete spalling of protective arch subjected to close-in TNT explosion (Xie et al., 2014).

The strengthening effects were revealed through explosion experiments. An analysis model was proposed to estimate the equivalent static load of the arch under blast loading, and the dynamic strengthening mechanism of CFRP was explained.

2. Experimental protocol

Eight RC arches were designed and fabricated for the blast-resistance experiment. As shown in Fig. 2, two arches marked A10 remained un-strengthened. The intrados bonding method was applied to strengthen the other six arches, marked A11 to A13, with two arches strengthened using each method. The internal radius r of the arch is 500 mm, the thickness d is 100 mm and the width b is 300 mm. The span-to-thickness ratio is 10. All the concrete arches were cast one-time, and the average static compressive strength of the concrete is 29.1 MPa, which was acquired through compression testing of $150 \times 150 \times 150\,mm^3$ concrete cubes. The RC arches have a steel-rebar reinforcement ratio of 1%. The elasticity modulus of the steel rebar is about 200 GPa, and the yield strength and ultimate tensile strength are 335 MPa and 455 MPa, respectively.

Arches A11 were strengthened with one piece of 100 mm-wide CFRP sheet, while arches A12 and A13 were strengthened with two and three pieces of CFRP sheet, respectively. The CFRP sheets consisted entirely of carbon fibers and epoxy resin, and the carbon fiber cloth used was unidirectional woven fabric with an average thickness of 0.167 mm and tensile strength of 3.4 GPa. The detailed experimental program for those eight arches is presented in Table 1. The standoff distance h denotes the closest distance between the geometric center of the TNT block and the extra surface of the arch. The strengthening ratio is defined as the area of the strengthening material (carbon fiber cloth) used in each unit area of strengthened cross-section. The intrados of the arches A13 were bonded with three pieces of CFRP sheets, so the calculated strengthen ratio is $(0.167b)/(db) = 0.167\%$. Jiangsu Yitai Carbon Fiber Co., Ltd., provided the strengthening materials and their properties.

The anti-explosive experimental schemes of the strengthened arches are shown in Figs. 3–6. Most of the arches were tested under close-in explosion. Two standoff distances were set up, 0.4 m and 0.8 m. Arch A10-1 was subjected to a contact explosion ($h \approx 0$). In addition, arches A10-2, A11-1 and A13-1 were exposed to explosions twice in the experiment. The explosive used is an approximately quadrate TNT charge, assembled with a standard 0.2 kg weighted TNT unit with a geometric size of 100 mm × 50 mm × 25 mm. The scaled distances of the explosions are $0.431\,m/kg^{1/3}$, $0.543\,m/kg^{1/3}$ and $1.086\,m/kg^{1/3}$, respectively.

In the experiment, the lateral displacement of each arch was restricted by the rigid steel frame. The constraint at the feet can be assumed to be pin-jointed. The researchers attempted to record the dynamic displacement history underneath the vault of some arches through LVDT. For the close-in explosion scheme, the reflected pressure at the vault and hance of selected arches were recorded with pressure sensors. No data testing was conducted with A10-1 because of the special explosion scheme. The sampling frequency of the LVDT is 20 K/s, while the value of the pressure sensor is 1 M/s.

3. Structural performances during explosions

3.1. Dynamic responses

Figs. 3–6 present the results of explosion experiments of arches with different CFRP strengthening ratios (A10, A11, A12, and A13) under different scaled distances. As shown in Fig. 3(a), arch A10-1 exhibited concentrated damage after contact explosion and the concrete was shattered at the vault, with only the steel bars connecting the two remaining parts of the arch. Arch A10-2 experienced two explosions with the same standoff distance of 0.4 m. Under the first impact of a 0.4 kg