Effect of Steel Fibres And Wire Mesh Reinforcement on Flexural Strength and Strain Energy Steel-Epoxy-Aluminium Composite Laminates

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ABSTRACT

This paper evaluates the effect of reinforcement materials on the flexural strength and strain energy in metal laminates under bending tests. Traditionally, high hardness monolithic steel has been utilised in lightweight armoured vehicles. In order to increase the performance of the armoured plates, their weight is reduced by incorporating adhesive bonding metal laminates technology. Simultaneously, the application of metallic fibres in construction is also being developed for the same purpose. Therefore the incorporation of metallic fibres in adhesive layer can reduce the weight and increase the strength of armoured panels. It is important to assess and predict the flexural strength and strain energy in the metal laminated armour. The effects of steel fibres and stainless steel mesh were investigated through flexural tests. The flexural strength was assessed by a three-point bending test using a universal testing machine. The strain energy was measured from the stress-strain curve using the data from the bending test. From the results, the steel fibre-reinforced and wire mesh-reinforced composite laminates exhibited higher flexural strength compared to non-reinforced composite laminate by 10% and 9%, respectively. Further, steel fibre-reinforced and wire mesh-reinforced composite laminates had higher strain energy at 23% and 31% compared to non-reinforced composite laminate, respectively. Cracks occurred at the back layer of the aluminium

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alloy and propagated vertically through the aluminium and adhesive layer and stopped at the steel layer. This is due to the higher strength and ductility of the steel in withstanding the load. Reinforcement with steel fibres and wire mesh enabled the metal laminate to bear higher load, while decreasing the damage and delamination due to its higher strength, strain energy and ductility compared to the non-reinforced composite laminate. The reinforcement materials have the potential to produce tough adhesive-bonded metal laminates for ballistic impact applications.

Keywords: *Reinforcement Materials, Flexural Strength, Strain Energy, Metal Laminates, Bending Test*

Introduction

Monolithic metallic materials have been used in armoured vehicles for a long time due to their higher strength and hardness. However, these materials are very heavy causing difficulty in maneuverability and increasing in fuel consumption rate. Development of new armour materials such as high strength steels, nanomaterial and composites have been developed to overcome these problems. Composite armour, consisting of layers of different materials is one of the most promising material for application in armoured vehicles. Multi-layered and reinforcement materials are being developed because of their superior performance as they are lightweight and easily designed. These composite laminates offer the best potential, especially in terms of strength and structural integrity, compared to monolithic metallic materials [1]. Composite laminates, which are mainly used for impact resistance applications, are commonly reinforced by non-metallic reinforcements such as Kevlar, carbon fibre-reinforced polymer (CFRP), E-glass and T300 carbon [2-5]. Nowadays, metallic fibres are being widely used as reinforcement materials in composite laminates for impact conditions due to their high strength, toughness and good energy absorption [6-8]. Further studies are needed in order to investigate the use of metallic fibre-reinforced composite laminates with regard to the aspect of ballistic.

The metallic fibres of stainless steel wire mesh and steel fibre-reinforced composite laminates can enhance the protective aspect. Lin et al. [9] studied the ballistic performance by using stainless steel wire mesh in non-woven fabric. Their analysis revealed that the fibres can transfer and spread energy due to their rigidity and the presence of ductile wire. The research by Khanlou et al. [10] also found that the strength, stiffness and crack resistance performance can be improved by inserting stainless steel mesh in a glass fibre-reinforced polymer. This was supported by a study by Qeshta et al. [11], which revealed that the mechanical performance of flexural strength, cracking behaviour and energy absorption capability can be increased by the addition of stainless steel wire mesh with epoxy in a composite structure. Other than that, a study by Zhou et al. [12] mentioned that the ballistic performance is increased when steel fibre is added into different metals by explosive welding due to its ability to absorb the kinetic energy produced by the projectile during impact. The author also suggested that a higher amount of steel fibre in concrete can enhance its toughness, strength and impact resistance [7, 13-14]. In addition, steel fibre limits the propagation of cracks along the fracture surface [15].

