Reinforcement of Notched PBX Simulant Beams with CFRP Patches-Experimental Study

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Abstract. Strength degradation induced by geometrical discontinuities is a primary cause of structural failure for polymer bonded explosive (PBX). To restore structural integrity and extend service life, reinforcement of weakened PBX structures is urgently demanded. In the present work, carbon fiber reinforced polymer (CFRP) patches are employed to notched PBX simulant beams. By using digital image correlation (DIC) technique, the influences of CFRP patches on mechanical behavior of the beams under bending load are explored. Results show that the CFRP patches endows the beams with increased strength and stiffness. Due to the load-sharing and deformation-confining of the patches, stress concentration at the notch is relieved, and crack propagation in PBX simulant matrix is prevented. These discoveries may provide important enlightenment for the reinforcement and repair of the weakened PBX structures, and in addition, provide basis to the potential application of CFRP patches in energetic materials.

1. Introduction
Polymer-bonded explosive (PBX) is a highly particle-filled composite. As a high explosive, it is widely used in civil engineering blasting and military explosive charges [1-4]. Because of the high costs of the material, PBX is usually intended for use in situations where common explosives are not easily melted into the required final shapes or difficult to machine [5]. For this reason, PBX structures are normally in complex shapes with presence of various geometrical discontinuities.

For the record, PBX is a brittle material with low strength. Cracking induced by tension load is the primary cause of failures for the material [6-8]. In fact, for PBX structures with complex shapes, threats are not confined to the material itself. Due to the reduction of the section which supports the load, the presence of geometrical discontinuities may cause local amplification of stress near the discontinuities, resulting in the initiation and extend of cracks. However, cracks are always unexpected in PBX. In addition to the functional malfunctioning, they may cause accidental ignition, thus seriously influence the security and validity of the structure [9-13]. In this prospective, relieving stress concentration and increasing strength at the geometrical discontinuities are significant for improving the security and validity of PBX structures.

Recently, a lot of effort has been devoted to the reinforcement/repair of the weakened/damaged structures to restore its integrity and effectiveness [14-17]. Among these techniques, the most promising is carbon fiber reinforced polymer (CFRP) patch. CFRP is a composite with excellent properties (e.g. high strength and stiffness, lightweight, corrosion resistance and great formability) [18, 19]. Investigations demonstrated that the adhesively bonded CFRP patch can offer a smooth stress...
Transfer from the weakened/damaged part to the patch, therefore reduce stress concentration in weakened/damaged area and delays the crack propagation in the structure [20-24].

In this study, CFRP patches are employed to notched PBX simulant beams for reinforcement. By using digital image correlation (DIC) technique, strain distributions in unreinforced, bottom-reinforced and lateral-reinforced beams under bending load is explored. Results demonstrate that CFRP patches can reduce stress concentration at the notch and delay crack extension in PBX simulant matrix, thus avoid catastrophic failure of the beam at low stress.

2. Experimental

2.1. Material and Specimens
A PBX simulant material is used in this study, with 94 wt.% rigid particles (Ba(NO3)2 and Melamine) bounded together by a 6 wt.% fluoro-rubber. After hot pressed, the blocks were precision-machined into notched beams. The dimension of the beam is shown in figure 1a.

Carbon fiber reinforced polymer (CFRP) composite is used for preparing reinforced patches. The carbon fiber used is in weight of 200 g/m² and the polymer used is bi-component epoxy adhesive. After the CFRP composite panel was manufactured, rectangular patches were cut from parent panel, polished and bonded to the bottom and lateral side of the notched beams. The dimensions and plaster modes of the CFRP patches are indicated in figures 1b and 1c.

2.2. Bending Test
The bending tests were carried out in a conventional SHIMADZU AG-1C loading frame. The loading velocity is 0.1 mm/min, and the fixture span is 60 mm. The experimental process image is exhibited in figure 1d.

2.3. DIC Measurement
A DIC measurement was employed to explore the deformation fields of the different specimens (as indicated in figure 1e). Before the experiment, random speckle patterns were made on the specimen surface. The speckle patterns images were recorded by using a CCD camera. The resolution of the CCD is 1624 × 1236 pixels and the framing rate is 5 frame/s. We processed the captured images by employing Vic 2D software. The sub-image was set as 29 × 29 pixels and the step size was set as 5 pixels. Detailed principles of the DIC techniques are available in [25-27].

![Figure 1](image-url)

**Figure 1.** (a) Dimensions of the unreinforced PBX simulant beam; (b) Sketch of the bottom-reinforced beam; (c) Schematic diagram of the lateral-reinforced beam; (d) Image of the bending test; (e) Image of the DIC measurement.

