Experimental Investigation on the Behaviour of RC Panels Retrofitted with Polymer Coatings under Blast Effects

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Abstract

Elastomeric polymers (such as polyurea and polyurethane) are finding relevance in retrofitting applications for structures being subjected to blast and impact loadings. This approach, an alternative to various existing retrofitting techniques, capitalises on the elastomeric properties, high strain capacity, high ductility and strength of the polymers, as well as on the ability of the coating layer to act as a shield in containing debris and fragments from the blast. This paper presents the findings from an experimental study undertaken to evaluate the effectiveness of using polyurea coatings to enhance the blast resistance of reinforced concrete (RC) panels. The performed experimental blast trials, designated as Vietnam Trial 2, were conducted in Vietnam with the collaboration from the Vietnam Institute for Building Science and Technology (IBST). Four RC panels with dimensions of 1700 (L) × 1000 (W) × 60 (T) mm, were tested during the trials. Of these, one panel was an unretrofitted panel while the remaining three were coated with polyurea albeit with a variation in the coating thickness and location. All the panels were subjected to blast loads resulting from the detonation of 1.0 kg Ammonite charge placed at 1.0 m stand-off. The behaviour and responses of various polyurea coated RC panels were compared to the unretrofitted RC panels in terms of panel's deflections, crack formation and damage to the polyurea coating layers. The findings from the experiments indicated that proposed technique of using polyurea coating to retrofit RC structural elements is practicable and feasible to enhance the capacity of structures against blast loading. A higher level of protection is provided when the protective coating is applied on the blast-facing face of the structure. It was also observed that the bond between concrete and the polymer did not damage even after the the application of the blast loads. These findings assert the possibility of using the proposed technique as a practical alternative to the existing techniques in strengthening structures being subjected to blast effects.

Keywords: Blast loads, deflection, reinforced concrete (RC), polyurea, retrofitting.

1. Introduction

The Brundtland Commission defined sustainable development as the development that "…meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). An essential segment in sustainable development which is commonly overlooked is the need to preserve and protect existing critical infrastructures from man-made and accidental destructive forces. The increase in accidental and terrorist detonated explosions has resulted in buildings and infrastructures across the globe becoming more vulnerable to extreme impulsive loadings. Nowadays, such incidents are not confined to military structures, but also to civilian infrastructures such as transportation networks including concrete bridges, power generation facilities, petrochemical plants, oil and gas facilities, sporting facilities and even heritage and tourist attractions.

The losses from such events cannot be measured from the economic aspects alone since many of the target structures are iconic and carry substantial heritage, architectural and sentimental values. In response to these threats, structural and material engineers are seeking to develop robust and cost-effective protective solutions to mitigate the damage caused by such extreme loading events. Elastomeric polymers such as polyurea and polyurethane are finding the niche as retrofitting materials for structures being subjected to blast and impact loads. The feasibility of these polymers are mainly due to the elastomeric, high strain capacity and ductility, as well as on the ability of the coating layer to act as a shield in containing debris and fragments from the blast.

This research explores the potential of using polyurea as a structural retrofitting material for concrete structures being subjected to blast effects. Polyurea is an elastomeric polymer derived from the reaction of an isocyanate component and a polyamine. Its chemical composition and stoichiometry contributes significantly to its properties and behaviour (Roland et al., 2007). Polyurea elastomers are typically 100% solids, exhibit low shrinkage resistance to moisture, are odourless, and bond well with many substrates (concrete, plastic and steel) (Tekalur, 2007). Polyurea coatings have been used widely as truck bed liners, as well as for coatings of pipelines due to their high durability and watertightness.

In the proposed retrofitting application, polyurea will be applied to the structure as a protective coating, by using spray-on procedure. Though similar approaches have indicated promising results on masonry structures (Davidson et al., 2005; Davidson et al., 2004; Knox et al., 2000), steel structures and plates (Ackland et al., 2007; Amini et al., 2006, 2010; Chen et al., 2008), as well as on composite sandwich structural systems (Bahei-El-Din & Dvorak, 2007a, 2007b; Tekalur et al., 2008), the application of this technique on reinforced concrete (RC) structural system is yet to be explored comprehensively. This research endeavour was initiated by the authors to address this gap by investigating the feasibility of polyurea application on RC panel type of structures. This paper presents the findings from a methodically planned and implemented experimental blast trial, undertaken to evaluate the effectiveness of using polyurea coatings to enhance the blast resistance of RC panels.