Hence, these reinforcement materials play a role in increasing the performance of the mechanical properties. The addition of the fibres in composite laminates may increase the strength and strain energy capability in the metal laminate plate. Although many researches have been carried out on metallic fibre-reinforced polymer composites, few have focused on adhesive-bonded metal laminates. So it is necessary to do an in-depth research on the mechanical performance of these composite laminates. Therefore, it is essential to study in greater detail the flexural strength and strain energy of metal laminated armour. This paper investigated the effect of metal laminates reinforced by steel fibres and stainless steel mesh on the flexural strength and strain energy. The metals were joined adhesively using epoxy resin. This study explored the possibility of steel fibres and stainless steel mesh as reinforcement materials in steel-epoxy-aluminium composite laminates for ballistic applications.

Experimental Procedures

The metal plate used to develop the multi-layered composite were Abrex 500 (AR500) and aluminium alloy 7075 (Al7075). The mechanical properties of AR500 and Al7075 are shown in Figure 1 and Table 1, repectively.

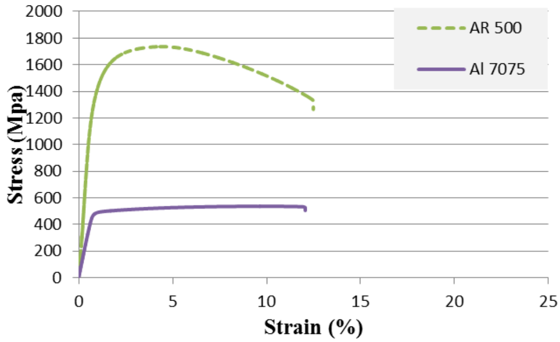
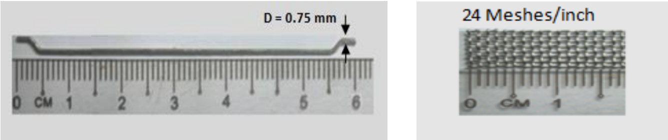


Figure 1: Stress strain curve for AR500 steel and Al7075

Table 1: Mechanical properties of AR500 steel and Al7075

Material	**Young's modulus (GPa)**	**Yield Strength (MPa)**	**Tensile Strength (MPa)**	**Elongation (%)**
AR500	220	1370	1740	12.5
Al7075	73	480	536	10

AR500-Al7075 composite laminate were bonded using an epoxy embedded with reinforcement materials, i.e. steel fibres and stainless steel wire mesh as shown in Figure 2. The configuration of composite laminate are shown in Figure 3. Table 2 and 3 showed the specification and mechanical properties of steel fibre and wire mesh used. Hooked end steel fibre, with a length of 60 mm and diameter of 0.75 mm was used. A stainless steel wire mesh, having a diameter of 0.35 mm with 24 meshes/inch, was selected for reinforcement to the adhesive-bonded joint.



(a) (b)

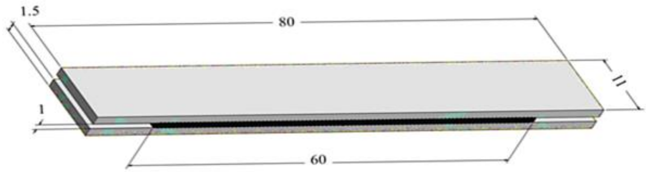
Figure 2: Geometry (a) Steel fibre and (b) stainless steel wire mesh used for reinforcement materials

Table 2: Specification and mechanical properties of the steel fibre

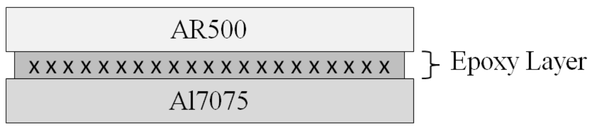
Properties	**Steel Fibre**
Length, L (mm)	60
Diameter, D (mm)	0.75
Aspect Ratio (L/D)	80
Specific Gravity (kg/m^3)	7850
Tensile Strength (MPa)	1229
Strain at Failure (%)	8.8

Table 3: Specification and mechanical properties of stainless steel wire mesh

Meshes/ Inch	**Wire Diameter (mm)**	**Aperture (mm)**	**Open Area (%)**	**Tensile Strength (MPa)**	**Strain at Failure (%)**
24	0.35	0.71	44.80	87	74



(a)



(b)

