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ELASTOMERIC POLYMERS FOR BLAST AND BALLISTIC RETROFITTING OF STRUCTURES

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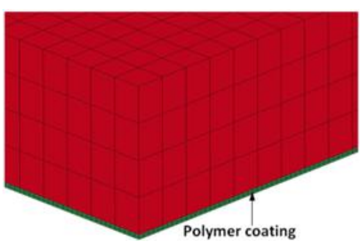
Graphical abstract



Abstract

In many parts of the world, terrorism has become a major threat to nations, and terrorist activities and accidental explosions have been directed towards the destruction of buildings and critical infrastructures. As a result, almost every new development requires the consideration of safety and security aspects such that even a new building incorporates protective engineering features in its design. In this aspect, researchers have been investigating the use of elastomeric polymers (such as polyurethane and polyurea) for structural retrofitting applications due to attractive characteristics and morphology exhibited by these materials. This paper provides a review on this novel approach of strengthening structural elements and systems to enhance their capacity against blast and ballistic threats. The discussions in this review have been focussed on the application of this technique on the most widely used structural systems of masonry, concrete, metallic and composite structural systems. This technique offers an alternative to existing strengthening techniques in protecting structures against the risks of blast, ballistic and impact loads.

Keywords: Blast loading, ballistic loading, polyurea, polyurethane, retrofitting, coating

Abstrak

Di serata tempat di dunia, keganasan telah menjadi satu ancaman yang besar kepada kebanyakan negara, dan aktiviti-aktiviti pengganas dan letupan tidak sengaja terarah kepada kemusnahan bangunan dan infrastruktur yang kritikal. Akibatnya, hampir setiap pembangunan baru memerlukan pertimbangan dari aspek keselamatan, di mana pembinaan sebuah bangunan baru juga diperlukan untuk menggabungkan ciri-ciri kejuruteraan perlindungan dalam reka bentuk. Dalam aspek ini, para penyelidik sedang mengkaji penggunaan bahan polimer elastomer (seperti poliuretana dan poliurea) untuk aplikasi penguatan struktur di mana ia disokong oleh kecirian dan morfologi menarik yang dipamerkan oleh bahan-bahan ini. Kertas kerja ini memberikan ulasan mengenai pendekatan novel ini untuk pengukuhan elemen dan sistem struktur untuk meningkatkan keupayaannya terhadap ancaman beban letupan dan balistik. Perbincangan dalam ulasan ini telah difokuskan kepada aplikasi teknik ini ke atas sistem struktur yang paling luas digunakan iaitu sistem-sistem struktur perbataan, konkrit, logam dan komposit. Teknik ini menawarkan alternatif kepada teknik penguatan yang sedia dalam melindungi struktur terhadap risiko beban-beban letupan, balistik dan hentaman.

Kata kunci: Beban letupan, beban balistik, poliurea, poliuretana, penguatan, salutan

1.0 INTRODUCTION

Events occurring around the globe for the past two decades, such as terrorist activities, accidental explosions and proliferation of weapons, have literally "forced" asset owners and managers to consider protective measures and technologies in the design and construction of critical infrastructures. Safety and security researchers have found it to be an obligation to invest in developing innovative and cost effective protective solutions for structures that may be subjected to the possibility of such threats. Blast, ballistic and impact loads, unlike other types of quasi-static and dynamic loads, act within very short time duration while transmitting very high impulsive pressures [1-5]. Huge losses of lives, injuries and failures of buildings have been incurred in many parts of the world due to such extreme loading events. Loss of life and injuries can be due to many reasons, such as direct blast effect, collapse of structures, impact of debris and smoke. Bomb explosion causes catastrophical damage to the building's external and internal structural frames. Preventing or reducing the structural damage in a building in such cases tends to be in the minds of protective structural engineers at the analysis and design stage. Maintaining a sufficient stand-off distance is one of the most effective "passive" technique to minimize the damage due to an explosion and this can be achieved by providing barriers, walls, fences, boulders and other landscaping features [2-3].

On the other hand, several advanced engineering materials, such as Ultra High-Strength Concrete (UHSC), fibre reinforced polymers (FRP), steel plating and jacketing, geotextile fabric application, woven polypropylene and elastomeric coatings have been investigated as active protective applications for structural elements [1-8]. In recent times, a considerable amount of work has been undertaken on researching the viability of utilising (unreinforced) elastomeric polymers (such as polyurea and polyurethane) to develop innovative and cost effective protective solution to mitigate the damage from such extreme loads. This is mainly due to the attractive characteristics and morphology of the polymers, such as high elongation capacity, ease of application, high energy absorption capacity, high resistance in aggressive environments, ability to act as a protective layer for structural materials, thermal stability, chemical resistance, and their possible contribution towards the overall durability and sustainability of the structure [7-10].

This paper discusses on the work undertaken by various researchers on the utilisation of elastomeric polymers for retrofitting application of structural elements and systems subjected to blast and ballistic threats. The emphasis of the discussions will be on applying this technique on the most common construction materials and systems such as masonry, concrete, steel and composite structures.

2.0 BLAST AND BALLISTIC LOADINGS ON STRUCTURES

Discussion on the fundamentals of blast and ballistic loadings on structures would be imperative prior to the examination of feasible protective techniques to counter it. An explosion occurs as a resultant of a rapid large scale release of stored energy in parts as thermal radiation, ground shocks and in shock waves [1, 6]. Those lead to several types of damages in structures such as damage to the external façade and the load bearing structural frame of the building, collapse of non-load bearing structural elements such as walls, fragmentation of concrete, glass windows and other fixtures, sudden failure of the critical life-safety system, and progressive collapse of the structure. Generally blast loads differ from the other types of loadings due to their impulsive behaviour, since they transmit very high impulsive pressure (10^2 – 10^4kPa) usually within short time duration (in milliseconds) [1,8]. In addition, the geometrical configuration of the structure, and the orientation of the structure with respect to the detonation and condition of the ground surface also highly influence the magnitude of the peak pressure and peak loads. Though a range can be provided, it is very difficult to quantify the peak pressures since the weight of explosives can vary from small hand bag or back pack, to a large truck load. Moreover in the cases of close-in detonations, shock waves generated can be up to 30 times the speed of sound, undergo pressure up to 20 GPa, and experience strain rates up to 10^8 s^{-1} depending on the charge weight and characteristics of the target material [11].

