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PREDICTION OF RESIDUAL TENSILE STRENGTH OF LAMINATED COMPOSITE PLATES AFTER LOW VELOCITY IMPACT

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ABSTRACT

Laminated composite materials are extensively used in aerospace and marine industries because of their advantageous ratio between high stiffness and low weight as well as high strength and low weight. However, in this application these composites are subjected to low-velocity impact due to birds, hail, and rain and from dropped tools used during manufacture or maintenance. Low velocity impact damage is often internal and invisible, but can minimize the residual strength. In this study, the residual tensile strength of three stacking sequences of Glass Fiber Reinforced Plastic (GFRP) composites is determined after low velocity impact experimentally using threshold energy. A model has been selected based on linear elastic fracture mechanics for predicting residual strength of impacted GFRP composites. Experimental results show the reliability of the model in the field of low velocity impact and its usefulness in determining the residual tensile strength. The correlation between the analytical and experimental results was found to be very good. The determination of residual strength in impacted laminates is very useful for predicting product-life cycle.

Keywords: composites, low-velocity impact, residual strength, threshold energy.

INTRODUCTION

Glass Fiber Reinforced Plastic (GFRP) composites, because of their superior strength and stiffness, are used in some aircraft components and marine components. However, in this application these are composites are occasionally subjected to low-velocity impact due to birds, hail, and rain and from dropped tools used during manufacture or maintenance. If any composite laminate is subjected to a low-velocity impact with impact energy, the impact could cause a variety of damage in the form of matrix cracks, delamination, fiber fracture and fiber pull-out on the front and back face of the laminates. Such damage also affects the structural stiffness and strength properties of the laminate. The composite material's behaviour under low velocity impact situations requires careful examination. It is well known that composites, unlike metals, can experience a severe reduction in tensile and compressive strength after impact [1, 2, 3].

Minak and Ghelli [4] reported that among various factors that affect impact damage, the boundary conditions and the specimen size noticeably affect the residual strength, and the specimen shape rather than boundary conditions more seriously affect the impact damage. Davies *et al*., [5] concluded that the residual strength-impact energy relationship is completely independent of its laminate thickness, but this relationship shows distinctive trends, in which the thicker laminates have higher residual compressive strength than the thinner laminates. Mitrevski *et al*., [6] inspected the influence of the impactor shape on the impacted subject and reported that a blunt hemispherical impactor creates larger area of damage than ogival and conical impactors. Santiuste *et al*., [7] stated that the beam width and the impactor nose are influenced in the damage growth of the laminates after determining their residual flexural strength. Yigit and Christoforou [8] presented that increasing the size of the impactor slightly increases the damage zone, while permanent deformation is smaller. Alternatively, Shim and Yang [9] reported that damage area in the laminates increases in the case of smaller impactor tip radius and larger impact energy. The deviation between both cases was a result of the various boundary conditions applied on the edges of the laminates. Jenq and Wang proposed a model to predict the tensile strength of the GFRP specimens. This model is based on a combination of the targets residual strength and the kinetic energies transferred to it by the impactor [10].

Most of the studies are concentrated on residual strength of composite laminates after impact. So it is evident that an important requirement of GFRP plates is highest residual strength after impact. The applications of woven fabric composite materials are increasing in the area of advanced composite technology. Fabric reinforcements are widely used in pressure vessels and boats etc., because they can provide more balanced properties in the fabric plane than a unidirectional laminate. The low fabrication cost and ease of handling has made fabric composites more competitive than conventional unidirectional composites. So in this work, it was aimed to examine the residual strength of a set of fabric GFRP composites when subjected to localized low velocity transverse impact loading.

LAMINATE PRODUCTION

In this work, three types of composite plates were selected and the configurations of the plates are given in Table-1. The fibers used in the specimens are glass woven roving. The matrix selected for the fabrication is polyester resin. The laminates are prepared using hand layup technique. The laminates were cured by pressing rollers. The weight fraction of the reinforcement was determined

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using the burn off method. Then the laminates were cut into individual specimens using a diamond -tipped -slitting wheel and each measuring 175 mm x 175 mm.

For determination of the mechanical properties of glass/polyester laminated composite plates under static loading conditions, the laminate samples were prepared according to the ASTM standards [13]. All the tests were performed on LR-30K Universal Testing Machine with 30kN load capacity. The calculated mechanical properties are listed in Table-2.

