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A Review on the Use of Polymeric Coatings for Retrofitting of Structural Elements against Blast Effects

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ABSTRACT: An increase in terrorist activities, accidental explosions and the proliferation of weapons in recent years has made infrastructures across the globe more vulnerable to extreme impulsive loadings. Both in research and in practice, strengthening by the use of composite laminates such as fibre reinforced polymers (FRP) has been the most popular technique for strengthening structures facing the risk of blast loads. Alternatively, in recent years, researchers have been working towards the possibility of using elastomeric polymer coatings for structural retrofitting applications since they show the potential in enhancing blast and impact resistance of structural elements. However, the knowledge on this technique is still at its infancy considering that the related information on its application is very limited and tends to be scattered. This paper attempts to address the gap by providing a review on the current state of this novel technique in retrofitting structural elements against the explosive effects of blast. The discussions provided are mainly focussed on the application of this technique on masonry, steel and composite structures and systems, as well as on reinforced concrete (RC) panels. The areas in which more in-depth research is required, and where there exist a critical lack of knowledge, have also been highlighted.

Keywords: Blast loading, Polymer coating, Polyurea, Structural elements, Structural retrofitting.

1 INTRODUCTION

The main distinction of blast load from the other types of extreme loads is its impulsive nature. Blast loads usually act for a very short duration (usually in milliseconds) but transmitting very high impulsive pressures ($10^1 – 10^3$ kPa). Considering that most existing structures were not designed to withstand extreme loads of blast and impact in nature, such dynamic loads can result in the failure of the main load bearing members in the structure, and consequentially in the collapse of the entire structure. The total collapse of a structure will result in larger damage in terms of human casualties and economic loss.

The ASCE Report on the 1995 Oklahoma City Bombing (ASCE, 1996), as quoted by Malvar et al. (2007), mentioned that an estimated 87 % (153 out of 175) of the occupants of the collapsed section of the Alfred P. Murrah Building were casualties, compared to only 5 % (10 out of 186) casualties in the uncollapsed section. This indicates that in case the structure had the capacity to withstand the extreme loads, the casualties could have been much lesser (Malvar et al. 2007).

On the other hand, the disintegration and propellation of debris and fragments of structural elements, windows and others fittings, equipments, vehicles and any other non-secured items during an explosion pose additional risk to the occupants of a structure. This occurrence causes more casualties and damages rather than the pressure, heat or other events related to the blast itself (Knox et al. 2000, Davidson et al. 2005). Considering the threats present during an explosion, the need to enhance the capacity of the structural members to withstand the destruction from such extreme loading events becomes essential. There has been considerable interest among structural and material engineers in recent years to seek and develop innovative and cost-effective protective solutions to mitigate the damage caused by such extreme loading events. The efforts include modifications to structural analysis and design procedures, as well as design codes, besides identifying new structural retrofitting and strengthening methods.

One of the areas that have been considered is the possibility of using elastomeric polymer coatings for structural retrofitting applications, since these coatings show potential in enhancing blast and impact resistance of structural elements. However, the knowledge on this technique is still at its infancy considering that the related information on its application is very limited and tends to be scattered. This paper attempts to address the gap by providing a comprehensive review on the application of this novel technique in retrofitting structures against the explosive effects of blast.

2 PRESENT RETROFITTING PRACTICES AND THEIR LIMITATIONS

One of the approaches to enhance the resistance of the structural elements (i.e. columns, beams, walls and slabs) to blast loads is by increasing their mass and ductility. These may be done by using additional concrete and reinforcement for concrete structures, and by using larger sections for steel structures, or alternatively, by using external strengthening techniques such as composite laminates or steel jacketing. Extensive experimental and numerical investigations have been undertaken in recent years to evaluate the performance of existing structural strengthening applications to withstand blast effects.

Most of the present practices in strengthening of structures against blast loads are focussed on the utilisation of composite laminates such as fibre reinforced polymer (FRP) applications (Malvar et al. 2007, Buchan & Chen 2007). This can be attributed to the improved properties of modern FRP composites, which include its high strength to weight ratios and their corrosion free characteristics, as well as the cost effectiveness when compared to other strengthening techniques such as using bonded steel plates (Buchan & Chen 2007). Research and the subsequent application of this technology have largely focussed on the use of carbon fibre reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP), even though other materials such as aramid fibre reinforced polymers (AFRP), aramid/glass (A/G) hybrid applications and GFRP rods have also been studied. Malvar et al. (2007) and Buchan & Chen (2007) have undertaken comprehensive reviews and summarised the findings from researches in recent years, in the area of strengthening and retrofitting of structures subjected blast effects.

While a lot on focus have been dedicated towards identifying new approaches to enhance the efficacy of structural retrofitting against blast effects, and improvising the properties of existing strengthening materials, there is yet to be any specific and cost effective technique or material established to be considered as principally suitable in retrofitting structures facing the risks associated to blast and impact effects. A similar observation was provided by Buchan & Chen (2007), who also suggested that a more systematic direction is required to determine the advantages and limitations of the various strengthening applications.

Even though FRP have indicated to be a potential solution, they do come with their own set of limitations. For example, in some situations, the excessively thin sheets of the material require an impractical number of layers or wraps on the structure to function effectively. Besides, in cases of close-in detonations, the strain demand of the strengthening material is beyond the strain capacity of FRP (Malvar et al. 2007). Another drawback of FRP strengthening is that it may lead to a premature brittle failure, such as through FRP de-bonding and FRP-concrete cover delamination when subjected to such high intensity loading.