Figure 3: Composite laminate of (a) specimen size and dimension (b) configuration for flexural test

The AR500 was used as the front plate and Al7075 as the back plate. The metals were cleaned with acetone in order to remove dirt and grease for better adhesion between lamination. The dirt was removed by the ultrasonic method in acetone for 25 minutes. Epoxy resin was used to bond AR500-Al7075 composite laminate. The mechanical properties of the epoxy were identified by the density 1.5 g/cm^3, tensile strength 23MPa, and flexural strength 40MPa. The steel fibre and stainless steel wire mesh were embedded between the metal before it was joined using the epoxy resin. After that, the laminated specimen was placed in an oven at 150^{o}C for one hour in order to cure the epoxy bonding. A three-point bending test was carried out using a Zwick Z-100 universal testing machine according to ISO 14125, at a cross head speed of 5 mm/min in the room temperature. The load was applied until specimen break. The flexural strength of the specimen was calculated by measuring the fracture force from the stress-strain curve as in Eq. (1):

$$\sigma_f = \frac{3FL}{2bd^2} \quad (1)$$

where σ_f is the flexural strength (MPa), F is defined as the load at fracture (N), L denotes the distance between the support points (mm), while b and d indicate the cross-sectional width (mm) and height (mm), of the specimen respectively. The strain energy was then measured from the area under the stress-strain curve. Strain energy represents toughness by the area under the curve.

Results and Discussion

Flexural Strength

The adhesive-bonded metal laminates with non-reinforced materials showed the lowest flexural strength and strain energy compared to the reinforced composite laminates as presented in Figure 4. The flexural strength of the steel fibre-reinforced and wire mesh-reinforced composite laminates were higher than that of the non-reinforced composite laminate by 10% and 9% respectively. Comparing all the reinforcement types, the steel fibres were able to withstand higher load before cracks started to propagate at the metal-epoxy interlayer. In this study, it is assumed that the fracture load is corresponds to the load that the metal laminates were able to withstand before the cracks were initiated. The high flexural strength of the closely-packed fibres in the matrix improved the load resistance [16]. More energy was required to pull the fibres from the matrix until the fibres were broken [17]. Hence, the presence of the reinforcement materials increased the mechanical performance of the adhesive-bonded composite laminates.

The area under the load deformation graph showed the strain energy and the ability of the materials to absorb energy up to fracture. The strain energy of the steel fibre-reinforced and wire mesh-reinforced composite laminates were greater than that of the non-reinforced composite laminate by 23% and 31% respectively as presented in Table 4. The higher strain energy, which represented a higher toughness, was depicted by the larger area under the graph. The higher strain energy in the reinforcement materials was due to the ability of the fibres to absorb more energy in the composite laminates. In addition, wire mesh-reinforced composite laminates displayed good strain energy compared to steel fibre-reinforced composite laminates. The rigid structure and higher amount of wire per unit area in the mesh allowed the material to disperse the energy. More wire per unit area in the mesh compared to steel fibre gave it a superior ductility to transfer the stress and distribute the energy throughout the specimen. This was reflected in the findings of Lin et al. [9], who stated that the presence of many wires in a stainless steel screen mesh can increase the impact resistance by spreading the impact stress in composite laminates.

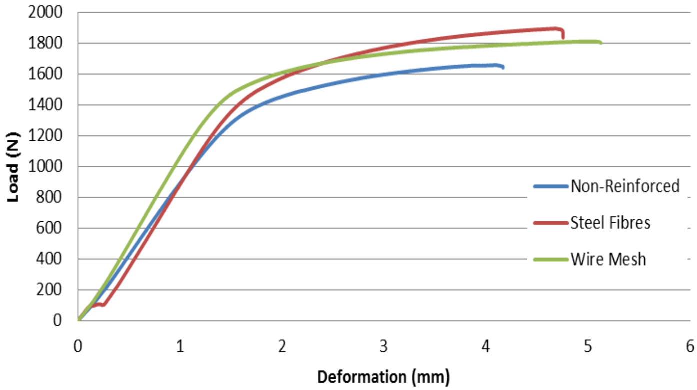


Figure 4: Load-deformation curves for non-reinforced, steel fibres reinforced and wire mesh reinforced composite laminate materials