2. Experimental Programme

A series of experimental blast trials were conducted to evaluate the feasibility of using polyurea coatings in enhancing the blast resistance of RC panels. These blast trials, i.e. Vietnam Trial 2, were conducted in MyDuc Province in Hanoi, Vietnam, as a collaborative venture between The University of Melbourne and the Vietnam Institute for Building Science and Technology (IBST), Hanoi. The trials comprised of four spherical air blast experiment on one unretrofitted and three polyurea coated panels. The following sections describe the design, methodology, implementation and findings of the experimental programme.

2.1 Test Specimen Design

Four identical RC slab-like panel specimens were prepared for the blast trials. The design of the panels was adopted as a scaled model from an existing real precast concrete panel [Dimension: 3000 (L) × 2000 (W) × 160 (T) mm] and modified to the dimensions of 1700 (L) × 1000 (W) × 60 (T) mm. The panels were constructed with 43 MPa concrete and were reinforced with one layer of 5 mm bars at 100 mm spacings at the mid-thickness of the specimens, in both longitudinal and transverse directions. This provided a reinforcement area of 196 mm^2/m, representing a reinforcement ratio of 0.33 %. The nominal yield stress of the reinforcement was 500 MPa. The geometry and the reinforcement details of the test specimens are shown in Figure 1. All the panels were subjected to blast pressures resulting from the detonation of 1.0 kg Ammonite charge placed at a stand-off distance of 1.0 m.

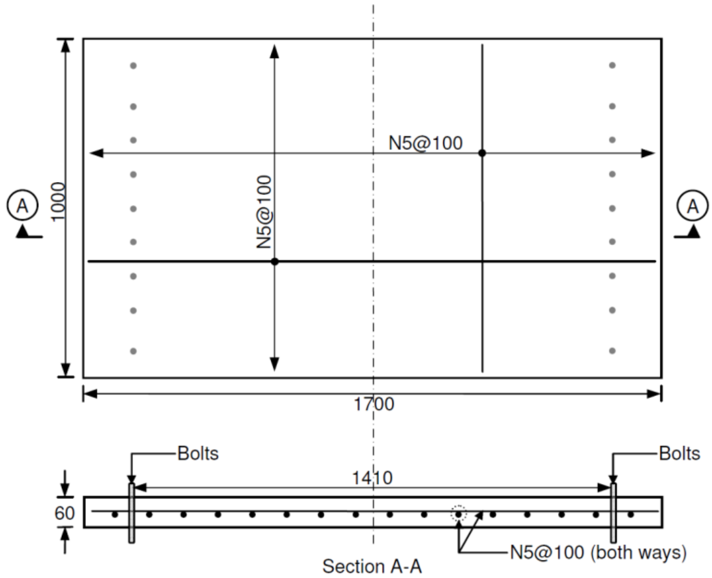


Figure 1: Details of reinforcement layout for the panels

2.2 Retrofitting Schemes and Specimen Designations

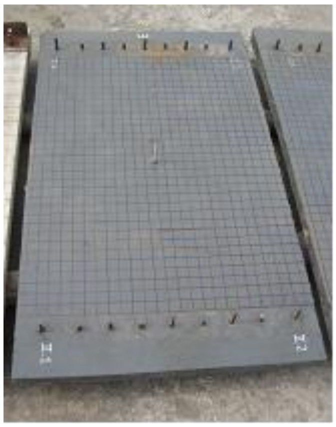
The four specimens were designated as UR2, PUB4, PUB10 and PUTB4. Specimen UR2 was the control unretrofitted panel, whereas PUB4, PUB10 and PUTB4 were subjected to polyurea coatings at different locations and with different thickness. Table 1 indicates the assigned designations, and the location and thickness of the polyurea coatings that were applied on each panel. The specimens were constructed and cured at the IBST facilities and were transported to the test site just prior to testing. Polyurea coatings on specimens PUB4, PUB10 and PUTB4 were applied by using a proprietary spray-on technique with high precision spraying equipment. The variations in the coating thickness and location were practiced in order to assess the contribution of these factors to the effectiveness of the retrofitting scheme and the overall response of the structural element. Figure 2 shows of the retrofitted specimen PUB4, with 4 mm polyurea coating on the bottom surface.