Primarily, two parameters define the severity of an explosion, the weight of the explosive charge and the stand-off distance to the target. Figure 1 shows a typical blast pressure-time history profile. At arrival time t_A after the explosion, the pressure at the target will suddenly increase up to a peak value, P_{so}, over the ambient pressure P_o. The positive pressure then reduces to the ambient value during positive pressure duration, t_d, after then where the pressure is further reduced by forming a partial vacuum of peak pressure, P_{so}^- and finally it returns to ambient pressure at the time $t_A + t_d + t_d^-$.

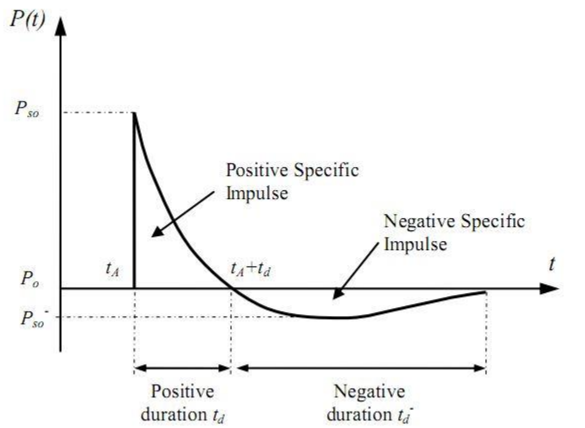


Figure 1 Blast pressure-time history profile [1]

In general, blast loads results in high-intensity lateral dynamic pressure, being applied rapidly over a large area of the structure. On the other hand, ballistic impacts generates localised failure of the target and the mechanism of real ammunition initiates by creating a ductile cavity on the target and enlarging it until the ammunition penetrates completely or loses momentum completely [9, 10]. Most conventional firearms propel the projectiles in nose velocity ranging from 500 to 1300 ms^{-1}, which can vary depending on the type of firearm. During the process of penetration, the target structure undergoes variety of processes, such as the propagation of elastic, plastic and hydrodynamic waves, plus local and gross deformations resulting from frictional heating [12].

The working process and the projectile penetration phenomena depend on several criteria, such as the behaviour of the material during the process, and the structural dynamic effects associated with the impact and penetration process such as the angle of occurrence of the impact, the material characteristics and configuration of the target structure and the penetrator, and the initial velocities of the projectiles [10, 12]. In order to investigate the mechanism and the ability of the protective materials in reducing the destructive effect due to projectiles' impact, investigation on the behaviour of the material and the ammunition penetration process at recommended velocities should be undertaken [10].

3.0 ELATOMERIC POLYMERS FOR STRUCTURAL RETROFITTING

One of the governing limitations of composite retrofitting materials is failing under low strains [5]. But considering that high elongation capacity is one of the key factors in cases of high strain rate impulsive loadings like blast and ballistic, elastomeric polymers are envisaged to play better performance in retrofitting under such situations. Elastomeric polymers like polyurea and polyurethane, which in many instances exhibit elongation capacity of 100% or more, can be applied easily by spraying, brushing or bar-coating on the surface of structural elements [7, 8]. In addition to these, other benefits of polyurea and polyurethane in comparison to other polymer variations, include their light-weight characteristics, fire- and abrasion-resistant nature, bonding ability with many substrates such as concrete, masonry, steel, and timber, as well as their environmental- and long-term stability [7, 8, 13].

Polyurea is an elastomeric polymer derived from the reaction of an isocyanate (–NCO) component and a polyamine (having two or more primary amino groups $–NH_2$). Polyurea exhibits highly ductile nature and significant rate dependency due to their viscoelastic nature. It can be categorized as a typical large strain elastic-plastic material [7, 8]. Polyurea coatings have been used widely as truck bed liners, as well as for coatings of pipelines due to their high durability and water tightness [7]. Recent research have indicated that this material may contribute positively towards enhancing the capacity of structures to withstand the effects of impulsive loadings.

On the other hand, polyurethane polymers are products from the reaction of diisocayante (a monomer with at least two isocyanate (–NCO) functional groups) with diol (another monomer containing at least two alcohol (hydroxyl, or –OH) groups), in the presence of a catalyst [8]. Today, polyurethane polymers cover an extremely wide range of applications, such as foams in bedding materials, thermal insulation, adhesives, the manufacture of tyres, as well as in structural elements. Polyurethane is an attractive material due to the possibility of modifying its microstructure and it leads to wide range of mechanical behaviour. Thermoplastic polyurethane is also highly elastomeric, and exhibit resistance to impact, abrasion and weather.

4.0 STRUCTURAL RETROFITTING UNDER BLAST AND BALLISTIC LOADINGS

The application of elastomeric polymers for retrofitting of structures against blast and ballistic effects is a new approach in recent times. Different types of polymers were analysed initially and findings from those investigations highlighted the potential of using elastomeric polymers such as polyurea and polyurethane for such applications. Table 1 summarises the work of various researchers to investigate the use of polymer coatings for structural retrofitting under blast and ballistic loadings. This paper provides a review of the investigations undertaken and the findings of these work.

At the present stage, most work on polymer retrofitted structures has been focused towards the application of distributed dynamic impulsive loads caused from a blast event. Limited attention has been given to evaluate the capability and behaviour of elastomeric polymer-retrofitted structures under localised impact loadings induced from ballistic events, and those studies in this area have focused more on metallic structures (steel and aluminium plates).