Table-1. Composite plate's configurations.

Laminate type	**Stacking sequence**	**Nominal thickness** (mm)	**Density** (kg/m^3)	**Weight fraction**
Laminate 1	$[0/45]_S$	2.2	1730	58%
Laminate 2	$[0/60]_S$	2.2	1740	58%
Laminate 3	$[30/60]_S$	2.2	1700	56%

Table-2. Mechanical properties.

Strength (MPa)	**Laminate 1**	**Laminate 2**	**Laminate 3**
Longitudinal tensile strength (X_t)	195	185	165
Transverse tensile strength (Y_t)	176	160	148
In plane shear strength (S)	90	83	88

IMPACT TESTING

The impact tests were carried out in a drop-weight test rig shown schematically in Figure-1 which is capable of impact velocities of 7.4 m/sec. The impactor nose was formed with steel spherical ball with a 25.4 mm diameter. The specimens were clamped with specimen holder. By changing the mass of the impactor carriage, the incident impact energy was varied form 11.4 J to 17.3 J. In this work, three different heights were considered with constant impactor mass. Table-3 shows the test parameters which were investigated for each configuration.

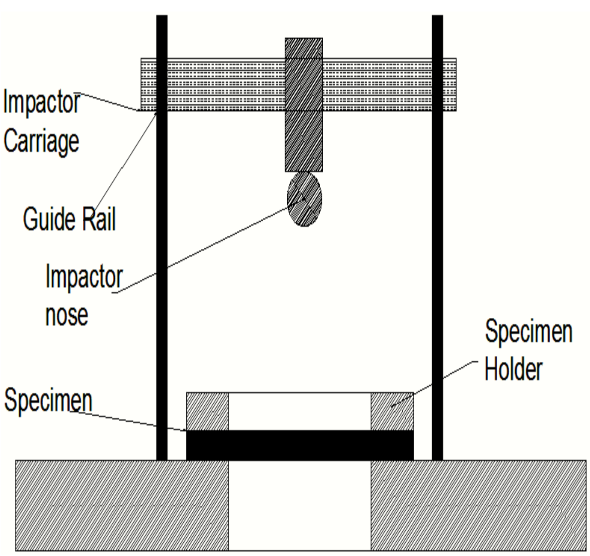

Figure-1. Drop weight Impact test rig.

Table-3. Impact test parameters

Impactor mass (Kg)	**Height of the impactor** (m)	**Impact velocity** (m/sec)	**Impact energy** (J)
1.17	1	4.42	11.47
1.17	1.25	4.95	14.34
1.17	1.5	5.43	17.3

RESIDUAL TENSILE STRENGTH TEST

For determining the residual strength of GFRP plates, impact damaged specimens were cut into size of 25 mm x 175 mm at the centre of the plate as shown in Figure-2. The static tensile tests were performed on LR-30K universal testing machine in a displacement control with the cross-head speed of 2mm/min. The residual tensile strength of all the specimens is measured and the results are listed in Table-4.

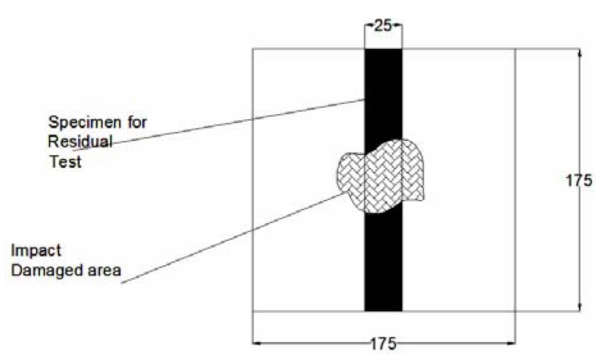

Figure-2. Specimen for residual test.

Table-4. Residual strength.

