Literature Review on Blast Protection by Externally Bonded FRP Reinforcement

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Introduction

One of today's state-of-the-art techniques is the use of Fibre Reinforced Polymer (FRP) composites as Externally Bonded Reinforcement (EBR). This method consists in gluing strips or flexible sheet in the tension zone to increase the resistance capacity or service behaviour of structures. The use of FRP as externally bonded reinforcement has been demonstrated as a very efficient technique mainly for static load conditions. More recently, a number of studies have also been conducted regarding the use of FRP EBR for strengthening critical infrastructure (concrete and masonry) against blast loading. This paper presents a brief literature review of research on FRP EBR and blast loading and describes the efficiency of FRP composites for blast protection.

Blast Load Characterization

Explosion

An explosion is defined as a release of energy from chemical reactions on a large scale in a short period of time. This sudden release of energy changes the surrounding air to a high temperature and very high pressure (UFC 3-340-02, 2008). The expansion of explosion gazes leads to the formation of blast waves travelling through the air.

Air Blast Wave

When a blast wave hits a structure, it is reflected with a maximum pressure which is greater than the peak pressure of the incident blast wave. The duration of the reflected wave is assumed to be equal to the incident pressure profile. Figure 1 shows the blast pressure-time profile for the reflected blast wave; two main phases can be observed in this profile: the portion above the ambient pressure is called positive phase with duration t_0, while the portion below the ambient pressure is called negative phase with duration t_0^- (UFC 3-340-02 2008). Blast loading hence typically yields a compression and tension loading stage on a structure.

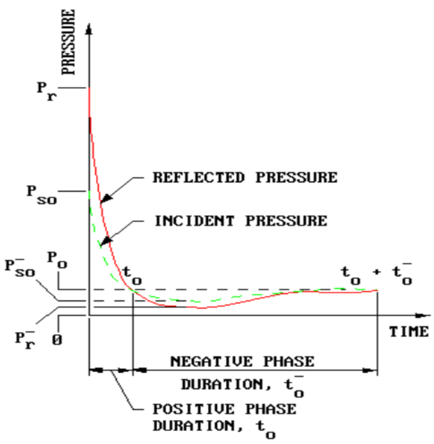

Figure 1: Blast pressure-time profile for a reflected wave (UFC 3-340-02, 2008)

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Previous Blast Research

Literature Review

A literature review has been conducted on experimental or analytical/numerical studies reporting the behaviour of FRP strengthened reinforced concrete and masonry structures under blast loads. Hereby, a previous review by Buchan and Chen (2007) has been taken as a starting point.

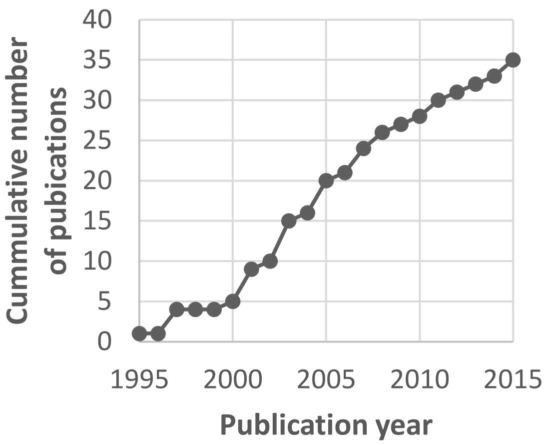

Figure 2: Database in terms of publication year

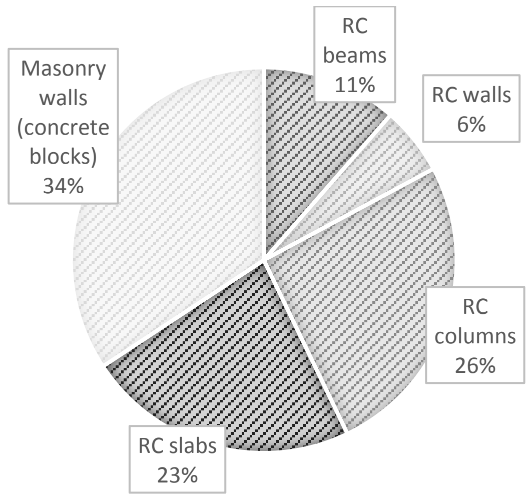

Figure 3: Database in terms of element type

The collected database so far covers 35 publications (see appendix A and reference section). Figures 2 and 3 give a representation of the database in terms of year of publication and in terms of type of material/structure.