Table 1: Location of application of polyurea coating on each panel

Panel designation	Polyurea coating on	
	Top surface*	Bottom surface
UR2	–	–
PUB4	–	4 mm
PUB10	–	10 mm
PUTB4	4 mm	4 mm

* Note: Blast-receiving face

(a) Top (blast-receiving) face

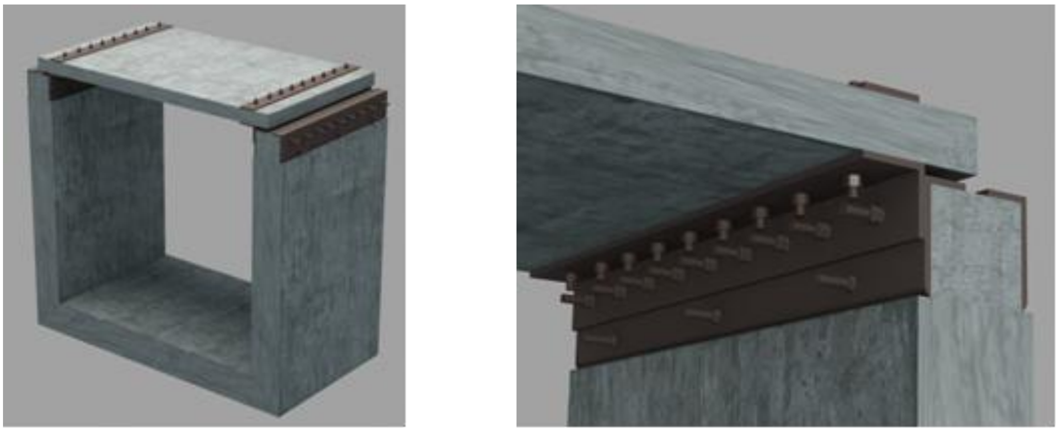


(b) Bottom face

Figure 2: Specimen PUB4 with 4 mm polyurea coating on the bottom face

2.3 Test Bunker and Specimen Fixing Assemblage

The test frame for the present research was constructed with RC of 100 MPa high-strength concrete (HSC) material (Figure 3a). The overall dimension of the test bunker was 1900 (L) × 1000 (W) × 1780 (H) mm, constructed with a 200 mm thick RC wall and base. 10 mm reinforcement was used to reinforce both the walls and the base of the frame (Figure 3a). The construction of the test bunker was completed by building two 400 mm masonry brick walls at the two open sides of the test frame to reduce the clearing effects during the blast. The fixing assemblage utilised to install the test specimens onto the test frame was by angled cleat and bolt connections, as shown in Figure 3b. At each support, nine M20 bolts (vertical bolts) were used to attach the shorter span of the test specimen (1000 mm) to a 100 × 100 × 10 mm steel cleat (Steel Cleat A). Another nine M20 bolts (horizontal bolts) were then used to attach Steel Cleat A to a 150 × 70 × 10 mm cleat (Steel Cleat B). To attach the fixing assembly onto the test frame, two sets of Steel Cleat B were tied to the test frame using three M22 bolts (Figure 3b).



(a) (b)

Figure 3: The: (a) test frame; and (b) specimen fixing assemblage

2.4 Instrumentations

The instrumentations utilised during the experimental work were mainly for the purpose of displacement and blast pressure measurement. The central mid-span displacements of the specimens were determined using mechanical displacement measurement devices. The device was designed by the authors to capture the maximum inward, maximum outward and residual displacement of the test specimens. This system essentially consisted of one threaded steel rod, one cubic clay block, which was placed on the floor of the test bunker, and four hollow rectangular tubes. The performance of the device was already calibrated with a linear variable differential transformer (LVDT) during Vietnam Trial 1 (Pham, 2010).