Laminate type	Impact energy (J)		
	11.47 J	**14.34 J**	**17.3 J**
Laminate 1(MPa)	165	142	131
Laminate 2(MPa)	142	138	126
Laminate 3(MPa)	147	127	101

RESIDUAL TENSILE STRENGTH

Residual tensile strength normally follows a curve, which is given in Figure-3. In region I, no damage occurs when the impact energy is just lower the threshold value for damage initiation. Once the threshold energy has been reached, the residual strength reduces rapidly to a minimum in region II as the degree of damage increases. In region III, residual strength has a constant value because the impact energy has reached a point where clean penetration occurs. In this region residual strength can be estimated by the damage to be equivalent to the size of the impactor. The minimum value in region II is less than the constant value in region III because the damage spreads over larger area. As the fibers carry the majority of tensile load in the longitudinal direction, fiber damage is the critical damage mode [3].

For determination of residual strength of GFRP laminates, threshold energy is very important and it is determined using Caprino's model.

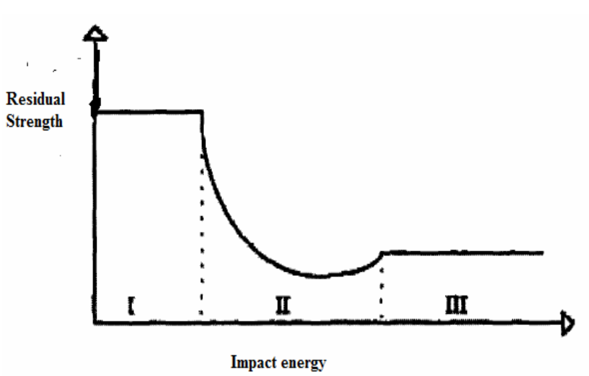

Figure-3. Residual strength curve for a composite laminate.

IMPACT THRESHOLD ENERGY PREDICTIONS

Caprino [11] developed the following relationship for predicting the residual strength based on fracture mechanics concepts

$$\left(\frac{\sigma_r}{\sigma_o}\right)=\left(\frac{U_o}{U}\right)^{\alpha} \quad (1)$$

where σ_r is the residual strength, σ_o is the undamged strength, U_o is the threshold impact energy, U is the Impact Energy and α is the constant. By taking the logs on both sides of Equation (1), the equation is obtained in the following form:

$$\log(\sigma_r/\sigma_o)=\alpha\log(U_o)-\alpha\log(U) \quad (2)$$

The parameter α, the residual degradation rate is determined of the composite laminates with incident impact energy. The applied impact energy is less than U and there is no strength degradation would occur. A α would clearly depend on the architecture of the fibre reinforcement, the fracture toughness of the material and the loading and supporting conditions. Furthermore, α will also depend on the residual strength which is being determined is tensile or compressive because the failure mode in each case is quite different. In tension the strength degradation would depend mostly on the extent fibre breakage only. Due to the dependence of α on many factors, it should be seen that it would have to be obtained experimentally from a few tests with different impact energies. By plotting log (σ_r/σ_o) against the log (U) of three laminates in Figures 4-6, it is clear that the results of tensile specimens fall approximately along straight lines [12]. This is also verified by the Caprino model shown in equation 1 and it is valid for residual strength prediction of these laminates. Using a linear regression analysis, the obtained values of α and U are listed in Table-5.

Table-5. Impact threshold energy and exponent.

Laminate type	**Threshold energy** (U_o) **J**	**Exponent** (α)
Laminate 1	7.2	0.363
Laminate 2	6.76	0.289
Laminate 3	6.05	0.581

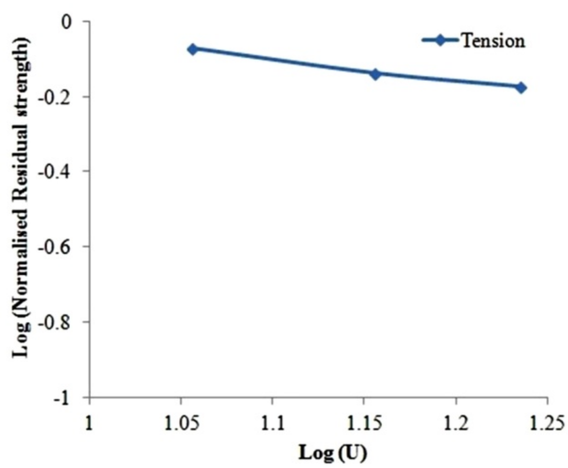

Figure-4. Log-log plot of normalized residual strength vs impact energy for laminate 1.