Table 1 Summary of investigations undertaken to analyse the use of polymer coating for structural retrofitting under blast and ballistic loadings

Structural element	Studies	Polymer type
Masonry structures	Knox *et al*. (2000) [7]	Polyurea and polyurethane
	Davidson *et al*. (2004a, 2004b, 2005) [14,15,16]	Polyurea and polyurethane
	Hoo Fatt *et al*. (2004) [17]	Polyurea
	Baylot *et al*. (2005) [18]	Polyurea
	Hrynyk and Myers (2008) [19]	Polyurea and GFRP-Polyurea
Concrete structures	Raman (2011) [8]	Polyurea
	Raman *et al*. (2012a, 2012b, 2014) [20-22]	Polyurea
Metallic Structures	Amini *et al*. (2006, 2010a, 2010b, 2010c, 2010d) [23-27]	Polyurea
	Ackland *et al*.(2006, 2013) [28,29]	Polyurea
	Chen *et al*. (2008) [30]	Polyurea
	Roland *et al*. (2010) [31]	Several including Polyurea
	Sayed *et al*. (2009) [32]	Polyurea
	Xue *et al*. (2011) [33]	Polyurea
	Mohotti *et al*. (2013a, 2014a, 2013b) [9,10,34]	Polyurea
Composite structural systems	Bahei-El-Din *et al*. (2006) [35]	Polyurea
	Bahei-El-Din and Dvorak (2007a, 2007b, 2008) [36-38]	Polyurea and Polyurethane
	Tekalur *et al*. (2008) [13]	Polyurea
	Grujicic *et al*. (2010, 2012a, 2012b) [39-41]	Polyurea

4.1 Application on Masonry Structures

The use of unreinforced masonry (URM) walls is common in construction in many parts of the world. Typically, URM exhibit low flexural capacity and are highly susceptible to undergo brittle failure when exposed to out-of-plane loads like blast loads [7, 19]. During an explosive event, fragments and debris from walls, glasses, windows, other fixtures, and equipment cause major damage to occupants of the building, and ensuring that the exterior walls remain intact without fracturing during such events is a key tactic to defeat this threat. To overcome this problem, the Air Force Research Laboratory at Tyndall Air Force Base, Florida initiated and undertook series of experiments to investigate the use of polymer materials to prevent fragmentation of light weight structural elements like concrete block walls and temporary light weight buildings [7]. Davidson *et al*. [14-16] reported on explosive tests on masonry walls (2.24 m × 3.66 m × 0.2 m) with wide range of composite materials including elastomeric polymers. The success of the initial experiments led to further investigations and another 21 prospective polymer-based materials were evaluated. This included seven extruded thermoplastic polymers, 13 spray-on polymers and one brush-on polymer [7, 14, 16]. Knox *et al*. [7] reported that although the failure of structural elements still occurred, the elastomeric material remained intact and was able to contain the resulting debris.

Based on the findings obtained by Knox *et al*. [7], Hoo Fatt *et al*. [17] developed a Single-Degree-of-Freedom (SDOF) model to evaluate the dynamic response of masonry structures subjected to impulsive loadings. They suggested that the model was only applicable when the maximum deflection of the wall is expected to be higher than the thickness of the wall, since the SDOF model was developed on the bending and membrane resistance of the wall [17]. Meanwhile, Baylot *et al*. [18] conducted a set of experiments that can be used to validate numerical models and to develop engineering tools to predict the response of concrete masonry unit (CMU) walls using three types of retrofitting applications, i.e.: (1) a 1 mm thick FRP layer bonded to the rear face of the wall; (2) approximately 3.2 mm thick spray-on polyurea coated on the back side of the CMU wall; and (3) a 1 mm thick hot-dipped galvanized A-36 steel sheet placed behind the CMU walls. In the third retrofitting application, the steel sheet was not attached to the CMU, but was overlapped by 76 mm onto the reaction structure at the top and bottom using steel clamp plates. Even though most parts of the polyurea retrofitted wall failed during the experiment, the coating was successful at reducing the hazard level inside [18]. This outcome exhibits the advantage of polymer coating retrofitting technique under blast loads.

Hrynyk and Myers [19] analysed the capabilities of several materials to mitigate damage to URM walls under blast effects. Two strengthening techniques were investigated: a spray-on polyurea and a glass fibre reinforced polymer-Polyurea (GFRP-Polyurea) system. Eight URM walls, constructed from three different masonry materials were tested. A 3 mm thick polyurea layer was used in the spray-on polyurea system. The polyurea retrofitting increased the deflection capacity of the infill walls and it led to significant improvement in energy dissipation. Much larger increments of the out-of-plane load capacity were obtained in walls utilising the GFRP-Polyurea retrofit, but the deflection capabilities were decreased in comparison to the un-strengthened URM walls. Although both retrofitting techniques increased the energy dissipation capability, the polyurea retrofitted walls proved to outperform all other type walls on an energy basis [19].

4.2 Application on Concrete Structures

Although concrete is the most widely used construction material worldwide, research conducted in the area of retrofitting of concrete structures using elastomeric polymer coatings can be considered as very limited. Most of present retrofitting techniques are focused on composite laminates such as FRP and its variations. But, considering the behaviour and positive impact of the polymer materials on other types of structural materials, the research and application of this technique on concrete structures is progressing extensively. One of the main advantages of this technique is that it provides cost and time effective retrofitting solution to enhance the blast and ballistic resistance of concrete structures compared to other types of retrofitting.

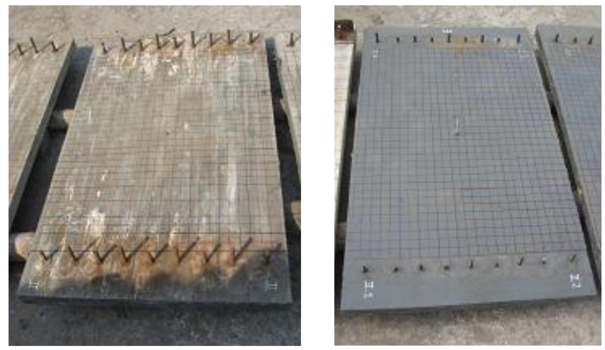
4.2.1 Experimental and Computational Analysis by Raman et al.

Raman *et al*. have been actively researching on the application of elastomeric polymers for retrofitting of concrete structures subjected to blast effects [8, 20-22]. They conducted a series of blast trials to investigate the feasibility of using polyurea coatings in retrofitting of reinforced concrete (RC) slab-like panels. Four RC panels dimensioned 1700 (L) mm × 1000 (W) mm × 60 (T) mm, made of 43 MPa concrete, which were scaled models from a real precast concrete panel with 3000 (L) mm × 2000 (W) mm × 160 (T) mm dimensions, were tested in this study. The panels were reinforced with one layer 5 mm bars spaced at 100 mm at the mid-depth of the panels, in both transverse and longitudinal directions [8, 21, 22]. One of the tested panels was an un-retrofitted control panel, while the remaining three were coated with polyurea with variations in coating thickness and locations. Table 2 shows the assigned designation, and the thickness and locations of the polyurea coatings, while Figure 2 shows the sample of panel PUB4 which was retrofitted with 4 mm polyurea coating on the tension (non-blast-facing) face. All the test specimens were subjected to blast load caused by the detonation of 1.0 kg Ammonite charge placed at 1.0 m stand-off distance. The behaviour and response of all polyurea coated RC panels were analysed and compared with the un-retrofitted panel in terms of deflection, crack formation and damage to the coating layers [8, 21].