The crack patterns and crack widths on the panels were recorded in-situ after each test, based on the 50 mm mesh drawn on both surfaces of the test specimen prior to the test. An EL35-2505 type crack detection pocket microscope (CDPM) was used to measure the dimensions of the cracks. The CDPM has the capacity to measure maximum cracks up to 4 mm with a precision of 0.02 mm, and has a magnification capacity of 40×. Meanwhile, the data acquisition system (DAS) used in the study was manufactured by HBM with 16 input channels corresponding to 16 integrated cards. The configuration of the DAS was completed with a high capacity notebook workstation that was used to collect the transmitted data and subsequently recorded the sequential data. The pressure gauge utilised to measure the blast pressure throughout the experimental trials was the 113B21 model which is a piezoelectric gauge of a printed circuit board. The piezoelectric gauge had the capacity to measure dynamic and short-term transient pressure up to 6895 kPa.

3. Results and Discussion

The results presented and discussed in this section include those obtained on the blast parameters and the test specimen's displacement and deformation. The damage profile of the specimens, such as the crack patterns, and concrete scabbing and spalling, were documented from visual observations after the explosion. Similarly, any damage sustained by the polyurea coatings was recorded through visual observations. The crack widths on the concrete surface were measured using the specialised CDPM apparatus. The effectiveness of the polyurea coatings in retrofitting RC panels is also discussed.

3.1 Blast Parameters

Blast pressures were measured during both Vietnam Trial 1 and Vietnam Trial 2. However, the two pressure gauges setup to measure the blast pressure resulting from the 1.0 kg Ammonite charge at 1.0 m stand-off distance during the Vietnam Trial 2 malfunctioned, and thus no data were recorded from these pressure gauges. Due to this, only blast parameters recorded during Vietnam Trial 1, i.e. from the 5 kg and 0.5 kg Ammonite charges were used for the analyses and calibration of blast parameters. The analyses and calibration process were performed using computational fluid dynamics (CFD) based Air3d code (Rose, 2006) and CONWEP empirical code (Hyde, 1993).

The TNT equivalence ratio for the Ammonite charge was determined by comparing the arrival time, peak reflected pressure, peak reflected impulse, positive phase duration, and the overall pressure profile including the negative phase of the experimental findings to the data computed from Air3d and CONWEP. These values were then compared with those reported in literatures (Pham et al., 2009; Pham, 2010). While Pham et al. (2009) and Pham (2010) proposed a TNT equivalence ratio of 1.1, the analyses performed in the present study suggests that a more suitable TNT equivalence ratio for Ammonite would be 1.0. The details of the comprehensive analyses performed can be obtained from Raman (2011).

Subsequently, the similar blast modelling characteristics was adopted to simulate the spherical free-air explosion of the 1.0 kg Ammonite charge with a stand-off distance of 1.0 m, as practiced in this experimental trial. The comparisons of reflected pressure–time history profiles as computed from Air3d and CONWEP are shown in Figure 4. The reflected impulses computed by Air3d and CONWEP were 640 kPa.ms and 559 kPa.ms, respectively. The corresponding peak reflected pressures were 3543 kPa and 4265 kPa, respectively. The reflected pressure and impulse varied along the span of the panels. The lowest reflected pressure was recorded at the four corners of the panels.

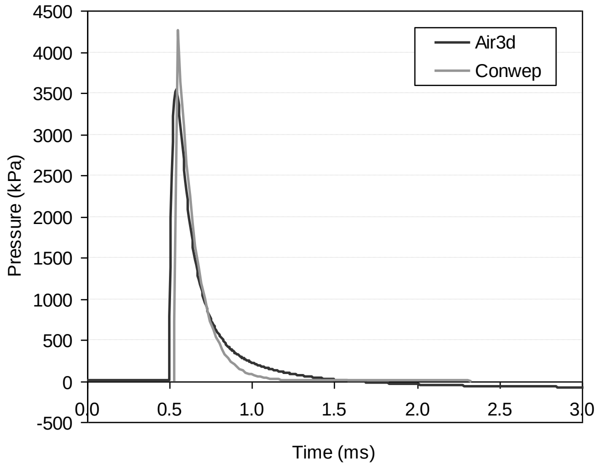


Figure 4: Air3d and CONWEP prediction of the blast reflected pressure–time history resulting from the detonation of 1.0 kg Ammonite charge at 1.0 m stand-off distance

3.2 Specimen UR2

During Vietnam Trial 2, specimen UR2 was the only unretrofitted panel investigated, while the remaining three were polyurea coated. As described in the previous sections, all the specimens tested had surface dimensions of 1700 × 1000 mm and were 60 mm thick, with one layer of 5 mm reinforcement at 100 mm spacings, spread in both directions. The displacement measurement devices were attached to the bottom surface of the specimens.