3 APPLICATION OF POLYMERIC COATINGS FOR STRUCTURAL RETROFITTING

One of the limiting factors in the performance of composite laminates such as FRP and other retrofitting materials is the material's low failure strains (Malvar et al. 2007). This characteristic plays a more significant role in cases of high strain rate impulsive loadings. Consequently, materials which possess higher strain to failure property would be expected to perform better in retrofitting structures subjected to blast and impact. This is where the elastomeric polymers can play a part as a potential structural retrofitting material. These materials, specifically polyurea and polyurethane, in most cases posses elongation capacity of 100 % or more, and can be applied easily by just spraying on to the face of a structural element. This technique capitalises on the elastomeric, high strain capacity, high ductility and strength of the polymer coatings, as well as on the ability of the coating layer to act as a shield in containing debris and fragments from the blast.

The stress-strain behaviour of both polyurea and polyurethane exhibit significant rate dependence (Roland et al. 2007, Sarva et al. 2007, Yi et al. 2006). Polyurea is an elastomeric-thermoset polymer with highly ductile nature, and is derived from the reaction of an isocyanate component and a synthetic resin blend component. The chemical composition and stoichiometry of a polyurea contributes significantly to its properties and behaviour (Roland et al. 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. On the other hand, polyurethanes, first introduced by Otto Bayer in 1937 as a substitute for rubber (Yi et al. 2006), are products from the reaction of a monomer with at least two isocyanate functional groups with another monomer containing at least two alcohol groups, in the presence of a catalyst. Thermoplastic polyurethane is an attractive material within the polyurethane family considering the possibility of modifying its microstructure, and thus the mechanical behaviour the material. Thermoplastic polyurethanes are highly elastomeric, possess the resistance to abrasion, impact and weather (Yi et al. 2006).

The application of these polymers for blast retrofitting of structural elements is rather a new approach. Different types of polymers were initially experimented on concrete masonry units (CMU). The achievement in these initial efforts prompted more systematic research to be undertaken lately to exploit the potential of these materials. Table 1 provides a summary of research in using this technique to retrofit different types of structural elements. The subsequent sections of this paper provide a comprehensive review on the research undertaken and the application of this innovative retrofitting technique on various structural elements.

Table 1. Summary of research analysing the use polymeric coatings for structural retrofitting

Studies	Structural elements	Category of research*	Type of experiment	Finite element package
Knox et al. (2000)	CMU walls & light weight steel structures	A, E	Blast trials & laboratory tests	-
Davidson et al. (2004)	CMU walls	E	Blast trials	-
Hoo Fatt et al. (2004)	CMU wall	A, N	-	ABAQUS
Davidson et al. (2005)	CMU walls	E, N	Blast trials	LS-DYNA
Baylot et al. (2005)	CMU walls	E	Blast trials	-
Amini et al. (2006)	Steel plates	E	Reverse ballistic	-
Ackland et al. (2007)	Steel plates	E, N	Blast trials	AUTODYN
Bahei-El-Din & Dvorak (2007a)	Composite	N	-	LS-DYNA
Bahei-El-Din & Dvorak (2007b)	Composite	N	-	LS-DYNA
Bahei-El-Din & Dvorak (2008)	Composite	N	-	LS-DYNA
Hrynyk & Myers (2008)	Unreinforced masonry walls	A, E	Static	-
Chen et al. (2008)	Steel plates	N	-	LS-DYNA
Tekalur et al. (2008)	Composite	E	Shock tube	-
Raman et al. (2008)	RC panels	N	-	LS-DYNA
Raman et al. (2009)	RC panels	N	-	LS-DYNA
Amini et al. (2010a)	Steel plates	E	Reverse ballistic	-
Amini et al. (2010b)	Steel plates	N	-	LS-DYNA

*A: Analytical; E: Experimental; N: Numerical

3.1 *Application on Masonry Structures*

The Air Force Research Laboratory (AFRL) at Tyndall Air Force Base, USA initiated the research into this area in 1999. Initial studies looked at the application of this technique to strengthen masonry structures, as well as light weight steel structures against the effects of blast (Knox et al., 2000). The positive outcome from this investigation paved the way for this technique to be evaluated on other types of structural materials. The following sections provide a more detailed description on the application of this technique on unreinforced and lightly reinforced masonry structures.

3.1.1 *Research at Tyndall Air Force Base, USA*

The AFRL at Tyndall Air Force Base, USA have been conducting experimental and theoretical research towards identifying and developing lightweight expedient applications for strengthening structures and non-structural elements against blast loading. A wide range of strengthening materials including composite materials was initially investigated. Although these composite materials demonstrated the capacity to enhance the resistance of structures against blast, their widespread application in practice is challenged by the availability of cost and time efficient techniques in applying the material to the structure (Davidson et al. 2005). AFRL began experimenting with sprayed-on polymers in 1999, initially with a commercially available spray-on truck bed liner. The material was tested on unreinforced masonry walls, and the outcome proved to be promising. It was able improve the blast resistance of the masonry wall by containing the debris, even though it had undergone large deflections and was severely fractured (Knox et al. 2000).

