BLAST MITIGATION USING FIBER-REINFORCED POLYMER SYSTEMS

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ABSTRACT

In recent years, there has been an increase in explosion incidents due to accidents or terrorist acts. Such incidents result not only in damages to structures, but also more importantly in the loss of lives, especially in urban areas. This paper presents a study carried out at the National University of Singapore to strengthen un-reinforced masonry brick walls against blast effects. A scheme, using a primary externally bonded fiber-reinforced polymer system and a secondary steel anchorage and stiffener frame, was conceptualized, developed and tested both in the laboratory and in the field. Thirty-seven wall specimens were tested in the laboratory to characterize the response under lateral loads, which was checked with results from analytical modeling. Four prototype in-built walls were subsequently tested to verify the anchorage and stiffener system for practical use. Field tests carried out in Australia, where similar walls were subjected to 27-tonne and 5-tonne blasts, agreed with results from dynamic analysis using DIANA finite element software and thus confirmed the viability of the developed scheme. A simplified method to derive the blast resistance of strengthened masonry walls from static test results was also established. By performing a parametric study using this method or dynamic analysis, charts to aid in strengthening design to mitigate blast effects may be developed.

1. INTRODUCTION

In recent times, there has been an increase in the number of explosion incidents in urban cities around the world, either due to accidents or terrorist acts. These incidents do not only cause damages to building structures, they also result in loss of innocent lives. The protection of infrastructures and lives against blasts is therefore of increasing concern.

In most reinforced concrete buildings, the walls are usually constructed of masonry bricks and are not designed to be load-bearing, especially against lateral out-of-plane loads. As these walls effectively form the envelope for a building, it becomes crucial for them to be strengthened to fortify the building. The use of externally fiber-reinforced polymer (FRP) systems is viewed as an efficient strengthening method. Comprising of high-performance continuous fiber sheets laid up in a manner similar to wallpaper pasting, it provides speed in installation, and workability in areas that are difficult to access.

This paper presents a study carried out at the National University of Singapore on the strengthening of un-reinforced masonry brick walls with FRP systems against blast effects. Static tests were carried out on isolated wall components and in-built prototype walls to examine the failure characteristics of the strengthened walls. Analytical models were proposed to predict the load-deformation response and failure modes. The later information provides input for a simplified method that was proposed to estimate the blast resistance of the strengthened walls. Field tests and dynamic analyses on numerical models were further carried out to verify the performance of the walls.

2. STATIC RESPONSE OF FRP-STRENGTHENED WALLS

Two test programs were conducted. In the first program, thirty half-brick (110-120 mm) thick and seven full-brick (240 mm) thick wall specimens were tested to examine the failure characteristics of masonry walls strengthened with FRP systems, with focus on the effect of FRP type and amount, and effectiveness of anchorage systems. Each wall was laid horizontal on four line supports and subjected to either a concentrated load or a patch load applied via an airbag at its center, as shown in Fig. 1(a).

The second program on four prototype in-built walls was carried out to verify the effectiveness of a steel anchorage and stiffener system to prevent sliding failure of the wall as well as to enhance the performance by compartmentalizing the wall. Fig. 1(b) shows the test set-up for the prototype wall, which measured 2 m wide, 1.5 m high and 120 mm thick.

(a) Wall specimens *(b) In-built walls*

Figure 1: Test set-up

2.1 Failure Modes and Ultimate Strength

The tests indicated four possible failure modes: (a) flexural compression failure due to crushing of bricks; (b) punching shear failure through the wall; (c) flexural bond failure due to delamination of the FRP reinforcement; and (d) flexural tension failure due to rupture of FRP reinforcement, as depicted in Figure 2.

(a) Flexural Compression

(b) Punching Shear

(c) Flexural Bond
(FRP sheets removed)

(d) Flexural Tension

Figure 2: Failure modes

The analytical predictions for the ultimate strength for each of the failure modes are presented elsewhere (Tan and Patoary, 2003a, 2003b). It is noted that most specimens failed by punching shear or flexural compression, provided that a proper roughening of the wall surface coupled with an anchorage system, either using fibre bolts at regular spacing or steel bars embedded in groves, had been incorporated (see Figure 3). For the case of very low strength fiber materials, it was noted that failure was governed by rupture of the FRP reinforcement.

Figure 3 also illustrates the effect of surface preparation and provision of anchorages on the load-deflection response of four series of strengthened wall specimens. In each series, there are four specimens. Except for specimens designated ~UG~, each of the other three specimens had its surface roughened prior to the installation of FRP reinforcement. In Specimens ~G~, no additional measures were made to anchor down the FRP reinforcement. Whereas Specimens ~BA~ had the FRP systems anchored with surface-mounted steel bars, Specimens ~BO~ had the FRP reinforcement anchored by fiber bolts spaced at 110 mm near the periphery of the wall. In the first two series, specimens were subjected to a center load, while in the other series they were tested under a patch uniform load.