After the explosion, specimen UR2 deflected globally with a permanent downward displacement of 19.2 mm. The maximum inward (↓ downward) and outward (↑ upward) displacements of the panel, as recorded by the mechanical devices were 37.3 and 7.9 mm, respectively. This maximum inward displacement was 62% of the panel's thickness. The crack formation indicated only a single flexural crack and there was no indication of shear crack formation (neither diagonal nor direct shear), especially at the supports. The visual examination of the fixtures indicated no elongation on the horizontal bolts, and the steel cleats and plates remained affixed to the specimen and the test frame.

The crack patterns formed on the top (blast-facing) and bottom surfaces of the specimen are presented in Figure 5, where the crack propagation profiles have been highlighted. There were three major cracks on both the top and bottom surfaces. On the top surface, the most critical crack line (No. 3) was located close to the mid-span and recorded an average width of 1.65 mm. This crack line recorded widths of 2.0 mm in many locations. The remaining two crack lines recorded average widths of 0.80 and 0.48 mm, respectively.

Crack line No. 3 on the top surface also penetrated through the thickness of the panel to form the most severe crack line on the bottom surface (Figure 5b). This crack line recorded an average width of 1.19 mm on the bottom surface. It stretched through the full length in the transverse direction on both surfaces of the panel. The remaining two crack lines were only minor, with average crack widths in the range of 0.1 mm. On both surfaces, all the crack lines propagated in the transverse direction of the panel. As it can be observed from Figures 5a and 5b, there was no occurrence of concrete scabbing or spalling on the specimen.

(a) (b)

Figure 5: The crack patterns and crack widths on the: (a) top, and (b) bottom surface of specimen UR2

3.3 Specimen PUB4

Specimen PUB4 was similar to specimen UR2 except that it was coated with 4 mm of polyurea on its bottom (non-blast-facing) surface. Upon the application of blast load, specimen PUB4 deflected globally with a permanent downward displacement of 14.3 mm. The maximum inward (↓ downward) and outward (↑ upward) displacements of the panel recorded by the mechanical devices were 33.3 and 9.4 mm respectively. Similar to the previous case, the crack formation indicated only flexural cracks and there was no indication of shear crack formation (neither diagonal nor direct shear). The visual examination of the fixtures indicated no elongation on the horizontal bolts, and the steel cleats and plates remained affixed to the specimen and the test frame.

The polyurea coating applied on the bottom face of the panel was inspected next and was found to be generally undamaged (Figure 6). The coating was entirely intact and was still bonded well with the concrete underneath. Only minor bulges or protuberances were noticed in some locations on the surface of the coating, as shown in Figure 6. The polyurea layer was subsequently removed to expose the surface of concrete underneath. It should be mentioned that the polymer was bonded very well with the concrete surface even after the blast that it had to be scrapped off the concrete surface. This was also evident from Figure 7b where the scrapped polyurea left greyish patches of the material on the concrete surface in some locations.

The crack patterns formed on the top (blast-facing) and bottom surfaces of the specimen are presented in Figure 7. There were three cracks on the top surface, with the most critical crack located closest to the mid-span and recording an average width of 0.30 mm. This crack line stretched through the full length in the transverse direction of the panel. The remaining two crack lines recorded average widths of 0.11 and 0.16 mm, with only one stretching the full length of the panel. Meanwhile, more crack formations were observed on the bottom (polyurea coated) surface of the panel. However, only two out of the seven cracks stretched through the full length of the shorter span. One of the two was the most severe crack with a width of 0.31 mm, and similar to the previous panels, it was located closest to the centreline of the panel. The average widths of the remaining cracks measured between 0.02 mm and 0.15 mm.