The success from the initial testing led to the evaluation of another 21 off-the-shelf polymers to identify the most suitable for further testing programmes. Of these, seven were extruded thermoplastic sheet materials, 13 were spray-on materials and one was a brush-on material (Davidson et al. 2005, Davidson et al. 2004, Knox et al. 2000). Although the extruded thermoplastics were advantageous in terms strength and stiffness, they were abandoned due to the inconvenience in installation. The brush-on polymer was rejected due to its weak, brittle and lengthy curing time. The 13 spray on polymers consist of seven polyurethanes, one polyurea and five polyurea/urethane hybrid. A spray-on pure polyurea was selected based on its strength, flammability and cost, to undergo further testing to evaluate its performance under blast effects (Davidson et al. 2005, Davidson et al. 2004, Knox et al. 2000).

Three full scale explosive tests were undertaken in the first phase of the study. One reaction structure consisting of two unreinforced masonry walls were constructed for each test, except for the third test where four walls were evaluated. Polyurea coatings were applied on the interior face of one of the walls, in the first two tests. In the third test, polyurea coatings were applied on the interior face of all the walls and on the front (blast-facing) face of only one of the walls. The findings indicated that the polyurea coatings on the interior face of the walls were able to increase their resistance to blast effects. Besides, the coatings were also observed to be beneficial in the aspects of fragmentation prevention. While the application of polyurea on both sides of the wall did enhance the capacity of the wall against the loads, it was deemed inadequate to address the extra cost (Davidson et al. 2004).

In the subsequent study, seven explosive tests were conducted involving a total of 12 polymer coated masonry walls, which included four walls with a window or door opening (Davidson et al. 2005). The failure mechanisms that were observed include: (1) propagation of stress waves through the wall, fracturing parts of the system; (2) fracturing of the front face shell of some of the masonry blocks in the initial stages of the blast due to the shock load pressure; (3) tearing of the polymer coatings, which may be due to the high localised stresses in the mortar/block interfaces nearest to the supports; (4) fracture in the front face of shell of some of the blocks resulting from flexural compression; (5) polymer coat tearing in tension when the wall flexes and mortar joints cracks; and (6) loss of bond of the polymer coat at the boundary to the host structure. In order for better understanding of the failure and fracture mechanism, finite element (FE) analysis of the walls' behaviour was undertaken by using LS-DYNA code (Davidson et al. 2005). Davidson et al. (2005) concluded that in the selection of the retrofitting material, consideration should be given to both stiffness and elongation properties of the material, with the key consideration to the elongation capacity.

3.1.2 *Analytical Work by Hoo Fatt et al. (2004)*

Based on the findings from the blast trials at the Tyndall Air Force Base, Hoo Fatt et al. (2004) developed an equivalent single degree-of-freedom (SDOF) model to predict the dynamic response of polymer-retrofitted concrete masonry units (CMU) walls when subjected to blast effects. The SDOF model was based on coupling of the bending and membrane resistance of the CMU (Hoo Fatt et al., 2004).

The predictions from the model were then compared with the numerical findings from the non-linear FE package, ABAQUS. The studied 3.05 x 3.05 m CMU wall was 0.194 m thick and was coated with 2.1 mm polyurea. The CMU wall recorded a maximum deflection of approximately 178 mm during the blast trials which imparted a peak pressure of 5.8 kPa associated to a pulse duration of 20 msec. The similarity between the prediction of deflection from the analytical model and the FE code was found to improve as the maximum deflection of the wall increased to be between 1 to 2 times of the wall thickness (Hoo Fatt et al., 2004). Hoo Fatt et al. (2004) suggested that since the SDOF model was based on the bending and membrane resistance of the wall, it should only be applied when the wall's maximum deflection is expected to be higher than its thickness.

3.1.3 *Baylot et al. (2005)*

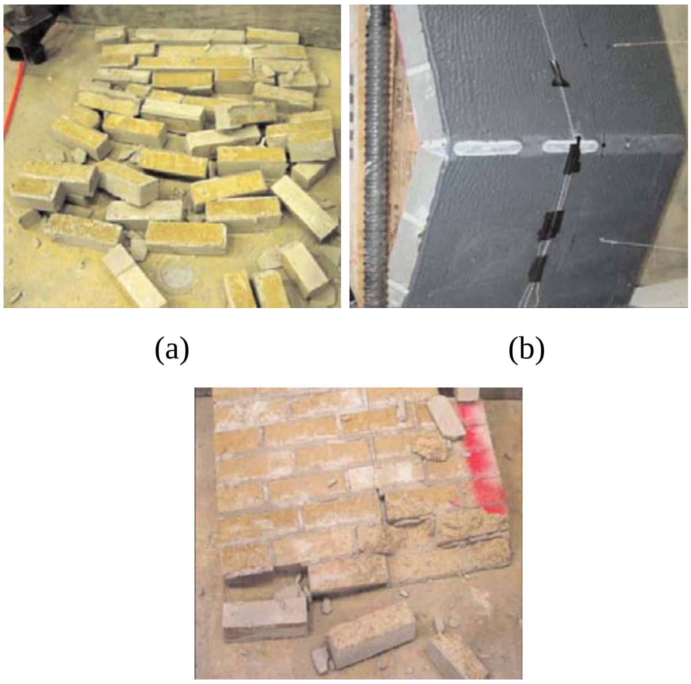
Baylot et al. (2005) evaluated three types of retrofitting applications on 1/4-scale models of typical 203 mm CMU walls. The first consist of 1 mm thick E-glass FRP attached to the back face of the wall, and the second type consist of a two-part sprayed-on polyurea coating on the back face of the wall, with an approximate thickness of 3.2 mm. In the third option, a 1 mm thick hot-dipped galvanized steel sheet was placed at the back of the CMU wall. The plate was not attached to the wall, but was overlapped by 76.2 mm at the top and bottom of the reaction structure. Although all the retrofitted walls failed during the tests, the polyurea coating and the FRP were successful in containing the fragments and debris inside the structure (Baylot et al. 2005). This finding validates one of the main advantages of the polymer coating retrofitting application, i.e. in preventing of debris and fragment from propelling and injuring the occupants inside the structure.