Table 2 Summary of the assigned designation, and the thickness and locations of the PU coatings [8, 21]

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

The findings from the experimental trials indicated that the panel which was coated with polyurea on both its faces (PUTB4) experienced the lowest deflection and damage. By comparing the behaviour of the tested specimens, between the panels coated on both sides (PUTB4) and those panels that were coated only on one face (PUB4, PUB10), it was deduced that a higher level of protection was provided when the protective coating was applied on the blast-facing face of the panel. The experimental findings also indicated that the polyurea bonded very well with the concrete even with minimal surface preparations [8, 21].



(a) Top (blast-receiving) face (b) Bottom face

Figure 2 Specimen PUB with 4 mm polyurea coating on the bottom face, from Raman [8]

Subsequently, Raman *et al*. [22] modelled the same panels using the Lagragian formulation of the non-linear finite element (FE) code, LS-DYNA. The polymer coating was analysed with three different material models, namely Mat_Strain_Rate_ Dependent_Plasticity (MAT_019), Mat_Piecewise_ Linear_Plasticity (MAT_024) and Mat_Plasticity_ Polymer (MAT_089). The findings of the numerical analysis compared reasonably well with the experimental findings and Mat_Plasticity_Polymer (MAT_089) was identified as the most suitable constitutive model, among the three material models evaluated, to simulate the characteristics and behaviour of the polyurea coating. The FE analysis was also found to be in agreement with the experimental findings in terms of the location of coating application, i.e. the coating on the blast-facing face was more crucial in reducing the damage sustained by the structure due to the blast [22].

In comparison, in the Tyndall Air Force Base study on blast loaded CMU walls, Davidson *et al*. [15, 16] selected Mat_Piecewise_Linear_Plasticity (MAT_024) to model the polyurea material in their numerical analysis with LS-DYNA after analysing a total of 7 material models. Meanwhile, Aghdamy *et al*. [42] considered 3 material models, namely Mat_Plastic_ Kinematic (MAT_003), Mat_Piecewise_Linear_ Plasticity (MAT_024) and Mat_Rate_Sensitive_Polymer (MAT_141), to model nano-particle reinforced polyurea coating in their study to investigate the behaviour of retrofitted unreinforced CMU walls subjected to blast loads. More recently, Mohotti *et al*. [43] proposed a rate dependent constitutive model for polyurea, by basing on the nine parameter Mooney-Rivlin constitutive model, using high strain rate tensile test data. This constitutive model [43] was also validated against the polyurea sample's experimental data reported by Raman *et al*. [22, 44].

4.3 Application in Strengthening Metallic Structures

Various researchers have investigated on improving the dynamic fracture resistance and enhancing the energy absorption capacity of metallic structures by using elastomeric polymer coatings. These applications are inclined towards defence and military applications such as strengthening of armoured structures and vehicles which experience impulsive forces due to blast, ballistic and collision loads. Several polymer protection techniques have been investigated in recent times. A comprehensive experimental and numerical investigation programmes on polyurea coated steel plates under impulsive loadings were performed by Amini *et al*. [23-27], while Ackland *et al*. [28, 29] studied the behaviour of polyurea-coated D36 steel plates under blast effects through a detailed experimental and numerical analysis programme. On the other hand, Chen *et al*. [30] highlighted that the energy absorption and fragmentation mitigation capacity of a steel-polymer plate can be achieved by increasing the weight of the composite, i.e. by increasing the thickness of the polymer rather than increasing the thickness of steel alone.

In addition to these, various studies have also been undertaken to investigate the ability of polymer material to reduce the destructive effects to metallic structures caused by projectile impacts. Roland *et al*. [31] and Sayed *et al*. [32] undertook experimental and computational assessment on polyurea retrofitted high strength structural steel plates under ballistic effects and highlighted the ability of polyurea coating in enhancing the resistance of high hardness steel (HHS) plates to ballistic effects. Xue *et al*. [33] performed detailed experimental and numerical investigations to study the mechanism of rigid projectile penetration when polyurea was coated on rear face of steel plates. Meanwhile, Mohotti *et al*. [9, 10, 34] performed comprehensive experimental and numerical analysis programmes to study the low and high velocity impact behaviour of polyurea-coated composite aluminium plates. The following sections provide more detailed description on the work performed by these researchers.

4.3.1 Experimental Investigation by Amini et al.

Amini *et al*. [23-25] undertook experimental work to investigate the effect of polyurea coating on the dynamic response of 76 mm diameter steel plates (Two types: Monolithic DH-36 steel plates and steel-polyurea bilayer plates) using reverse ballistic test method. The main focus of this study was on the significance of the coating location with respect to the loading direction, i.e. whether applying the polyurea on the blast receiving face or the back face of the steel plate would contribute more effectively [23-25]. The designed experimental setup was to allow the failure of the test specimens to occur closer to the mid part as deformation localisation and necking, together with radial and circumference crack propagation, as well as to permit petalling and disking [24, 25].

During the experimental investigation, two sets of test were undertaken, and total of 6 and 24 plates were evaluated in the two sets, referred as set-I and set-II [24, 25]. Under set-I, only monolithic steel plates were tested, whereas under set-II, polyurea-steel bilayer plates were evaluated together with several monolithic plates. Further, under set-II, the direction of the impulsive loading (Flat side and Dish side) and the membrane thickness were varied while maintaining the direction of the load only in the flat side under set-I. The damage to the plates were observed and divided in to three categories, i.e.; no failure, moderate failure, and severe failure. If test specimens did not display any cracks but had multiple parallel necks in the central region in some of the plates, they were categorised under no failure category. Meanwhile, if test specimens displayed severe necking with crack initiation and minor petalling, they were categorised under moderate failure category, and if the specimens displayed radial and circumferential cracks with petalling and possibly disking or edge tearing, they were categorised under severe failure category [24, 25]. One of the main observation from this experiment was that, severe failure of the polyurea coated sample (SP-36) was observed with low kinetic energy per unit thickness, although the rim rotation was significantly higher than those recorded in monolithic plates. This finding implies that the application of polyurea on the impulse facing face of the steel plate may not be able to mitigate the failure of the plate [24, 25].