All FRP-strengthened specimens failed at a much higher load than the un-strengthened wall. It was noted that the un-roughened walls failed by flexural bond whereas the other specimens failed by punching shear under the concentrated load, and by flexural compression under the patch uniform load. Compared to the un-roughened specimens, specimens with fiber bolt anchors appeared to perform best, especially under the patch uniform load.

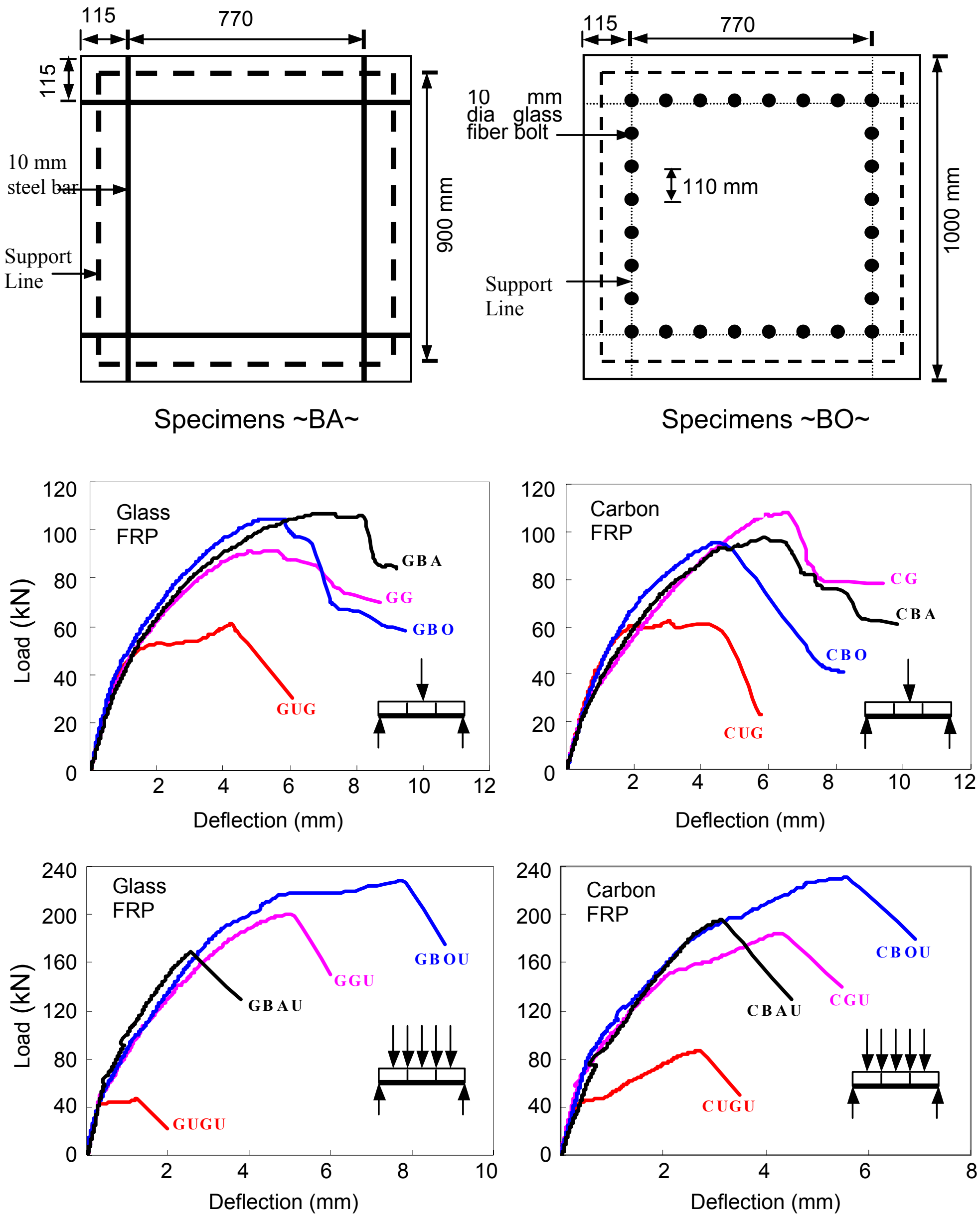


Figure 3: Load-deflection response of isolated wall specimens

2.2 Anchorage and Stiffener

Figure 4 shows the load-deflection response of the in-built walls subjected to patch uniform load over a 1 m by 1 m area at the center. All four walls were bolted to the RC frame using steel angles. In addition, a “tip-tac-toe”-shaped steel stiffener frame was installed in one of the walls, which essentially resulted in the centrally loaded area being bounded by the steel angles of the frame. All walls failed by debonding or rupture of the FRP reinforcement at the boundary with the RC frame, followed by load punching through the wall. It is interesting to note that the stiffener frame further increased the ultimate strength and energy absorption capacity (as measured by the area under the load-deflection curve) of the wall.