3.1.4 *Research by Hrynyk and Myers (2008)*

Hrynyk & Myers (2008) on the other hand evaluated the capacity of two schemes, i.e. a spray-on polyurea retrofit and a GFRP-polyurea retrofit system (GFRP grid embedded within the polyurea), in strengthening framed unreinforced masonry (URM) infill walls against blast effects. While the aim of the research was to investigate the blast resistance of the retrofitted URM walls in comparison to control URM walls, the loadings were applied in static conditions in order to simplify the testing program as well as to allow the findings to be extended for other out-of-plane retrofit applications. Thus the findings of the research should not be taken as a direct indication of the performance of the retrofitted walls in blast conditions, rather as a relative representation of the effectiveness of the retrofitting techniques in terms of blast mitigation (Hrynyk & Myers 2008).

A total of 8 URM walls, of which 2 were constructed of clay brick (CL) units, 3 were constructed of CMU and the remaining 3 were constructed from masonry units produced from wood-fibre fly ash (WFFA) material. The walls were tested under one-way arching action, replicating the loading case where the walls are effectively nonslender in one direction only. One control unretrofitted wall as well as two retrofitted walls by using the retrofitting scheme described earlier, was constructed for each type of URM materials, except for the CL wall where only the GFRP-polyurea retrofitting option was evaluated. A 3 mm polyurea layer was sprayed-on to the walls that were retrofitted with polyurea exclusively, whereas the GFRP-polyurea retrofit was approximately 10 mm thick in CMU and WFFA walls, and 19 mm thick in the CL wall. The spray-on polyurea was overlapped by 51 mm for anchorage to the surrounding RC framing members for both retrofitting techniques (Hrynyk & Myers 2008).

An airbag system was used to impose the quasi-static pressure. The failure modes that were observed for the walls can be divided into three categories: (1) instability failure; (2) flexural failure; and (3) failure of polyurea anchorage by debonding or shearing at the boundary locations. Figure 1 shows the: (a) debris scattering of the control wall; (b) polyurea coated CMU wall undergoing flexure; and (c) collapse of the GFRP-polyurea retrofitted WFFA wall. While all the control URM walls failed by some form of wall instability due to the out-of-plane deflection, the polyurea coated CMU wall failed in flexure after undergoing extreme out-of-plane deflection and breaching the polyurea layer at mid-span, as shown in Figure 1b. The polyurea layer acted as a buffer by containing the fragments and debris of the masonry materials after the collapse of the wall (Hrynyk & Myers 2008).



(a) (b)

(c)

Figure 1. Wall failure mechanism: (a) debris scattering of the control wall; (b) polyurea coated CMU wall undergoing flexure; and (c) collapse of the GFRP-polyurea retrofitted WFFA wall, from Hrynyk & Myers (2008).

The most common failure mode of the retrofitted walls were by polyurea anchorage failure at the boundary locations, where polyurea overlap was observed to debond and separate from the RC beam element, after initial cracking and minor crushing of the mortar at the wall boundaries. Hrynyk & Myers (2008) discussed that the application of the polyurea retrofit contributed significantly towards enhancing the deformability of the wall, and thus improving the energy dissipation mechanism. While both retrofitting schemes exhibited improvements in energy dissipation capabilities, the polyurea retrofit was superior in terms of energy dissipation, besides its ability to act as a shield in containing the debris and fragment of the collapsed walls (Hrynyk & Myers 2008).

3.2 *Strengthening of Steel Structures and Plates*

More recently, polymer coatings particularly polyurea have also been investigated for strengthening of steel structures and plates subjected to blast and projectile impacts. One of the main contributions in this area is towards the defence application such as in strengthening of armoured vehicles and marine fleets against impulsive loads. Similar to masonry structures, the polymers were applied as a coating onto the steel elements.

3.2.1 *Research at Defence Science and Technology Organisation, Australia*

The Defence Science and Technology Organisation (DSTO) of Australia undertook assessment on the influence of polyurea coating on the blast resistance of steel plates (Ackland et al. 2007). D36 (36 mm thick) steel plates were used in this investigation where a bare plate and two plates with different thicknesses of polyurea coatings were tested with explosive charge of 0.5 kg pentolite sphere at 61 mm stand-off. Besides the experimental testings, 3D FE analyses were also performed by using the explicit non-linear FE code, AUTODYN. Both the experimental and numerical findings established that the polyurea coating improved the blast resistance of the steel plates, where the polyurea coated plates recorded much lower permanent deformation compared to the bare plate. Besides, the plate which was coated with a thicker polyurea layer indicated much lower deformation compared to the plate with thinner layer of polyurea coating (Ackland et al. 2007).

3.2.2 *Research by Amini et al. (2006, 2010a & 2010b)*

Amini et al. (2006, 2010a,b) reported the findings of comprehensive research undertaken at the University of California at San Diego, to assess the effect of polyurea coating on the dynamic response of steel plates, through a newly developed test known as the reverse ballistic test. Besides experimental investigations, Amini et al. (2010b) also performed detailed numerical analyses by using LS-DYNA. The primary focus of their study was on the significance of the coating location with respect to the loading direction, i.e. either the coating on the loaded face or the unloaded face of the plates, could impart optimal blast protection.