3. Results
Shown in figure 2 are the load-time curves obtained for different specimens. As expected, the mechanical behaviour of a specimen is evidently dependent on its reinforcement condition. For the bottom-reinforced and lateral-reinforced beam, the maximum load is 475.47 N and 654.69 N,
respectively, increased by 132.89% and 220.67% respect to the unreinforced one which is only 204.16 N. Detailed observation on curve profile of the specimens reveals that, the load of the unreinforced and lateral-reinforced beam decreases rapidly after reaching its maximum value. Whereas, the bottom-reinforced beam sustains a platform before the final failure (shown by a blue arrow), indicating a ductile fracture behaviour.

Figure 2. Load variation as a function of time for the unreinforced, bottom-reinforced and lateral-reinforced PBX simulant beams.

Figure 3 exhibits the micrographs of the cracked specimens. The unreinforced beam displays a nearly straight crack path, which extends vertically through the PBX simulant matrix. The main crack morphology of the bottom-reinforced beam is similar to that of the unreinforced one. Whereas, additional cracks along the interface between the PBX simulant matrix and the CFRP patch is identified, indicating debonding of the patch. More need noting is the lateral-reinforced beam, which shows a deflected crack trajectory. Rather than initiating at the notch, the crack originates from the bottom right of the beam matrix, propagates along the patch edge and deflects at the patch corner.

Figure 3. Micrographs of the cracked beams: (a) Unreinforced, (b) bottom-reinforced, and (c) lateral-reinforced. Rectangular boxes indicate the locations of the enlarged areas.

To detect failure process of the specimens, whole field deformations of the beams in real time were obtained by using DIC technique. For the unreinforced beam, ten specific moments during the deformation are selected, among which moment e corresponds to the maximum load. Figure 4 displays the corresponding contour plots of the horizontal strain $\varepsilon_{xx}$. Before the load is applied, the strain field in the specimen is nearly uniform (figure 4a). With the load applied, the strain fields at the notch show variety gradually. In figure 4b, a localized strain band is identified at the overhead of the notch. Then this band propagates and evolves continuously with an increasing load (figures 4c-4d). As load reached the maximum value (figure 4e), the localized deformation becomes more profound and initial damages underneath the specimen surface may be activated, leading to the subsequent reduction of the load-carrying capacity. Soon after that, the localized deformation fully develops (figures 4g-4i) and instability fracture of the beam finally occurs (figures 4i-4j).
Figure 4. Tensile strain field in unreinforced PBX simulant beam at specific moments/loads.

Figure 5 presents the horizontal strain distribution of the bottom-reinforced beam. Just like the unreinforced beam, a localized strain first occurs at the overhead of the notch (figure 5b). As external forces applied further, the localized strain band propagates toward the boundaries where compressive load is applied (figures 5c-5d). At moment e, fully-developed localized strain is observed. Meanwhile, additional concentrated strain band emerges at the notch edge in the vicinity of the matrix/patch interface (indicated by an arrow in figure 5e). Soon afterwards, the load-time curve exhibits a slight drop. Crack in PBX simulant matrix is identified, accompanied by the alleviation of strain concentration near the matrix/patch interface (shown by an arrow in figure 5f). Due to the constraint effect of the well-bonded CFRP patch, the crack undergoes a steady extending process (figures 5f-5i), which is consistent with the platform in load-time curve (figure 2). At the last moment pioneer to instability fracture, new concentrated strain band occurs in the left vicinity of the matrix/patch interface (shown by an arrow in figure 5j), indicating the imminent debonding of the interface.

Figure 5. Tensile strain field in bottom-reinforced PBX simulant beam at specific moments/loads.

Figure 6 exhibits the tensile strain distribution of the lateral-reinforced beam. For clear observation and description, the edges of the notch and patch are outlined by dashed lines. Different from the unreinforced and bottom-reinforced beam, the contour plots in lateral-reinforced beam show multiple sites of localized strain. Instead of emerging at the overhead of the notch, the strain bands are almost distributed inside the notch contour (figure 6b). With the increase of external force, the range of the
strain concentration enlarges, accompanied by the aggravation of the strain concentration extent (figures 6c-6g). It is worth noting that the pattern of the localized strain bands is regular-arranged, which should be attributed to the woven fringe of the carbon fibers in CFRP patches. At moment e, new concentrated strain band located at right edge of the patch is observed (indicated with an arrow in figure 6e). As external loads applied further, the band evolves continuously (figures 6f-6h) and finally forms crack along the patch edge (figure 6i). By comparison, the strain bands around the notch have not changed apparently at the later stage of loading (figures 6g-6h).

Figure 6. Contour plots of the tensile strain field in lateral-reinforced PBX simulant beam at specific moments/loads.