Table 4: Flexural Strength of steel fibres and wire mesh reinforced composite laminates

Epoxy Reinforcement	Fibre Content (g)	Fracture load (N)	Deformation (mm)	Strain Energy (J)	Flexural Strength (MPa)
No Reinforcement	0	1640	4.2	5.11	838
Steel Fibre	0.9	1830	4.8	6.61	935
Wire Mesh	0.9	1800	5.1	7.38	920

Fracture Behaviour

Figure 5 shows the fracture behavior of the adhesive-bonded metal laminate specimen after the bending tests. The damage started with a dent on the steel skin layer of the top side, followed by crack initiation at the back layer of Al7075 and polymer resin and then, fibre breakage. During the bending process, the stress fluctuated through the laminate composite and was transfored from compression at the front layer skin, where the load was applied, to tension on the back layer skin, and shear stress in the middle layer [18]. The laminate structure was fractured by three types of stresses, namely compression stress, shear stress and tension stress. The crack started on the tension layer of the aluminium plate. Tension stress occurs at the back side of

Al7075. This crack propagated vertically along the aluminium plate and adhesive layers. This crack initiate in the back layer at the non-reinforced side due to plastic deformation by bending and the load applied was bigger than Al7075 strength. With an increase in the displacement, the crack had a tendency to propagate towards the compression layer. The finding is consistent with the findings of past studies by Ferrante et al. [19], which reported that metal laminate cracking occurred from the back layer to the front layer as the load increased. The cracks continued to propagate vertically along the adhesive layer (middle) and discontinued at the steel layer because of the higher strength and ductility of this steel in withstanding the load that was applied. AR500 steel has a higher strength and ductility of 1740 MPa and 12%, respectively, as shown in Figure 1 and Table 1. More strength and energy are needed to deform this steel layer. This allowed the steel plate to absorb higher stress from the load. Stress distribution is then peak at the interlaminar layer. Delamination continued to develop along the adjoining steel and adhesive layers. Meanwhile, Al7075 exhibited the lowest strength and ductility at 536 MPa and 10%, respectively. Good adhesive bonding (no delamination) was obtained between the aluminium alloy and the adhesive layer.

Crack propagates vertically from back layer of Al7075 to adhesive layer. The crack continues to propagates parallel to the steel plate orientation at the steel-epoxy interlayer until the edge as shown in Figure 5 (a). However, the damage and delamination was decreased with the addition of reinforcement materials to the metal laminate as illustrated in Figure 5 (b) and (c). The crack does not prominent from vertically side for the steel fibre-reinforced and wire mesh-reinforced composite laminates. It was found that the horizontal crack did not propagate until the edge of the specimen as seen in Figure 5 (b) and (c). This is because the reinforcement materials acted as a barrier, and controlled the crack propagation by delaying the formation of cracks in the metal laminates. Krasnikovs et al. observed a similiar cracking phenomena in short fiber reinforced concrete [20]. The reinforcement material was able to stop and prevent the propagation of cracks along the fractured surface of the specimen due to its higher flexural strength, strain energy and ductility, as mentioned in Table 4. Therefore, the steel fibres and steel wire mesh reinforced composite laminate are able to withstand the higher load and reduced the possibility of delamination. The reinforcement materials achieved lower damage in the development of cracks.