It was established that the polyurea coating would result in positive outcomes, both in terms of failure mitigation and energy absorption, only when it is applied on the back face or the unloaded face of the plate. It was also indicated that the application of the coating on the blast-receiving face of the plate would in turn increase the destructive effect of the blast, thus elevating the damage of the steel plate (Amini et al. 2006, 2010a,b).

Amini et al. (2010a) discussed that the stiffness of polyurea increases significantly when subjected to increasing pressure, and when confined polyurea is loaded in compression, its stiffness can be enhanced by 10-20 folds. This results in polyurea to achieve better impedance match with the steel plate thus causing more energy to be transmitted to the plate, and subsequently initiating the damage factors on the plate. However, when polyurea coating is applied on the non-impulse-facing face, the steel plate is loaded first, prior to part of the energy being transmitted to the polyurea coating. This process compresses the polymer and thus increasing its stiffness, and subsequently the amount of energy captured and damped due to its viscoelastic properties. Based on these findings, Amini et al. (2010a) concluded that when polyurea coating is applied on the blast-facing face of the sample, its presence may actually enhance the destructive effects of the blast, thus promoting the failure of the steel plates, depending on the bond properties between the two materials at the interface zone (Amini et al. 2010a).

3.2.3 *Chen et al. (2008)*

Chen et al. (2008) studied the effectiveness of polyurea as a blast mitigation tool for steel components. Explicit LS-DYNA code was used to evaluate the behaviour of polyurea coated steel plates under blast loads in comparison with unstrengthened steel plates. Steel plates of 1500 × 1500 mm were evaluated in this numerical investigation where the thickness of the plate were varied between the different models. The control specimen was 6.35 mm thick whereas six plates were coated with polyurea as shown in Table 2. Four of the plates were coated on the back surface with 6.35, 12.7, 19.05 and 25.4 mm polyurea respectively, while another panel was coated with 6.35 mm on the front (blast-facing) surface. The last polyurea coated panel was coated on both surfaces with 3.175 mm polyurea (Chen et al. 2008). Meanwhile, another four panels were modelled with thicker steel than the control, to match the weight of the polyurea coated panels in weight, when the coating thickness was increased.

All the plates were supported at all edges to restrain their transverse and rotational deformations. The various panels modelled and analysed by Chen et al. (2008) is shown in Table 2. The steel plate and polyurea coatings were modelled as solid elements, and the contact between these two elements was modelled as a perfect bond. The blast pressure from a spherical 34 kg TNT charge placed at 1.0 m stand-off was computed using an in-house CFD code, and was applied onto plates using a total of 3600 individual pressure-time histories. The main parameters evaluated between the various models were maximum displacement and kinetic energy (Chen et al. 2008).

Table 2. The different panels modelled and analysed by Chen et al. (2008)

Model	Panel thickness (mm)	Polyurea coating thickness (mm)	Coating location	Comment
1	6.35	-	-	-
2	6.35	6.35	Back	Similar weight as Model 6
3	6.35	12.7	Back	Similar weight as Model 7
4	6.35	19.05	Back	Similar weight as Model 8
5	6.35	25.4	Back	Similar weight as Model 9
6	7.215	-	-	-
7	8.08	-	-	-
8	8.945	-	-	-
9	9.81	-	-	-
10	6.35	6.35	Front	-
11	6.35	3.175	Both	-

The results obtained indicated that in all except one case, the bare steel plates were fractured at all edges. The polyurea coated panels also exhibited severe fractures along their edges. The effectiveness of the increasing polyurea thickness was evaluated by comparing their performance with the performance of the bare steel plate with corresponding weight. It was noted that while Model 3 exhibited lower kinetic energy compared to Model 7, the displacement of Model 3 was larger than that of Model 7. When the thickness of the polyurea was increased to 12.7 mm in Model 4, both the maximum displacement and kinetic energy was lower than those recorded in the corresponding Model 8. However, a similar finding was not observed in Model 5 and Model 9 (Chen et al. 2008).

While the variation in coating location, either on front (blast-facing) or back face, did not cause any major effect to the maximum displacements recorded in the panels, the plate which were coated on the blast-facing face indicated the lowest kinetic energy when compared to the panels which were coated on the back or on both faces. Due to this finding, it was concluded that application of polyurea coating on the blast-facing side would be more desirable. Besides, it was also stated that an optimal ratio between the polyurea and steel required to ensure effective blast protection for a prescribed loading should be established, since there exist a limit in terms of polyurea thickness versus their effectiveness in terms of the deflection and kinetic energy (Chen et al. 2008).

3.3 *Application on Composite Sandwich Systems and Structures*

The application of this technique on composite systems and structures is rather new compared to the other types of structures. While the polymer material is usually applied as a coating in masonry and steel structures, their most common application in composite systems can be divided in three categories: (a) as outer soft skins sandwiching a hardcore; (b) as an inner soft core sandwiched by two hard skins; and (c) as an interlayer or intermediate material between the skin and the core of the system. The following examples show practical representation of the approaches.