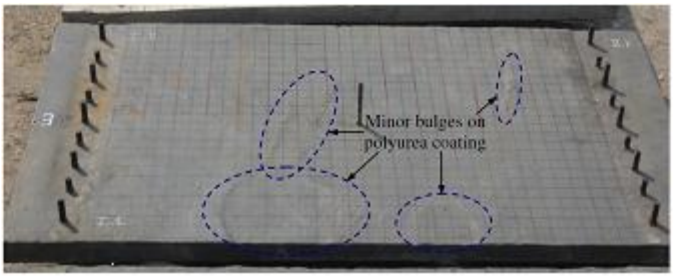
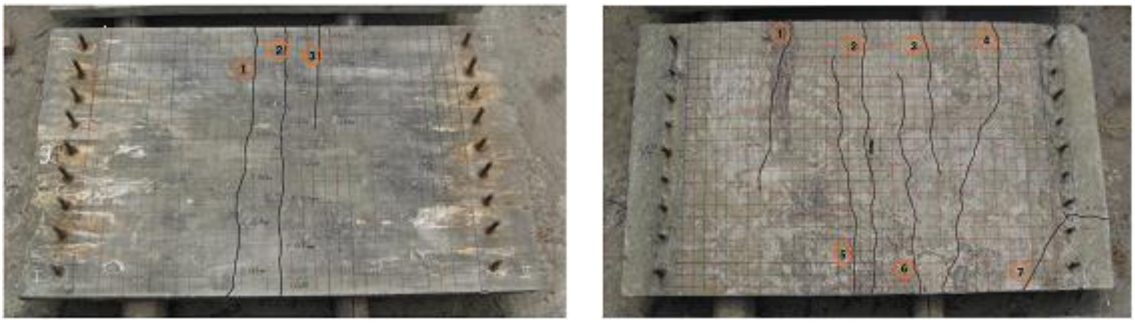


Figure 6: Polyurea coating on the bottom surface of specimen PUB4 (after load application)

It can be observed that the polyurea coating resulted in a significant reduction in the level of damage of the panel, especially in terms of crack formation. While the crack widths recorded on both surfaces of specimen UR2 were severe, these were reduced to only minor cracks in specimen PUB4. It should also be noted that the cracks formed on specimen PUB4 were only surface cracks that did not penetrate through the thickness of the specimen, unlike the cracks formed on specimen UR2.



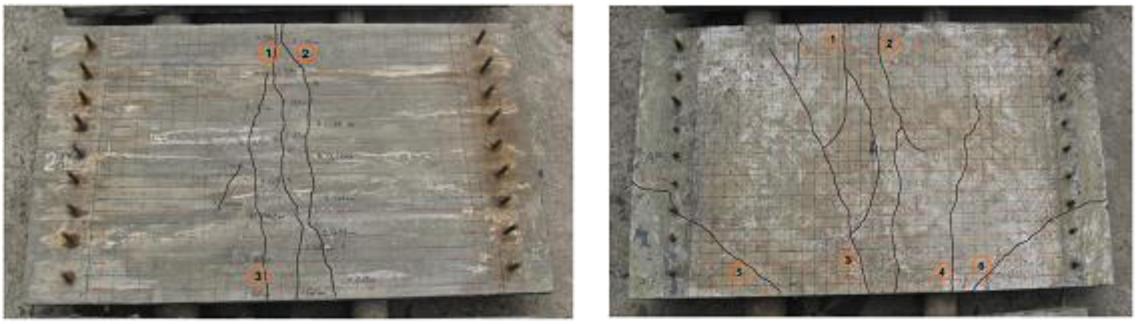
(a) (b)

Figure 7: The crack patterns and crack widths on the: (a) top, and (b) bottom surface of specimen PUB4

3.4 Specimen PUB10

After the explosion, specimen PUB10 deflected globally with a permanent downward displacement of 13.9 mm. The maximum inward (↓ downward) and outward (↑ upward) displacements of the panel were 30.1 and 8.9 mm respectively. Similar to specimen PUB4, the polyurea coating applied on the bottom face of panel specimen PUB10 was also undamaged. Only minor bulges were observed in some locations on the surface of the coating. The coating was entirely intact and was still bonded well with the concrete underneath.