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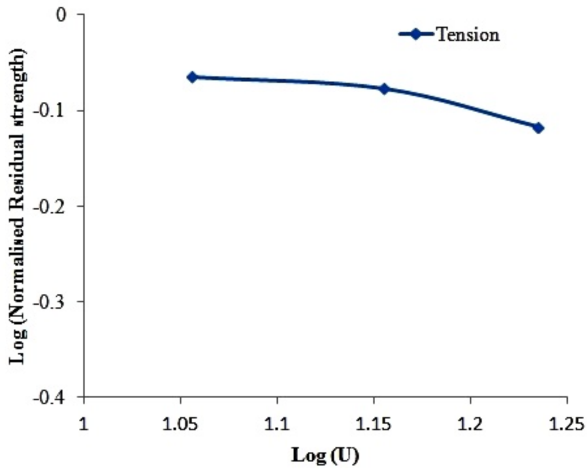

Figure-5. Log-log plot of normalized residual strength vs impact energy for laminate 2.

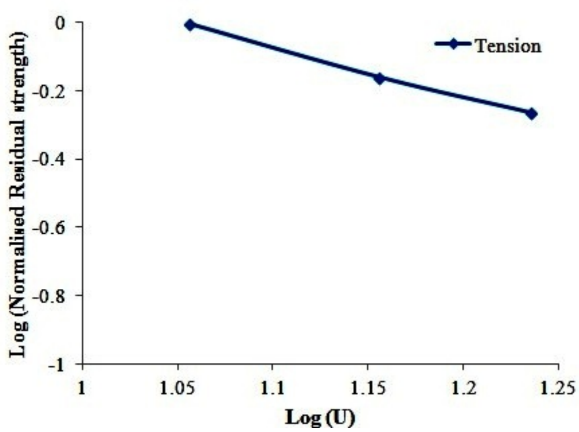

Figure-6. Log-log plot of normalized residual strength vs impact energy for laminate 3.

RESULTS AND DISCUSSIONS

After low velocity impact, all the specimens were visually inspected for appearance of damage. For low impact energy levels, no damage was found on both the front and on the back face of the composite laminates. At this point, the residual strength ratio of laminates is unity. Beyond threshold impact energy, first fibre failure and fibre splitting appeared on the back face of the laminate, whereas a barely visible indentation was noted on the front face (Figures 7 and 8). The damaged zone became more and more visible with increasing impact energy and the fibres of the bottom layer on the back face of the laminates were broken along an approximately circular path, with an evident indentation at an energy level of 17.4 J.

Figure-7. Front face damage appearance in laminate 1at Impact energy of 17.24 J.

Using Caprino [11] equation, the residual strength ratio curve is drawn theoretically for three laminates from impact energy of 1 J to 26 J. The experimentally determined residual strength ratio (σ_r/σ_o) is also compared with the theoretical obtained residual strength ratio. From Figures 9-11, it is illustrated that there is good agreement with the experimental results with theoretical results.

Figure-8. Back damage appearance in laminate 1at Impact energy of 17.24 J.

From Figure-9, it is shown that the ratio between residual strength and undamaged strength (σ_r/σ_o) is the function of the impact energy (U). It is evident from Figure-9 that three zones can be identified with regards to residual strength. In Figure-9, it is observed that when energy is at 7.2 J, the strength ratio is unity and it is influenced by impact energy. Between 7.2 J and 19 J, the strength reduces very quickly from 100% to about 70%. Beyond 14 J, the material strength decrease with minimum level with increasing kinetic energy.

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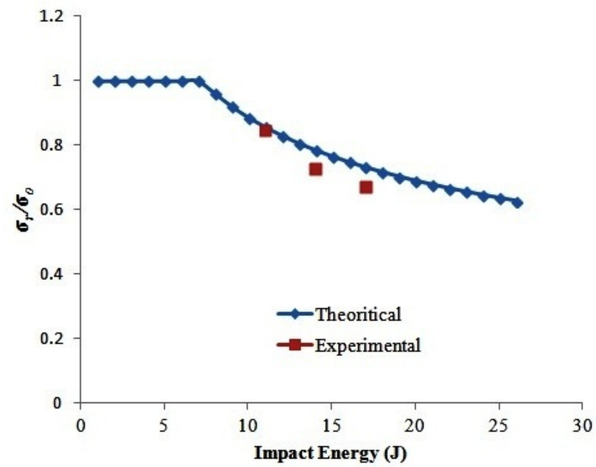

Figure-9. Residual Tensile strength ($\sigma r/\sigma_o$) vs impact energy (U) for laminate 1 specimens.