3.3.1 *Bahei-El-Din and Dvorak (2007a & 2007b)*

Bahei-El-Din & Dvorak (2007a,b) investigated the behaviour of composite sandwich plates with a polymer interlayer under blast loads, where a detailed assessment on the influence of underlying material and their properties on the through thickness propagation of the blast waves, were conducted by using LS-DYNA code. One conventional and two modified composite sandwich plate designs were modelled in the study. The conventional plate was designed as a closed cell foam core construction, whereas an interlayer of polyurea or polyurethane was included in each of the modified designs. The polyurea was represented as a strain rate and pressure dependent elastic-plastic material, while the polyurethane was modelled as a rate-independent hyperelastic material. The modified designs were known to perform well under impulsive loading due to the significant stiffening effect of the polymeric materials under high strain rates. All the plates were 57.2 mm in thickness and their cross-section are as shown in Figure 2. Assumed blast pressure of 100 MPa with a positive phase of 0.05 msec were applied on the outer facesheets of the plates, with the negative pressure phase neglected (Bahei-El-Din & Dvorak 2007a,b).

The findings showed that the conventional plate underwent extensive thinning in the central foam core and this layer was separated from both the outer (nearer to blast) and inner facesheets of the plate. Meanwhile, both the modified designs exhibited significantly reduced deformations. Considerable displacement of more than 80 % of the plate thickness was recorded of the debonded outer interface of the conventional plate. Remarkably, this was reduced by almost a factor 5.0 in the modified designs. In the case of the inner interface, although the displacements were initially larger in the modified designs than in the conventional plate, these were eliminated at later durations. The interlayers in the modified designs were also beneficial in reducing the compression in the core by about 50 %, with the polyurethane interlayer showing marginally better performance. The maximum strains recorded by the modified designs were also significantly reduced from the 0.98 % recorded in the conventional design, to 0.70 % and 0.62 % in the modified design with polyurea and polyurethane interlayers respectively (Bahei-El-Din & Dvorak 2007a,b).

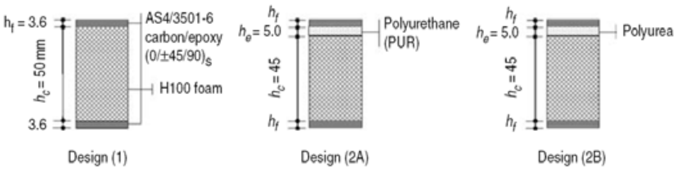


Figure 2. The cross-sections of the conventional and modified composite sandwich plates studied by Bahei-El-Din & Dvorak (2007b).

One of the main advantages of using the polymer layers for structures subjected to impulsive loadings is in terms of energy absorption and dissipation mechanism. This was evident in this investigations. The peak total kinetic energy dissipated in both the modified designs was only 35 J, compared to 60 J in the conventional design. Meanwhile, the total strain energy of 40 J in the conventional plate was reduced to 15 J in the plate with polyurethane interlayer, which was attributed solely for the reduction in foam crushing. Meanwhile, the total strain energy dissipated in the modified design with polyurea interlayer was 25 J (Bahei-El-Din & Dvorak 2007b)..

Although the findings of Bahei-El-Din & Dvorak (2007b) indicate that the performance of polyurethane was marginally superior to polyurea, it should be noted that the polyurethane material in the study was modelled as a rate-independent material. This is unlike the findings by Yi et al. (2006) and Sarva et al. (2007) where polyurethane were shown as a material which demonstrate strong rate-dependency in its stress-strain behaviour.

3.3.2 *Tekalur et al. (2008)*

Meanwhile, Tekalur et al. (2008) evaluated the blast resistance of layered and sandwiched composite materials by using a shock tube. The composite materials investigated comprised of conventional E-glass vinyl ester (EVE) composite as well as layered and sandwich composite structural system incorporating polyurea. The blast loading was applied over a circular region of 76 mm at the centre of the plates. A total of 5 configurations of plates were investigated, which included 1 plain-woven composite system, 2 layered composite system and 2 sandwich composite structures. The plain-woven composite panels were 6 mm thick whereas the layered panels were 12 mm thick (6 mm polyurea and 6 mm EVE). The layered composites were tested in various directions, i.e. with the polyurea facing the blast (referred as PU/EVE) and EVE facing the blast (EVE/PU). Two types of sandwich composite structures investigated included one with a soft core of 6 mm polyurea sandwiched between 2 hard skins of 3 mm EVE (referred as EVE/PU/EVE) and the other consisted of a hard core 6 mm EVE sandwiched between two soft skins of 3 mm polyurea (PU/EVE/PU). The blast resistance of these panels were evaluated through macroscopic visual examination, microscopic visual examination and real time measurement (Tekalur et al. 2008).

In the macroscopic visual examination, the panel was considered to be "completely failed" if the permanent deformation produced is more than the 2.5 times the thickness of the panel. It was recorded that while the plain-woven composite panels failed at an incident shock pressure of 0.62 MPa, the PU/EVE layered panel failed at a significantly higher incident shock pressure of 0.76 MPa. Meanwhile for the EVE/PU/EVE sandwich system, no damage was observed on the macroscopic scale though the plates were subjected to significantly higher pressure (1.17 MPa) than those subjected on plain-woven composite and PU/EVE layered material. Meanwhile, under a similar pressure the PU/EVE/PU panel indicated failure as wrinkles on the blast facing face and shear failure on the composite core (Tekalur et al. 2008).

Based on the microscopic examination, it was discussed that the damage modes of the plain-woven composite were in terms of fibre breakage and interface failure. Meanwhile the damage modes in PU/EVE, with polyurea facing the impact, were mainly tensile failure. Under blast loads, the interface between polyurea and transverse layer was weaker than the interface between polyurea and longitudinal fibre directions. When the loading direction was reversed with EVE on the impact side, compressive dominated failure mode (fibre crushing) was observed. Similar to PU/EVE, the bond between polyurea and transverse fibre was weaker than the bond between polyurea and longitudinal fibre direction. The enhanced blast resistances of the layered panels was attributed to the energy dissipation through the non-linear and highly rate dependent characteristics of polyurea as well as the energy dissipation due to the failure of the polymer-composite interfaces (Tekalur et al. 2008).