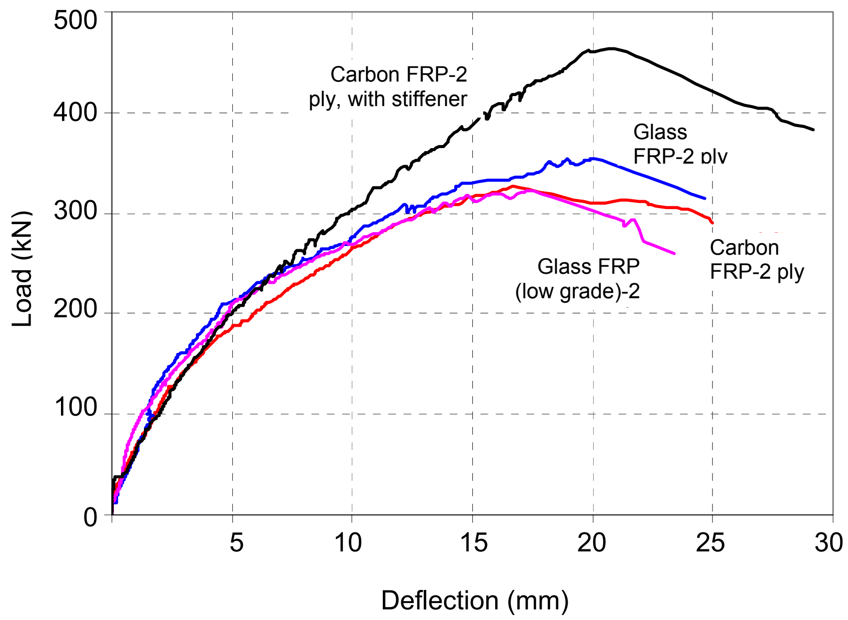


Figure 4: Load-deflection response of in-built prototype walls

3. ESTIMATION OF BLAST RESISTANCE

The blast resistance of the wall is evaluated in terms of its capability to resist an amount of TNT charge at a specified distance from the blast source. The procedure based on static properties of the wall may be used (Volkman, 1990). First, for a given charge, the pressure-time history is obtained either from the program CONWEP (TM5-855-1, 1986). Next, the pressure-time history is simplified to an equivalent triangular pressure pulse with zero rise time defined by peak pressure P and the positive phase duration t_d.

For a given structure or structural member, the natural period T_n could be determined from its mass and equivalent elastic stiffness, either based on static test results or analytical modeling. Thus, knowing the value of t_d/T_n, the dynamic load factor DLF, which is the ratio of the maximum dynamic deflection to the deflection that would have resulted from the static application of the peak pressure, could be read from the chart of TM5-1300 (1990). The required static resistance of the wall is calculated as the peak pressure multiplied by DLF. If the required static resistance is equal to the actual static resistance of the wall, then the blast resistance is determined. Otherwise, a different TNT charge is assumed and the procedure repeated until convergence is obtained.

Figure 5 shows the blast resistance in terms of TNT charge at 10 m stand-off distance for 1 m by 1 m walls strengthened with FRP systems. It is interesting to note that the blast resistance is linearly proportional to the static strength enhancement, defined as the ratio of the ultimate load capacity P_u of the strengthened wall to that of the un-strengthened wall P_o. Also, the blast resistance depends on the failure mode, being highest for flexural compression, next for punching shear and least for flexural debonding.