The authors concluded that the stiffness of polyurea increases significantly when it is 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. Although, 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 leads to an increase in its stiffness, and subsequently the amount of energy captured that when polyurea coating is applied on the blast-receiving face of the specimen, 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 [24, 25].

4.3.2 Numerical Findings obtained by Amini et al.

Amini *et al*. [26, 27] performed numerical analysis for the experimental investigations [24, 25] by using the explicit LS-DYNA code. The steel plates were modelled with temperature and rate sensitive constitutive material, developed by Nemat-Nasser and Guo [45], which was incorporated into LS-DYNA [26, 27]. The polyurea was modelled as a viscoelastic, experimentally-based, rate, pressure, and temperature sensitive constitutive material as discussed in Amirkhizi *et al*. [46].

Both Lagragian and Arbitrary Lagragian-Eulerian (ALE) formulations were used to model the monolithic steel plates and ALE formulation was used to model the polyurea-steel bilayer plates since it leads to more stable numerical solutions and was able to predict the experimental findings more accurately. The thickness profiles and principal stretches (radial, hoop and normal stretches) of selected monolithic and bilayer plates evaluated during the experimental stage were compared to the findings obtained from the numerical computations. The numerical models showed that the deformation of the plates was initiated at the rim (the central region was still un-deformed), and then it proceeds towards the central region of the plate until the maximum mid-span displacement is achieved [26, 27].

The inclusion of shear-failure strength for the polyurea-steel interface in the numerical computation was able to simulate the partial de-bonding of the polyurea layers from the steel plates, as observed in the experimental study. Since there was no experimental data to account for the interface bonding strength of the two materials, Amini *et al*. adopted a trial and error approach to replicate the experimentally observed partial de-bonding of the two materials [26, 27]. While the total de-bonding of the polyurea layer was observed when the interface shearing strength value was 100 MPa, and a partial de-bonding was observed when interface shearing strength was 140 MPa. The best correlation to the experimental measurements was observed, when the interface shearing strength was set to 100 MPa. These findings deduced that the steel-polyurea bonding strength did contribute significantly to the thickness profiles and principal stretches [26, 27].

4.3.3 Ackland et al. (2007 and 2013)

Ackland *et al*. [28] reported on the behaviour of one un-retrofitted and two polyurea-coated D36 steel plates under blast effects from the detonation of 0.5 kg pentolite explosive at 61 mm stand-off distance, and also simulated the experiments using a non-linear FE code. Both experimental and numerical findings evidently showed that the polymer layer improved the blast resistance capacity and reduced the permanent deformations of the steel plates, with the higher thickness of polyurea leading to further reduction in the permanent deformations [28].

In a subsequent study, Ackland et al. [29] performed comprehensive experimental, analytical and numerical investigations to study the effect of polyurea coating on mild steel plates under blast effects. Various geometries were obtained with combinations of steel plate thicknesses (4, 5 and 6 mm), polyurea coatings (7.7 and 15.7 mm) and different coating locations (front, back and sandwiched). Two coating thickness were selected to obtain the same areal density for all geometries. In the experimental investigation, Bluescope XLERPLATE 350 grade steel plates were used as a base material and three plate configurations were tested: (1) 6 mm bare steel plate: (2) 5 mm steel plate with 7.7 mm polyurea coating: and (3) 4 mm steel plate with 15.7 mm polyurea coating. The findings obtained deduced that the residual plate deformations increased as the thickness of polymer coating was increased and the de-bonding of the polyurea coating was also observed [29].

Numerical analysis was carried out using ANSYS® AUTODYN®. The modelling was done by providing smaller elements near to the centre of the plate where the highest pressures were expected, and larger elements at the boundaries. The de-bonding of polyurea in the numerical model was obtained by providing breakable bond which had a single element through its thickness of 0.2 mm. The effect of bonding on plate's residual deformation was studied by modelling three types of contacts between the materials: (a) No bond; (b) with an unbreakable bond; and (c) bond with a failure stress of 90 MPa between the plate and the polymer. It was observed in the analysis that the numerical model the of polyurea coatings which were not bonded to the plates performed the best in terms of reducing deformation compared to the unbreakable bond between the polymer and the plate. The authors concluded that it could be due to the way energy is transferred from the explosion to the polyurea coating and then to the steel plate. The findings also showed that the increase in areal density had led to reduction in the final plate deformations. The plates which had front face coating and sandwiched plates did not show any improvement compared to the bare plate and this result was in agreement with the findings of Amini *et al*., since they also concluded that the back face coating is more effective in contributing towards mitigating blast and ballistic loads [23-27]. Ackland *et al*. concluded that for a given areal density, bare steel plate is more effective than a polyurea coated steel plate in terms of deformation control, but this application is more practical than attaching steel in real applications [29].

4.3.4 Xue et al. (2010)

The impact behaviour and penetration of pointed and flat nosed projectile on steel plates with and without polyurea coating was studied by Xue *et al*. [33] through detailed numerical and experimental studies. Contribution of the polyurea layer in mitigating damage was discussed under two types of mechanisms; energy absorption and fracture occurrence in the steel plates. Three types of targets were tested; blank steel plate (4.7 mm), steel plate (4.7 mm) with polyurea back layer (11.18 mm), and sandwich plate made with two identical steel plates (2.38 mm, half of the thickness of steel plate used in previous cases) placing on the both sides of the polyurea layer (11.18 mm). Comparisons were carried out with experimental results and numerical simulation results obtained using LS-DYNA code (modelled with eight-noded hexahedral elements). Several common failure features were observed in the impact experiments. These included dishing and bulging at low impact velocities, petalling at intermediate velocities and shear plugging at high impact velocities [33].