It is evident from Figure-10 that three zones can be identified with regards to residual strength. Up to an energy level of 6.76 J, the strength ratio becomes unity. Between 6.76 J and 23 J, the residual strength reduces very rapidly from 100% to about 70%. Beyond 23 J, the material strength tends to level showing little decrease of strength with increasing kinetic energy.

Furthermore from Figure-11, it is also examined that an impact energy is equivalent to 6.05 J, the strength ratio is completely influenced by its impact energy and undamaged strength. Between 6.05 J and 11 J, the strength reduces very rapidly from 100% to about 70%. Beyond 11 J, the strength ratio decreases with slower rate with increasing kinetic energy.

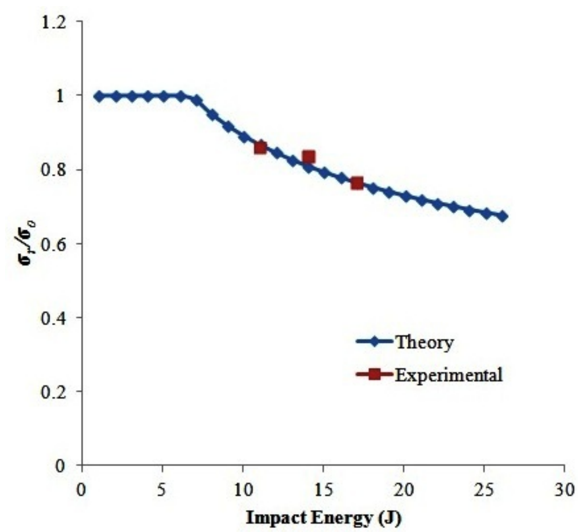

Figure-10. Residual Tensile strength ($\sigma r/\sigma_o$) vs impact energy (U) for laminate 2 specimens.

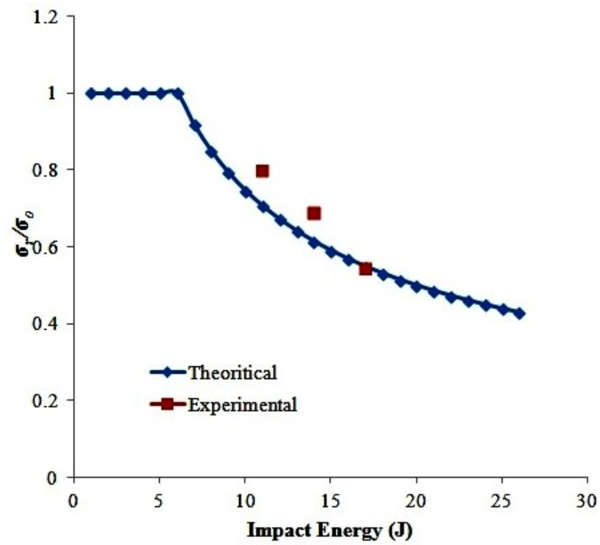

Figure-11. Residual Tensile strength ($\sigma r/\sigma_o$) vs impact energy (U) for laminate 3 specimens.

CONCLUSIONS

In this work, a model has been selected based on linear elastic fracture mechanics for predicting residual strength of impacted GFRP. Experimental results show the consistency of the model in the area of low velocity impact and its worth in predicting residual tensile strength. The correlation between the analytical results and the experimental and was established with good agreement.

The impact threshold energy and the exponent α of three different composite laminates calculated based on this analytical model. The impact threshold energy can be considered as a measure of impact damage resistance, which is the ability of the composite to sustain the damage without strength degradation. The exponent α determines the level of strength reduction for a given input impact energy greater than the threshold value, Uo

The prediction of residual strength of impacted laminated laminates influences the product life cycle of and the life of the product is also predicted using the residual strength ratio. The impact threshold energy is useful for predicting the impact damage tolerance levels for different loading conditions and supports conditions also.

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ARPN Journal of Engineering and Applied Sciences

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