The crack patterns formed on the top (blast-facing) surface and bottom surface of the specimen are presented in Figure 8. There were three main cracks on the top surface, with the most critical crack located closest to the mid-span and recording an average width of 0.40 mm. This crack line stretched through the full length of the span. The remaining two crack lines recorded average widths of 0.16 and 0.24 mm, with only one crack stretching the full length of the panel. Six crack formations were observed on the bottom (polyurea coated) surface of the panel. However, only two out of the six cracks stretched through the full length of the shorter span. The most severe crack (No. 3) had an average width of 0.48 mm. The widths of the remaining cracks at the mid-section of the span measured between 0.15 mm and 0.32 mm.



(a) (b)

Figure 8: The crack patterns and crack widths on the: (a) top, and (b) bottom surface of specimen PUB10

It was noted that on average, the crack widths recorded on specimen PUB10 were marginally larger than those recorded on specimen PUB4, though the thickness of polyurea coating applied on specimen PUB10 was higher. On the other hand, the maximum deflection of panel PUB10 was lower than the maximum deflection recorded in panel PUB4. These observations point towards the need to perform further evaluation on the contribution of an increased polyurea coating thickness on the overall protection offered by the retrofitting scheme. However, it should be noted that the level of damage in specimen PUB10 was significantly lower than that recorded in specimen UR2.

3.5 Specimen PUTB4

Specimen PUTB4 was coated with 4 mm of polyurea on both its top (blast-facing) and bottom surfaces. By volume, it utilises two times the amount of polyurea applied in specimen PUB4 and 80% of that applied in specimen PUB10. However, the mechanism of blast protection in specimen PUTB4 would be considerably different from the previous specimens because in specimen PUTB4, the similar blast pressure would have passed through a layer of polyurea coating prior to impacting the panel.

The permanent downward displacement recorded in specimen PUTB4 was 7.7 mm. Meanwhile, the maximum inward (↓ downward) and outward (↑ upward) displacements of the panel were 22.5 and 5.0 mm, respectively. These values were considerably lower than those recorded in the other panels. For example, the maximum displacement of specimen PUTB4 was reduced by 40% and 32% in comparison to specimens UR2 and PUB4, respectively, which indicates that the application of the protective coating on the blast-facing face of the panel does contribute positively in enhancing its capacity to withstand the applied impulsive loadings.

The subsequent inspection of the polyurea coating applied on the top surface of the specimen indicated that it was generally undamaged. The coating was entirely intact and was still bonded well with the concrete underneath. Meanwhile, similar to the other panels, the polyurea coating on the bottom surface indicated localised protuberances in some locations (Figure 9). The coating was also noticed to have torn at one location (top left in Figure 9), but this tear occurred when the steel cleat attached to the coating was removed, and not during the blast loading period. Similar to the top layer, the bottom layer coating was entirely intact and was still bonded well with the concrete surface underneath. The polyurea layers were subsequently removed to expose the surface of the concrete underneath. Similar to the other panels, the polymer layers were very well bonded with the concrete surface even after the blast and had to be scrapped off the concrete surface. The scrapped polyurea left greyish patches of the material on the concrete surface in some locations (Figure 10).