In addition, the two major types of failure mechanisms that were observed for the blank plates during the simulations were shear plugging and petalling. With a series of simulations, it was found that the bond between polyurea and steel is lower in strength compared to the base polyurea, and the estimated failure stresses were 300 MPa and 240 MPa, for the base polyurea and bond respectively. In the impact velocity study, the projectiles were stuck and blank steel plates showed small shear plug closer to the tip of the projectile and petalling at the inner rim of the outer annulus at low impact velocities. Furthermore, blank steel plates indicated large shear plug without petalling at higher impact velocities. For the flat projectiles, when fracture occurs, it resulted in large shear plugs at all impact velocities. When polyurea was coated on the back face of steel plates, the energy absorption capacity of the polyurea was 17% and 26% of the total energy for the point and flat nosed projectiles, respectively [33].

Furthermore, the V50 ballistic limit was increased by 42% and 13% from the blank steel plates to the polyurea coated steel plates for the scenarios above, respectively. However, Xue *et al*. reported that steel plates with sandwich configuration system did not show significant improvement in the ballistic limit and the energy absorption of the steel plate was reduced for the pointed projectiles, while energy dissipation was increased for the flat projectiles. In addition, the polyurea layer displayed a reduced energy absorption capability since it could not be stretched freely due to the steel layer at the back [33].

4.3.5 Experimental and Numerical Investigation by Mohotti et al.

Mohotti *et al*. investigated the behaviour of polyurea coated composite aluminium plates subjected to low and high velocity impact through experimental and numerical investigations [9,10,34]. In the high velocity impact study, steel-tipped 5.56 calibre (5.56 mm × 45 mm) projectiles were fired at fixed velocity of 945 m/s and 10 m away from polyurea coated aluminium plates, and their penetration behaviour through the plates were analysed in detail. Seven different configurations of polyurea coated plates having different total thicknesses were tested, where each configuration consisted of 5 and 8 mm AA5083-H116 aluminium alloy plates, and 6 mm and 12 mm polyurea layers [10].

The effectiveness of polyurea coatings were evaluated by examining the reduction of residual velocity, kinetic energy absorption of the composite, damage mechanism, and the effectiveness of different configurations of polyurea layers. Considerable reduction of the residual velocities were observed in the coated plates, when compared with the uncoated plates and the reduction of residual velocity was higher with increased thickness of the polyurea coatings. Generally, the failure mechanism of the target depends on several parameters such as thickness, material and configuration of the material, impact velocity and projectile geometry. In this composite system, complete ductile crater propagation through the thickness of the composite plate was identified as the major failure mechanism, and it was caused by the ductility of the aluminium alloy and the high elongation capacity of polyurea. The findings also indicated that the local deformation only spread over a radial area of 12-20 mm radius from the crater when plates were coated with polyurea. The average velocity was reduced by 63% when compared between the coated plate and uncoated plate, and the authors highlighted that each additional unit thickness of polyurea can reduce the residual velocity of the projectile by 1.63 times when compared with a unit increment in the thickness of the aluminium layers. Furthermore, the findings also deduced that the thicker polyurea coating on the rear face of the composite contributed positively towards the reduction of the residual velocity and increased the energy absorption capacity. The investigation also indicated that having a thin interlayer with a thicker back layer of polyurea was more effective in reducing the residual velocity of the projectile, rather than having a thick interlayer [10].

In addition to this, Mohotti et al. [9, 34] conducted another set of experiment and numerical analysis to identify the plastic deformation characteristics of polyurea coated composite aluminium plates subjected to low velocity impact. The experiment was undertaken on the same type of aluminium alloy plates (300 mm × 300 mm) with polyurea coatings, and with cylindrical projectiles of 37 mm diameter with a velocity range of 5-15 mm/s. Six different plate configurations were tested with two different base plates (3 mm and 5 mm) and two different polyurea coating thicknesses (6 mm and 12 mm) [9, 34].

The complete test was then modelled in LS-DYNA FE code to validate the experimental findings. During the modelling process, the behaviour of the materials were assumed as rigid perfectly plastic or linear strain hardening and all elements were modelled using 1.00 mm × 1.00 mm × 1.00 mm elements in order to keep the consistency of the different models. In order to check the compatibility of the numerical models, permanent deformations of each test specimens were measured and compared with the values obtained from the numerical analysis, and a good agreement was obtained in the comparisons. The findings indicated that the polyurea coating contributed significantly in reducing the permanent deformations of the aluminium plates [9, 34]. Both experimental and numerical deflection-time histories showed a considerable elastic recovery and spring-back effect. Furthermore, the increase in the thickness of the polyurea layer showed a higher contribution towards reducing the permanent deformation of the aluminium plates, and it was deduced that this polymer can be used as a damping material to coat structures for protection against blast and ballistic impacts [34].

4.4 Application in Composite Structural Systems

The use of composite structural systems, in the construction industry as well as in military application has increased significantly in the last few decades. The application of such system has also become quite common in medium and high-rise constructions. Composite sandwich systems consist of an inner core between two outer layer and those are made with various types of materials such as polymers, steel, concrete, foams and timber. Considering the popularity of these applications in recent times, researchers have started looking at the behaviour and response of these systems under blast and ballistic loadings [13, 35-41]. The following sections provide more detailed descriptions on studies undertaken to investigate the behaviour and contribution of elastomeric polymers in composite structural systems, under blast and ballistic effects.

4.4.1 Tekalur et al. (2008)

Tekalur *et al*. [13] investigated the blast resistance behaviour of composite systems manufactured from E-glass vinyl ester (EVE) and polyurea by using a shock tube. Blast tests were conducted on five different configuration systems by applying blast loads over a circular region of 76 mm at the centre of the plates. The five configurations of plates consisted of two sandwich composites, one plane woven composite and two layered composite systems, as following [13]:

1. 6 mm thick plain-woven composite
2. 6 mm Polyurea / 6 mm EVE (Polyurea side facing the shock blast)
3. 6 mm EVE / 6 mm Polyurea (EVE side facing the shock blast)
4. 3 mm EVE / 6 mm Polyurea / 6 mm EVE (EVE/Polyurea/EVE sandwich)
5. 3 mm Polyurea / 6 mm EVE / 6 mm Polyurea (Polyurea/EVE/Polyurea sandwich)

The blast resistance of these composite panels were examined through microscopic visual examinations and real time measurements. In the microscopic visual examinations, no damage was observed in the EVE/Polyurea/EVE sandwich system at a significantly higher incident shock pressure (1.17 MPa), while the rest of the composite systems failed under lower pressure (around 0.7 MPa). The findings also indicated that higher enhancement of blast resistance to the composite system was provided when the polyurea layer was applied on the impact facing face of the plate. Furthermore, when polyurea was applied on the strike face, it provided strengthening effects against compressive and shear failure, and additional energy was required to initiate damage in the system. In addition, the system of polyurea core sandwiched by two EVE skins exhibited the highest blast resistance characteristics among tested composites, and it showed 100% enhancement of blast performance while the layered composites showed 25% [13].