Tekalur et al. (2008) discussed that when polyurea was on the impact side, as in the PU/EVE panel, the resistance of the composite lamina in direct contact with the polyurea is strengthened against compressive and shear failure. Therefore, additional energy from the blast is required for initiate damage in the panels when compared to the plain-woven composite panel. However, when the composite lamina faces the blast such as in EVE/PU panel, the composite lamina undergoes severe compressive stress and begins to fail, thus reducing the overall strength of the structure. Since the polyurea layer was placed on the tensile face of the panel, the enhancement of blast resistance of this panel was lower than that of the PU/EVE panel (Tekalur et al. 2008).

It was also observed that the layered and sandwich construction recorded lower deflections compared to the plain composite plates. Similar to previously discussed, the PU/EVE construction indicated lower damage area and took a longer duration to reach the failure point when compared to the EVE/PU construction. Generally, it was found that the enhancement of the blast resistance of the glass fibre composite was more prominent when the polyurea layer was applied on the impact facing face of the system. Furthermore, it was also found that the composite sandwich system constructed by sandwiching a soft layer (polyurea) in between two composite hard skins (EVE) exhibited the best blast resistance characteristics when compared to layered and plain composite panels (Tekalur et al. 2008).

3.4 *Application on Concrete Structures*

Though concrete is the most widely used construction material in today's world, the research into the area of using polymeric coatings to retrofit reinforced concrete (RC) structures against blast effects can be considered as the least among the different types of structural materials. As described previously, most of the present practices in strengthening of concrete structures against blast loads are focussed on the utilisation of composite laminates such as FRP. Considering the positive impacts of the polymeric coatings in retrofitting masonry, steel and composite structures, its application on various types of concrete structures, is a natural progression considering the widespread use of concrete in the construction industry.

The authors have been involved in a research endeavour to investigate the possibility of using polymer coatings in retrofitting RC structures facing the risk of blast loads. The following sections provide a brief discussion on the published findings of the authors (Raman et al. 2008, 2009).

3.4.1 *Raman et al. (2008 & 2009)*

The authors undertook a numerical analysis to evaluate the application of polyurea coating to retrofit a 2190 × 1190 × 140 mm RC panel, which was subjected to a blast from 5000 kg of TNT at 40 m stand-off (Raman et al. 2008). The bare RC panel was tested under a full scale blast load from a similar charge during the 2007 Woomera blast trials (Tanapornraweekit et al. 2007). The same panel was then modelled and analysed by using the Lagrangian formulation of the explicit FE code LS-DYNA. The results of the FE analysis were then calibrated with the experimental findings.

Subsequently, modified designs of the same panel were modelled by applying polyurea coatings, by varying thicknesses and location of the coatings. The polyurea coatings were modelled as solid elements by adopting the quasi-static and high strain rate properties from Bahei-El-Din & Dvorak (2007a,b). Raman et al. (2008) reported that by applying a 5 mm coating on the non-blast-facing (tension) face of the panel, the maximum displacement of the panel was reduced by approximately 30 %, when compared to the unretrofitted panel. The displacement was further reduced when the thickness of the coating was increased to 10 mm or when both faces of the panel were coated with 5 mm polyurea. Besides, a reduction in the maximum tensile stress recorded on the back face of the panels was also noticed when the panel was coated with the polyurea layers (Raman et al. 2008).

The subsequent investigation by the authors was undertaken by using a 1700 × 1000 × 60 mm RC panels which were reinforced with 5 mm bars at 100 mm spacing in both directions, on the tension face only (Raman et al. 2009). The FE analysis was undertaken as pre-experiment analysis of the panel's behaviour, i.e. to simulate an experimental blast trial that will be conducted by the authors at a later stage in Vietnam. While the experimental trials would only involve one unretrofitted and three polymer coated panels, in the FE analysis, seven panels (one unretrofitted and six polymer coated panels) were modelled and analysed by using the Lagrangian formulation of LS-DYNA. The polyurea coating was represented by 4-node shell elements by using the MAT_PIECEWISE_LINEAR_PLASTICITY constitutive model, whereas the concrete elements were modelled as 8-node solid elements by using the MAT_CONCRETE_DAMAGE_REL3 constitutive model. Similar to the previous study, the quasi-static and high strain rate properties of polyurea was adopted from Bahei-El-Din & Dvorak (2007a,b). The panels were subjected to the blast load from a 2 kg Ammonite charge which was suspended at 1.6 m stand-off from the top of the panel (Raman et al. 2009).

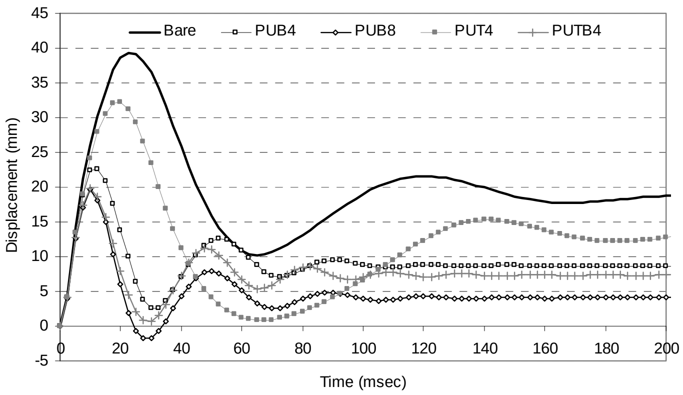


Figure 3. The displacement-time history of the unretrofitted panel (Bare) compared to various retrofitted panel as investigated by the authors (Raman et al. 2009).