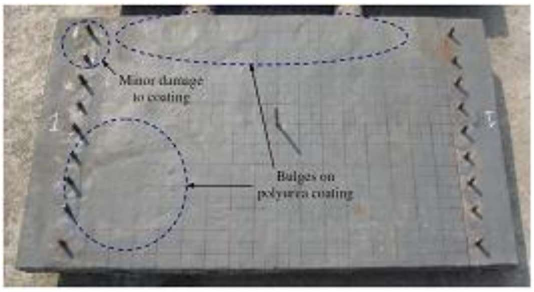
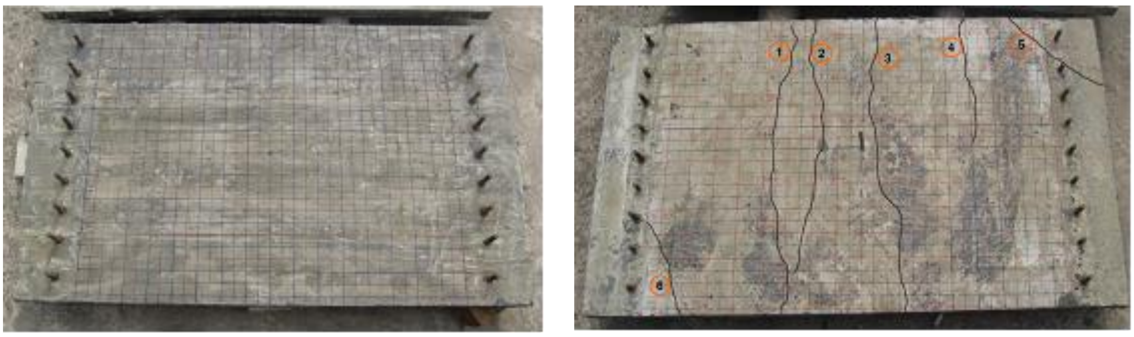


Figure 9: Polyurea coating on the bottom surface of specimen PUTB4 (after load application)

When the top surface of the concrete in specimen PUTB4 was exposed, it was revealed that there was literally no crack formation on this surface (Figure 10a). This discovery was significant and indicates the beneficial effects of applying the protective coating on the blast-facing face of the panel. Although six crack formations were observed on the bottom surface of the panel, only two of these cracks stretched through the full length of the shorter span. Unlike the other panels, the most severe crack line was found to be located away from the centreline of the span, and recorded an average width of 0.36 mm (Crack No. 1 in Figure10b).



(a) (b)

Figure 10: The crack patterns and crack widths on the: (a) top (no crack formation was observed), and (b) bottom surface of specimen PUTB4

3.6 Overall Findings

Table 2 compares the maximum inward, outward and permanent displacements of the various specimens. In general, it can be deduced that the polyurea material bonded very well with concrete, even with minimal surface preparation. The concrete surfaces were only dusted prior to applying the polyurea spray. The polyurea layers in all cases experienced very minor damage due to the explosion. They were still very well bonded to the concrete surface after the application of the blast loads and had to be scrapped off the surface of the concrete.

Table 2: Summary of maximum displacements of the test panels

Specimen ID	Maximum inward (downward) displacement (mm)	Maximum outward (upward) displacement (mm)	Permanent inward (downward) displacement (mm)
UR2	37.3	7.9	19.2
PUB4	33.3	9.4	14.3
PUB10	30.1	8.9	13.9
PUTB4	22.5	5.0	7.7

Among the three polyurea coated RC panels, it was observed that specimen PUTB4 suffered the least amount of damage from the same blast source. Furthermore, the top surface of concrete in specimen PUTB4 did not show any crack formation after the explosion. The main distinction between specimen PUTB4 and the other two retrofitted panels was the presence of a polyurea layer on the blast-facing face of the panel. However, when comparing between specimens PUB10 and PUB4, it can be observed that the increase in the thickness of the coating did not offer significant reward in reducing the level of damage sustained. Based on the findings and observations, it can be stated that the polyurea coating technique provides a feasible solution to protect RC structures being subjected to blast effects.

4. Conclusions

This paper presented the methodology, implementation and findings of the experimental blast trials undertaken on four RC panels, to evaluate the effectiveness of using polyurea coatings to enhance the blast resistance of structural elements. The configuration of the test panels, the details of the instrumentations employed during the blast testing and the test preparations and procedures were discussed. The findings of the experiments have been presented and discussed comprehensively. These findings suggest that the proposed technique of using polyurea coating to retrofit RC structural elements is practicable and feasible to enhance the capacity of structures against blast loading. A higher level of protection was provided when the protective coating was applied on the blast-facing face of the structure. It was also observed that the bond between concrete and the polymer did not damage even after the the application of the blast loads. These findings assert the possibility of using the proposed technique as a practical alternative to the existing techniques in strengthening structures being subjected to blast effects, and thus contributing towards sustainability through protection and preservation of existing critical infrastructures.

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