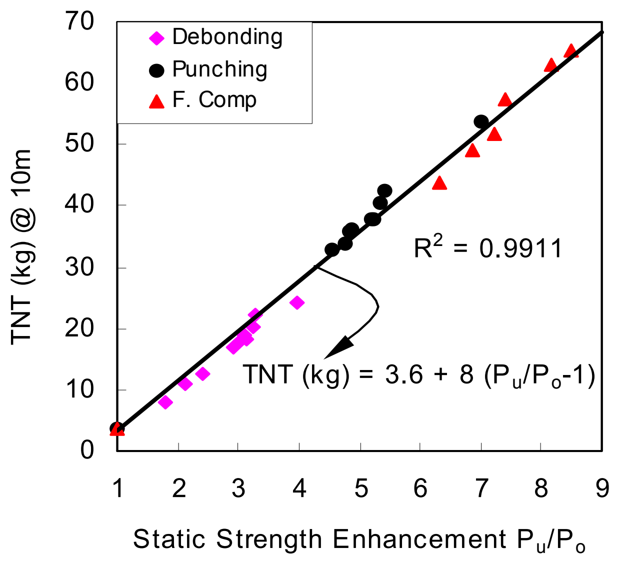
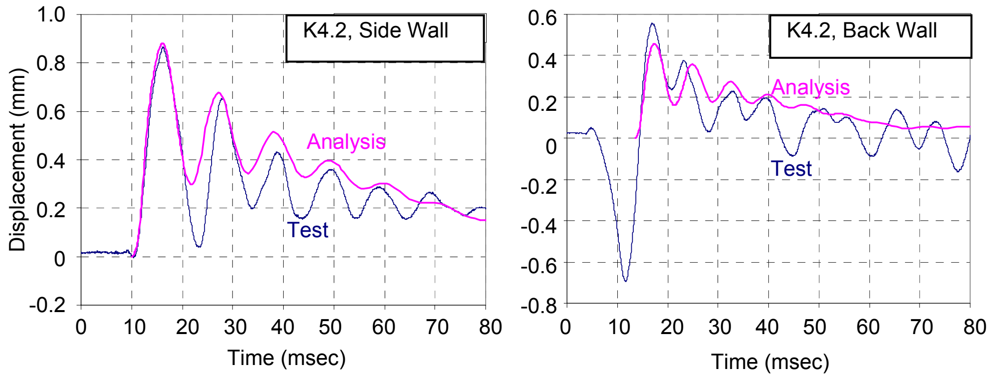


Figure 5: Relation between blast resistance and static strength enhancement

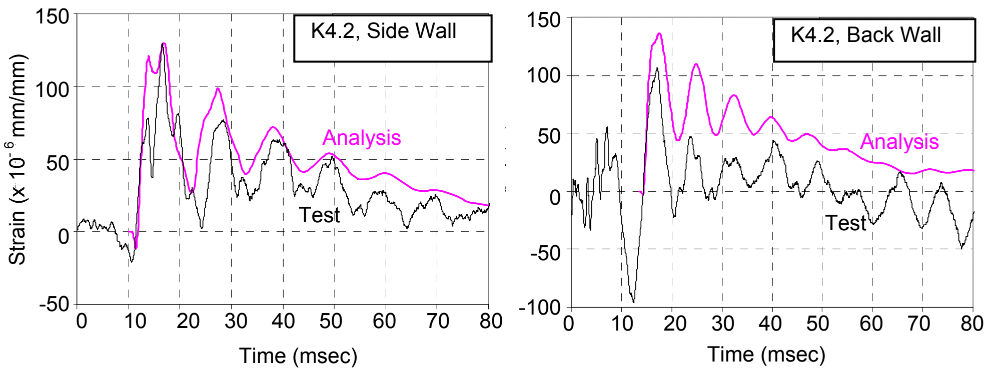
4. FIELD TESTS

Two large scale blast tests were carried out in Woomera, Australia, between September and October, 2002. One test involved 27 tonnes of explosives while the other test 5 tonnes of explosives. For each test, three box structures were located at scaled distance (defined as $R/W^{1/3}$ where R is the distance from the center of the charge in meters and W is the mass of spherical TNT charge in kg) of 2, 3 and 4.2. Each box module had two 2.4 m wide by 2.1 m high side walls and one 1.7 m wide by 2.1 m high back wall, all constructed of masonry bricks of half- or full-brick thickness and reinforced with FRP systems with or without intermediate stiffeners.

All the test walls survived the blasts without damage, as the blast pressure generated and recorded was much lower than that based on CONWEP (TM5-855-1, 1986) due to the presence of other targets in the path of the blast wave. Figure 6 compares the dynamic responses of two walls located at K4.2 with those obtained using the finite element package DIANA (Witte and Kikstra, 1999), version 8.1. The variations of central wall displacement and strains in FRP reinforcement with time were well predicted, at least up to the first few cycles. The numerical model therefore could serve as another means to evaluate the blast resistance of the strengthened walls.



(a)Displacement



(b) Strains in FRP reinforcement

Figure 6: Dynamic response of in-built walls subjected to field blast tests

5. CONCLUDING REMARKS

Structural protection against blasts has become an important issue in view of the increasing number of explosion incidents. The use of externally bonded fiber-reinforced polymer systems has been shown to be effective in mitigating the blast effects on masonry walls through analytical, experimental and field works. Failure modes of strengthened walls were clarified and a simple procedure based on static resistance of the wall has been proposed to estimate the blast resistance of the strengthened wall. Dynamic analyses and explosion field tests carried out further testified the applicability of FRP systems as a strengthening strategy.

The simplified procedure to estimate blast resistance or the numerical analysis using DIANA software may be used to generate design charts for strengthening purposes. Two design criteria may be considered; one based on “strength limit” that prevents collapse of the structure and the other based on “deformation limit” that controls damage to the structure. Applications of FRP systems for concrete members could be similarly considered.

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