4. Discussion
As an efficient and economic method for reinforcement and repair, CFRP patches have been significantly used in various engineering field like aerospace, automotive and civil structures [28-31]. Numerous investigations confirmed that CFRP patches can increase the service loads of structures effectively. By transferring stress from the weakened/damaged part to the patch, stress concentration in damaged/weakened area can be reduced and crack propagation in structures can be delayed [20-24].

In this investigation, CFRP patches are newly adopted on notched PBX simulant beams. Load-time curves exhibited in figure 2 demonstrate that the reinforced beams gain a substantial increase in load-carrying ability. DIC measurements reveal that CFRP patches change the strain distributions of the beams significantly. Due to the load-sharing effect of the patches, the beams evolve multiple localized strain sites, thus reducing the strain intensity at the notch and avoiding the catastrophic failure of the beam at low stress.

4.1. Effect of CFRP Patches on Strain Concentration Reliving at the Notch
To reveal the effect of CFRP patches on strain concentration reliving at the notch, strain evolution at the notch is analyzed. Figure 7 depicts the load variation as a function of the strain for different specimens and the image inset indicates the area selected for strain calculation. For all specimens, there is a nearly linear region in load vs. strain curve, in which the load climbs on an approximately constant slope with the increasing of strain. Whereas, fitted results suggests that the slope value of the bottom- and lateral-reinforced beam (1577 N/% and 1597 N/%, respectively) is obviously higher than that of the unreinforced beam (1020 N/%), indicating an increased stiffness and decreased strain at the notch. Meanwhile, we detect that, due to the contribution of the 6 wt.% binder, the unreinforced beam exhibits characteristics of yield deformation, with a failure strain of ~3.3% at the notch. For the bottom-reinforced beam, yield deformation also occurs. The slight fluctuation presented at the strain of ~3.3% (indicated by a blue arrow) is consistent with the crack initiation in PBX simulant matrix. In
contrast, the lateral-reinforced beam exhibits an obvious different curve profile. Due to the sufficient confinement of the CFRP patches, no characteristics of yield deformation are identified. During the entire loading process, the maximum strain at the notch is only ~0.9%, which is much smaller than that of the unreinforced and bottom-reinforced beams.

Figure 8 plots the variations of the strain as a function of the distance from the notch at the load of ~204 N and the image inset indicates the location of the analysis line. It can be clearly observed that as the distance from the notch increases, all curves exhibit a tendency to decrease. However, the strain of the bottom- and lateral-reinforced beams is always lower than that of the unreinforced one. For the unreinforced beam, the maximum strain at the notch is 1.31%. Whereas, the value is just 0.16% and 0.13% for the bottom- and lateral-reinforced beam, respectively. Combined with the results of figures 7 and 8, we suggest that the external-bonded patch confines the deformation and reduces the stress concentration at the notch significantly.

### 4.2. Effect of CFRP Patches on Crack Suppression of the PBX Simulant Matrix

Though the PBX simulant material used in this investigation undergoes yield deformation before failure, catastrophic fracture occurs inevitably as soon as the failure strain is arrived (figure 7: black curve for the unreinforced beam). On the contrary, this not happen to the bottom-reinforced beam, despite crack has initiated at the strain of ~3.3%. It can be noted that the load-time and load-strain curve of the bottom-reinforced beam sustain a platform after the slight fluctuation of the load (figure 2 and figure 7). DIC observation confirms that the platform is coincident with the steady propagation of the initiated crack (figure 5). This steady propagation does not terminate until the occurrence of the patch debonding. Figure 9 shows the crack length variation as a function of loading time, in which the crack tip location is determined by the failure strain at the notch (3.3%). It can be identified that the bottom-reinforced beam shows a slow increase in the crack length within the following seconds after the crack initiates. Further calculation suggests that the crack extension rate of the PBX simulant matrix during this period is 1.45 e^{-1} mm/s. According to the results above, it can be concluded that the CFRP patches play a positive role on the crack suppression of the PBX simulant matrix.
5. Conclusion
In the present work, an experimental study is carried out to investigate the reinforcement effect of CFRP patches on notched PBX simulant beams under bending load. Results demonstrate that the externally bonded patches can improve the structural stiffness and load-carrying ability of the beams significantly. Due to the load-sharing effect of the CFRP patches, strain distribution in matrix beam is modified and stress concentration at the notch is relieved. In addition, we found that the CFRP patches play a positive role on the crack suppression of the PBX simulant matrix, therefore avoiding the abrupt fracture of the beams effectively. This investigation may provide significant inspiration for the reinforcement and repair of the weakened PBX structures, and in addition, lay foundation to the potential application of CFRP patches in energetic materials.

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