4.4.2 Bahei-El-Din et al. (2006), and Bahei-El-Din and Dvorak (2007a, 2007b and 2008)

The behaviour of conventional and modified sandwich plates subjected to blast loadings were investigated by Bahei-El-Din *et al*. [35], and Bahei-El-Din and Dvorak [36-38] using non-linear FE code, LS-DYNA. In total, three types of thin interlayer materials (polyurethane, polyurea and closed cell polyethylene elastomeric foam) were interlayered in between face sheets, and the behaviour of sandwich plates under simulated blast loading were analysed. Due to the scope of the present paper, only sandwich plates which contained polyurethane and polyurea are discussed. All plates were tested under a peak blast pressure of 100 MPa with an extended time period of 5.0 ms and an exponential pressure impulse lasting for 0.05 ms. Figure 4 shows the cross sections of conventional and modified designs of the sandwich panels. The core compression, deflection of fibre laminates, face sheet vibration and overall deflection were observed during the experiment, and kinetic energy along with stored dissipated strain energy were analysed [35-38].

The polyurethane was modelled as an isotropic, nearly incompressible, and hyper-elastic rubber material, whereas polyurea was modelled as an elastic-plastic-hydrodynamic layer material. Under the applied blast loads, large compressive or crushing deformation was observed in the top half of the foam core layer and due to that, the core thickness was reduced. The highest compression was observed at the centre of the span during a uniform pressure application and it leads to a thickness decrease in that section compared to the section closer to the supports. Extensive thinning in the foam core and delamination of foam core from both inner and face sheets were observed, which lead to large displacement jumps. However, these deformations were reduced in the modified designs, and the deformation of outer face-sheet was reduced in both modified designs by a factor of 5.0 compared to the conventional design and no significant difference were observed between the deformations recorded in the modified designs [36-38].

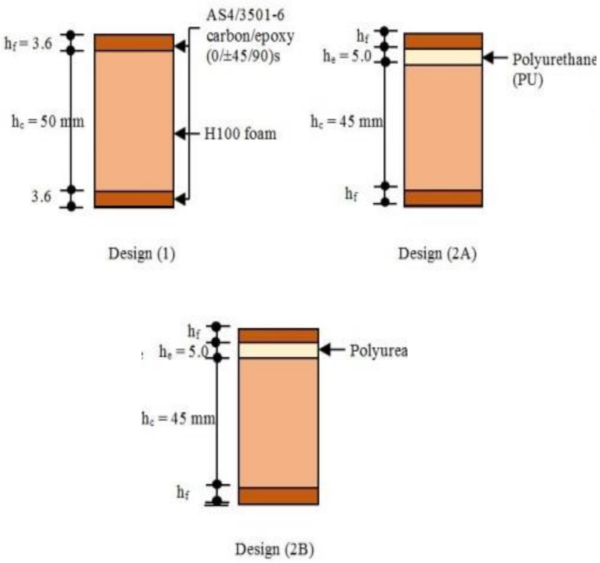


Figure 4 Cross sections of conventional and modified designs of sandwich panels, as shown in Bahei-El- Din and Dvorak [36]

The through-thickness strain of polyurea computed at the interlayer at the mid-span was displaced by two orders of magnitude larger than polyurethane, but the recorded stresses were much closer. Both interlayer materials provided protection to the foam core and minimised the imparted kinetic energy. These stiff interlayers reduced the amplitude of the compression waves delivered to the inner foam core, and the reduced compression lead to reduced dissipated energy, face-sheet strain, and deflections. Under the applied blast loading, the behaviour of the sandwich design with a hyper-elastic polyurethane interlayer indicated slightly better performance compared to the design with a rate-dependent, elastic-plastic polyurea interlayer. Another series of tests were conducted to compare the behaviour of conventional and enhanced sandwich plate designs with equal mass under blast loads [38], and the results showed considerable improvement in response of the modified designs with the interlayers compared with the conventional sandwich design of equal mass [36, 38]. The capability to absorb and dissipate energy is the one of the main advantage of elastomeric polymers like polyurea and polyurethane, and it leads to reduction in the damage and fragmentation sustained from the impulsive loading event such as blast [36, 38].

4.4.3 Computational Investigations by Grujicic et al. (2010)

Grujicic *et al*. reported on a computational investigation on energy absorption capacity of polyurea coated steel plates under ballistic loads, using ABAQUS non-linear FE code [39]. The interaction between the projectile and the polyurea coated steel test plate was analysed with the series of FE analysis. In addition, the glass transition temperature and its contribution for the energy dissipation process and enhancement were discussed. Under the FE analysis, first order, single-integration-point-eight-noded element with a normal edge length of 0.4 mm were used, and it consisted of a circular solid cylindrical (12.7 mm diameter, 12.7 mm length) steel projectile and 5.1 mm thick top coated plate (127 mm × 127 mm foot print) with a 6.4 mm thick polyurea layer. The AISI 4340 steel material was modelled as a linear elastic and strain-hardenable, isotropic, rate dependent and thermally softenable plastic material, while the polyurea was considered as a non-linear and visco-elastic material. The boundary conditions of the test plate was provided as stationary and stress-free at initial condition and all four back face edges were modelled as simply supported [39].

The projectile was assigned with a constant velocity of 900 m/s prior to the analysis. The findings indicated that the test temperature (difference between the test temperature and the glass transition temperature of polyurea) was affected by the mechanical response of polyurea under these loading conditions [39]. Since polyurea displayed a high ductility behaviour in its rubbery state at higher test temperatures, and tended to display its glassy-state during deformation at lower temperatures. Viscous type energy dissipation process was exhibited during the analysis and it showed that these mechanisms may contribute to the higher protection capability of polyurea under blast and ballistic conditions [39].