From the literature review it is observed that the use of FRP as retrofitting can significantly increase the blast resistance of a structure by increasing the structural strength, ductility and reducing fragmentation. Yet, the precise behaviour of FRP retrofitted structures under blast loading is still poorly understood as current research is in general rather qualitative in nature. Similar observations were also made by Buchan and Chen (2007). Some main conclusions per element type are given in the following sections.

FRP Retrofitted Concrete Slabs

Ten of the publications refer to the blast behaviour of FRP strengthened RC slabs. Silva and Lu (2007) used CFRP for strengthening on either one side only or on both sides. They concluded that slabs retrofitted with CFRP on both sides exhibited better blast resistance than those retrofitted on only one side. They explain this behaviour by the better resistance against negative bending moments due to rebounding. Razaqpur et al. (2007) investigated full scale explosive testing of GFRP retrofitted reinforced concrete slabs. They showed that for the explosive loading of 22.4 kg of ammonium-nitrate-fuel-oil (ANFO) at a standoff distance of 3.1 m, the GFRP retrofitted panels increased 75% in residual capacity compared to the control specimens.

FRP Retrofitted Concrete Beams

It may be observed that there is rather limited research available regarding FRP strengthened beams under blast. Only Ross et al. (1997) tested six simply supported RC beams. The tests were conducted with 110.6 kg ANFO explosive suspended over the mid-span of the beam. Unfortunately, not all the desired information was collected from the tests due to damage of the pressure transducers by the blast wave. Nevertheless, these preliminary results show that the FRP strengthened beams survived the explosions whilst a control beam without EBR, tested in the same conditions, failed in shear.

FRP Retrofitted Concrete Columns

The blast resistance of concrete columns is important for the assurance of the stability of concrete structures. Crawford et al. (2013) conducted tests on six reinforced concrete columns strengthened with CFRP for resisting to blast loads. They stated that the main benefit of wrapping a reinforced concrete column with FRP resides in the increase of strength and ductility of the concrete. Azrul et al. (2011) tested four rectangular RC columns retrofitted with longitudinal strips and others with wrapping. The results of this research indicate that longitudinal strips indeed increase the column flexural resistance capacity, FRP wrapping prevents the concrete to expand and increases the column shear resistance capacity.

FRP Retrofitted Concrete and Masonry Walls

Concrete and masonry walls are vulnerable structures for fragmentation under blast loading. Muszynski and Purcell (2003) tested two reinforced concrete walls which were retrofitted with carbon fibres and with aramid (Kevlar) fibres. The walls were subjected to the blast wave resulting from the detonation of 830 kg TNT at a standoff distance of 14.5 m. They reported that the reinforced elements retrofitted with carbon and aramid FRP respectively showed only 25% and 40% of the maximum deflection at mid span of the wall, compared to unstrengthened reference specimens. In the case of masonry walls, aramid was reported to be more effective because it resulted in more energy absorption. A reduction of 30% in maximum deflection is observed as well as a more ductile behaviour in comparison with the control specimens, e.g. in the work by Muszynski and Purcell (2003).

Conclusions

This paper presents a brief review of research on FRP strengthened concrete and masonry structural elements under blast loading. The main conclusions may be summarized as follows:

- the studies (database of 35 publications) generally indicate the benefits of FRP under blast loading in terms of increased strength, more ductile behaviour, reduced damage levels (including defragmentation);
- the information and results provided by these studies are not sufficiently detailed to develop rational design methods for blast design of FRP retrofitted reinforced concrete elements;
- little attention has been paid to the bond behaviour under dynamic loads and no predictive bond model suitable for blast loads is yet available.

Perspectives

It appears that the fundamental behaviour of FRP strengthened structures under blast loading still needs to be investigated. This is surely explained by the many difficulties in getting reliable experimental results due to the destructive nature and the short duration of the explosion load. A particular point of interest is the identification of the dynamic behaviour of the FRP EBR in terms of bond behaviour and dependency of material properties to high strain rates.

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