The findings of the FE analysis indicated that both the maximum displacements of the panel were reduced by more than 40 % when a 4 mm polyurea coating was applied on the tension (non blast-facing) face of the panel, i.e. for the case of PUB4 versus Bare, as shown in Figure 3. However, further reduction in the maximum displacement was not significant when the coating thickness was increased to 8 mm (PUB8) or when both faces were coated with 4 mm polyurea (PUTB4). The authors also found that that the polyurea coating tends to be more effective in controlling the displacement and deformation of the panel when it is coated on the tension face of the panel, when compared between applying a 4 mm coating on the bottom face of the panel (PUB4), or on the top (blast-facing) face of the panel (PUT4) (Raman et al. 2009).

4 DISCUSSION

While it can be observed from the previous sections, as well as from Table 1 that the technique of using polymeric coatings for retrofitting of structural elements has been gaining interest among researchers in recent years, it should also be mentioned that there is much more to be done to enhance the body of knowledge in this area to enable a successful and wholesome transition of this technique from research to practice. One of the areas that is yet to be investigated in detail is the bond properties and behaviour of the polymer with different types of structural materials. While Amini et al. (2010b) have used a trial and error approach to replicate their experimental findings, more in-depth research is required to investigate the bond behaviour of this materials at the transition zone of various structural materials before a range of feasible bond models can be developed.

Another area that should be further examined is the influence of location of coating on the blast mitigation capacity of the main structure. The findings of Amini et al. (2006, 2010a,b) are quite noteworthy in this aspect. First of all, it was established that the coating would result in positive outcomes, both in terms of failure mitigation and energy absorption, only when it is applied on the back face or the unloaded face of the plate. Amini et al. (2006, 2010a,b) have also indicated that the application of the coating on the blast-receiving face of the plate would in turn increase the destructive effect of the blast, thus elevating the damage of the steel plate. The underlying phenomenon of this occurrence has also been investigated, analysed and discussed satisfactorily (Amini et al. 2010a,b).

Secondly, this finding is a digression from those by Chen et al. (2008). They found that, while the location of coating does not play a significant role in affecting the maximum displacement of the tested plates when perfect bond is assumed between the two materials, the application of the coating on the blast-facing face is ‘preferred’ since they result in a reduction in the induced kinetic energy (Chen et al. 2008). Similarly, Tekalur et al. (2008) also indicated from his investigation that the enhancement of the blast resistance was more prominent when the polyurea layer was applied on the impact-facing face of the system, albeit it was for glass fibre composite system. Tekalur et al. (2008) have also provided a detailed discussion on the basis of this finding. Considering these distinctions in findings, it is clear to the authors that this area should be further scrutinised, and the governing physics behind phenomenon should be explicitly analysed and deliberated before a conclusion can be drawn.

In situations where the coating is applied on the blast-facing face of a structural element, then it is essential to evaluate the propagation of the blast waves through the thickness of the polymer coating before it contacts the structure. While the thickness of the applied coating is usually a small fraction when compared to the dimension of the structural element, the convergence (or the divergence) of the pressure waves as it passes through the coating, and subsequently impacting the structural element should be studied thoroughly. Another possible outcome is that the polymer coat may tear off at the first impact of the pressure waves on the structure, i.e. on the polymer layer.

The contribution of the polymer coatings in terms of absorption and dissipation of the high energy imparted during an explosion is another area which requires detailed assessment. Bahei-El-Din & Dvorak (2007a,b), Chen et al. (2008) and Amini et al. (2010a) have investigated this aspect and have indicated favourable results. However, more detailed analysis on the fundamentals governing this mechanism is required for this technique to be optimised comprehensively.

Besides, as it can be observed from Table 1, the assessment of this technique under real-life blast loading is critically lacking, especially for steel, composite and concrete structures. Most of the researches undertaken thus far for these types of structures are focussed on numerical methods and on scaled or simulated laboratory experiments. While it is not denied that laboratory experiments such as through a shock tube or a high energy impact loading may be able approximate a scaled blast load, the behaviour of a structure under real-life blast effects is very much influenced by the environment and surrounding of the structure. Taking these factors into account, the authors strongly believe that a more systematic and comprehensive experimental investigation, coupled with detailed numerical analysis is essential prior to arriving at any major deduction about the positive notion on this technique.

5 CONCLUDING REMARKS

This paper provided a review on the current state of research in using polymer coatings as a structural retrofitting tool to enhance the blast and impact resistance of structures. Application of this technique on masonry, steel, composite as well as RC structures have been discussed. While it can be observed some research has been undertaken to exploit this technique for the benefit in retrofitting structures, there are still a lot uncertainties that requires further detailed investigation. As discussed in the previous section, there is acute lack of information and knowledge in terms of the bond properties between the polymer and retrofitted structural material. None of the research undertaken thus far has addressed this issue deeply. Besides, significant efforts should also be provided to investigate the properties of polymers at high strain rates. Nevertheless, it should be noted that this technique has indicated the potential to be exploited as a novel structural retrofitting technique especially for structures facing the risks of blast and impact.

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