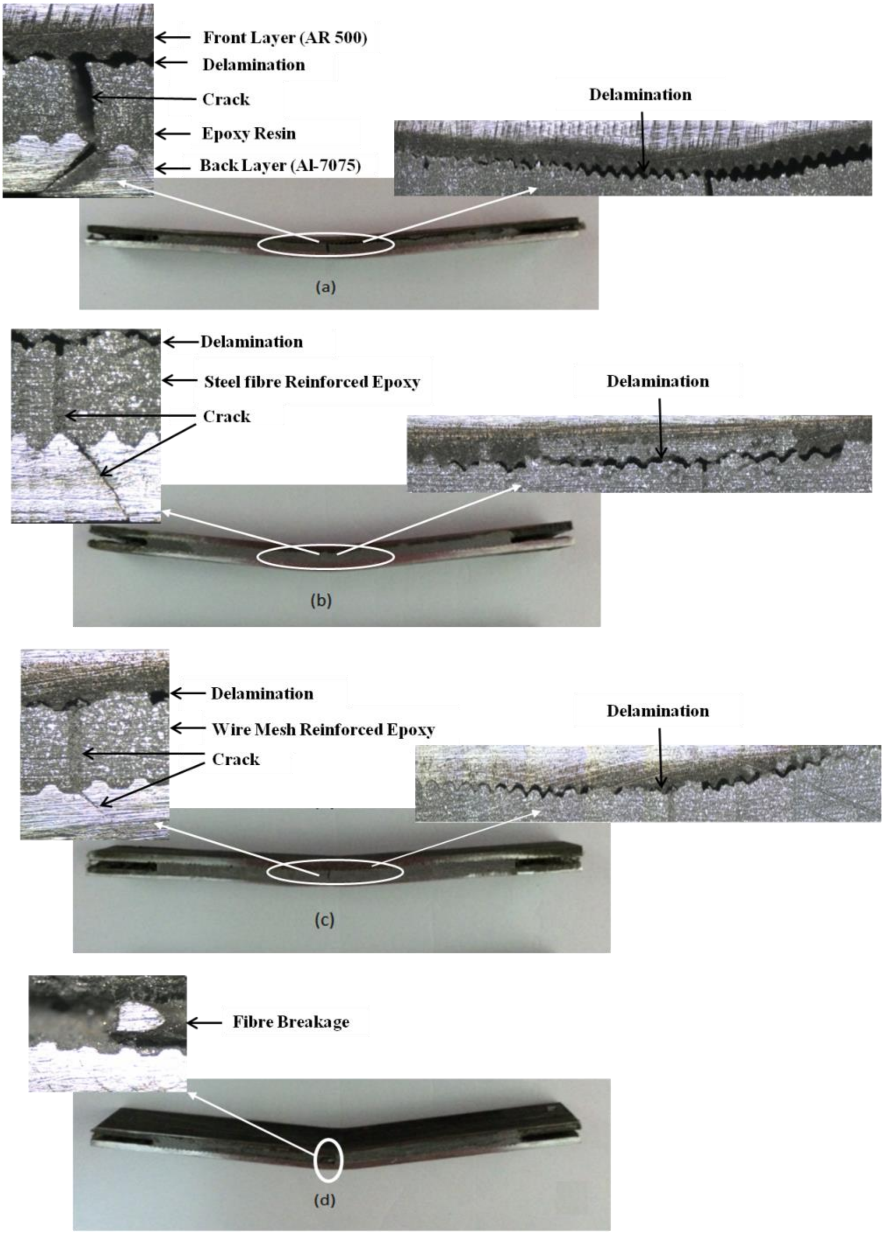

Front Layer (AR 500)
Delamination
Crack
Epoxy Resin
Back Layer (Al-7075)
Delamination
(a)
Delamination
Steel fibre Reinforced Epoxy
Crack
Delamination
(b)
Delamination
Wire Mesh Reinforced Epoxy
Crack
Delamination
(c)
Fibre Breakage
(d)

Figure 5: Fracture behaviour of metal composite laminate during bending test on (a) non-reinforced materials, (b) steel fibres, (c) wire mesh, and (d) fibre breakage

Conclusion

In this paper, the flexural strength of adhesive-bonded steel-epoxy-aluminum composite laminates with fibres and non-reinforced materials were evaluated. The reinforced composite materials exhibited a higher fracture strength, flexural strength and strain energy compared to the non-reinforced materials. Steel fibre-reinforced and wire mesh-reinforced composite laminates had a higher flexural strength than the non-reinforced composite laminate at 10% and 9%, respectively. Steel fibre-reinforced and wire mesh-reinforced composite laminates also presented good strain energy of 23% and 31% compared to non-reinforced composite laminate, respectively. The higher strain energy referred to the superior toughness obtained in the metal laminates. The mechanical properties of the metal laminates were increased by the addition of these reinforcement materials. The reinforcement materials hindered the development of cracks and delamination between the metals and the adhesive layer. This was due to their greater flexural strength, strain energy and ductility compared to the non-reinforced materials. The reinforcement materials have the potential to produce tough adhesive-bonded metal laminates for impact applications.

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