4.4.4 Computational Investigation by Grujicic et al. (2012a and 2012b)

The goal of most researchers in defence and military technology applications is to design light-weight, transportable, highly mobile, lethal battlefield and tactical vehicles. Development of monolithic ceramic armour; development of ceramic matrix composite; and development of polymer-based composite armour systems were notable among the recent practices and techniques aimed at designing a high performance armoured system [40, 41].

Along this focus, Grujicic *et al*. [40] undertook another set of studies by using the ABAQUS explicit FE code to recognise the role of adhesives used in ceramic strike-face/composite back-face hybrid armour. A simpler version of hybrid armour was considered in this study, consisting of three layers: (a) a strike face layer of discrete ceramic tiles; (b) an adhesive layer as the intermediate layer; and (c) a polymer-based composite material as a back plate [40, 41].

Polyurea and a Kevlar-reinforced Phenolic resin (laminated) composite material were used as the adhesive and the polymer-based composite, respectively. Polyurea was considered to be time-dependent and was treated using a geometrically-nonlinear, materially-linear visco-elastic formulation in the modelling. The selected composite was identified as a transversely isotropic material due to its bi-directional continuous fibre geometry. The test structure contained of a strike-face layer of ceramic tiles (50 mm × 50 mm × 6 mm) layer, 0.5 – 1.5 mm thick adhesive layer and 6 mm thick polymer-based backing layer. The conical pointed-tip of 7.62 mm (0.3 calibre), 35.6 mm long full metal jacket AP bullets (weighing ~ 10.75 g) were used in the ballistic analysis. Two loading conditions were considered: high loading-rate condition, representing impact of an armour-piercing projectile on the structure of the armour; and low loading rate conditions, i.e. those associated with the ingress of the loads which are generated at the road/tire contact interface and transmitted to the structure of the armour. The high strain rate conditions demonstrate the behaviour of the adhesive under ballistic loading conditions which control the overall penetration resistance of the armour structure [40].

Meanwhile, the low loading-rate condition exhibited the potential damage to the structure that the armour can experience due to sustained in-service loads. The findings indicated a significant improvement under ballistic loadings and enhanced durability of the hybrid armour can be achieved by proper modifications in the mechanical properties of the adhesive layer. However, it was also deduced that any single combination of those properties does not optimise all the performance requirements of the system [40, 41].

5.0 DISCUSSION

Based on the discussions provided in the preceeding sections, it can be deduced that the use of elastomeric polymers like polyurea and polyurethane in strengthening and retrofitting application of structural systems have been gaining interest among researchers due to the versatile characteristics and morphology of the those polymers, as well as due to the novelty of the application. In this aspect, the application of this technique on masonry structures indicated that it provides a feasible solution for strengthening URM walls, since this type of structure exhibit low flexural capacity and is highly susceptible to undergo brittle failure when exposed to out-of-plane loads like blast loads. It can be observed that although all the retrofitted walls failed during the testing conducted by Baylot *et al.* [18], they were successful at reducing the hazard level on the internal side of the structure. Furthermore, all researchers suggested that these polymer materials were beneficial in improving the energy absorption capacity and reducing the fragmentation effect of the structures.

Concrete, though being the most widely used construction material worldwide, the extent of research in the area of retrofitting of concrete structures using elastomeric polymer coatings is very limited. Through this limited findings reported by these researchers [8, 20-22], it was deduced that the elastomeric polymer (polyurea) bonded very well with the concrete substrate even with minimal surface preparations. However, it should be noted here that there is yet to be any investigation undertaken thus far to explicitly investigate the bonding characteristics of the polymer to the concrete substrate. The authors also suggested that the application of the protective coating on the blast-facing face of the RC panels would be more beneficial in controlling the deformation and damage sustained by the panel [21, 22].

On the other hand, findings of various researches have indicated that the polymer coating or interlayer technique improved the blast and ballistic resistance of metallic plates. Permanent deformations recorded in the coated plates were much lower, and higher thickness of polymer coatings leads to much lower deformations. It was also deduced that polymer coating would result in positive outcomes under energy absorption and failure mitigation capacity when it is coated on rear face as mentioned by Amini *et al*. [23-27] and Mohotti *et al*. [9, 10, 34]. In addition, Amini *et al*. concluded that the destructive effect increases when the coating is applied on the blast receiving face of the metal plates [23-27]. The influence of coating location is one area which should be considered for further detailed evaluations.

Generally strengthening of metallic structures can be achieved by increasing the weight of the composite. Ackland *et al*. [29] concluded that for a given areal density, the back steel plate is more effective than a polyurea coated steel plate in terms of deformations under blast effects, but the application of the coating is more practical than attaching a steel plate in real applications.

Even though, the design of composite sandwiched structures under impulsive loadings is (relatively) a new approach, the inclusion of polymer interlayers have indicated positively in absorbing and dissipating the energy imparted during the loading event, and this can be one of the main advantage of elastomeric polymers to be applied in sandwiched composite systems for defence and military applications.

Although only limited attention have been paid to evaluate the capability and behaviour of polymer retrofitted structures under localised loadings induced from ballistic events, considerable reduction of the residual velocity and kinetic energy absorption were observed in the studies undertaken thus far [9, 10, 34]. However, more in-depth research are required to enhance the knowledge in this area to obtain the necessary outcomes for real life applications. For that, the identification and analysis of physical and chemical characteristics of the polymers, the bond between the polymer and structural elements, influence of the location of coating, chemical resistance and the weathering effect, hazards levels and effect of this technique on the occupants of structures should be further investigated.

6.0 CONCLUSION

This paper provided a review on a novel approach being explored by researchers to utilise elastomeric polymers to strengthen and retrofit structures and structural elements subjected to blast and ballistic effects. The discussions provided have focussed on the application of this technique on major structural systems of masonry, concrete, metallic and composite structural systems. This technique provides cost and time effective retrofitting solution to enhance the blast, ballistic and impact resistance of structures, and provides an alternative approach in retrofitting structures facing the risks of impulsive loads. In addition, this technique also contributes in reducing damage and fragmentation effect, which in turn leads to reduction in the loss of life and injuries to the occupants in civil infrastructures resulting from those impulsive loading events.

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