Impact Analysis of Nonmetallic Laminated Composite Ship Panels

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***Abstract*— Traditionally steel has been the widely used material for ship construction. A stronger focus on both energy efficiency and environmental competitiveness and increasing fuel costs have created a large interest world-wide for using lightweight materials in shipbuilding. Lightweight hull construction can be achieved by using composites as construction materials. Use of composite materials will increase the operational efficiency and reduce ownership costs of ships and boats. Operational efficiency is increased due to increased range, stealth, payload and stability. Ownership costs will be reduced due to reduced operational and maintenance cost. Advances in composite materials and manufacturing technology during the recent years have strengthened the trend of increased use of composite materials in hull construction. Composite materials are engineered materials made from two or more constituent materials that are combined at a macroscopic level to produce a material with characteristics different from the individual components. When both the matrix and fibre are not of metallic origin, such composites are called as nonmetallic composites. These are used in laminate form in ship hull construction. Impact loads that act on ships are wave impact load, loads due to weapon discharge, collisions, explosions, flight operations and bulk operations. Even if impact loads are loads are small, repeated impact loads lead to fatigue failure. Impact strength of laminates has been defined in terms of the energy the material can absorb while an impact load acts on the plates. In the present study impact energy absorbed by various laminates generally used for ship hull construction has been calculated using FEA. For the various materials impact energy absorbed has been tabulated and compared.**

Keywords- nonmetallic composites; impact strength; laminate; matrix; fibre.

I. INTRODUCTION

Composite materials have emerged as a superior structural material having application in all spheres of life and essentially in marine environment, where high strength to weight ratio and noncorrosive nature of the material has great importance. Subsequently there has been a major shift in use of structural materials from steel to composite materials in marine structures. Advantages of FRP(Fibre Reinforced Plastic) composite materials over steel and other metals used for the construction of marine structures are high specific strength , high specific stiffness, good fatigue properties, low magnetic properties or high stealth properties, low electrical conductivity (for glass-reinforced plastics), resistance to corrosion, resistance to rot and marine growth, relatively high sonar transparency, maintenance of properties at low temperatures, and manufacturability to near net-shape. The life span of a composite ship can easily go up to 30 to 35 years. All these advantages make composite material a cost effective material for the construction of marine structures. One of the main advantages of construction using composite materials is the ability to choose the material, laminate and manufacturing method to suit the design requirements. In floating structures, application of composite materials varies from components to full structure. As components, composite materials are used in the manufacture of superstructures, decks, bulkheads, advanced mast systems, propellers, propulsion shafts, rudders, pipes, valves and machinery on large warships such as frigates, destroyers and aircraft carriers. At present as full structure, composite materials are used in the manufacture of racing powerboats, racing sailboats, canoes and kayaks, lifeboats, buoys and floats, utility vehicles, passenger ferries, deep sea submersibles, navigational aids, fishing vessels, etc. Naval applications in the present day include use of composites in submarines and surface boats.

II. IMPACT STRENGTH OF LAMINATES

Impact loads that act on ships are wave impact load, loads due to weapon discharge, collisions, explosions, flight operations and bulk operations. For military ships, major load can be created by the impact of explosions both in the air, underwater and directly against a ship structure. Ships must be designed and manufactured with sufficient strength to resist these forces. When the rate of load is high it will lead to brittle fracture loads. The brittle fracture failure mode involves the rapid propagation of a small crack, often deep below the surface, into a large crack ultimately leading to fracture. The risk of brittle fracture occurring depends on the material, temperature, geometry, and rate of loading. Even if impact loads are loads are small, repeated impact loads lead to fatigue failure. The introduction of composite materials into the shipping industry has led to lighter, stiffer and faster vessels. This requires increased impact performance, since higher speeds cause high energy impacts and stiffer structures usually absorb less impact energy before failure. Thus impact strength is an important consideration that needs to be addressed especially when non metallic composites are used as hull materials.

III. Literature Review

Norman [8] and Sun and Yang [9] have conducted impact resistance studies of different composites like aramid/epoxy, glass/epoxy, and carbon/epoxy. Akin and Senel[1] 2010) have studied the response of laminated plates of E-glass/epoxy subjected to low velocity impact loading experimentally. Impact response on laminates of different stacking sequences has been studied. Experimental and numerical studies have been conducted by Zike et.al. [14] to analyse the response of glass/polyester laminated plates subjected to low velocity impact loading for different fibre orientation angles. On comparing impact characterizing parameters as load, energy and deflection a good agreement between experimental and simulation results has been achieved. Wisheart and Richardson [11] have conducted a review on the impact properties of different composites. Faroop and Gregory[6] have developed a computational model to simulate and predict failure response of composite panels subjected to impact test using finite element analysis. Results have been compared with the results from the available literature and have been found to be in good agreement. From literature review it has been found that although experimental and numerical studies have been conducted on individual FRP's, a comparative study on all combination of available fibres and matrices is yet to be done.

IV. Methodology

Impact strength, is the capability of the material to withstand a suddenly applied load and is expressed in terms of energy. The result of the impact tests will give the energy needed to fracture a material and can be used to measure the toughness of the material. This can be evaluated if the problem is modelled using a 'damage model'. In the present study, damage model is excluded in the numerical simulation. Impact strength of laminates has been defined in terms of the energy the material can absorb while an impact load acts on the plates. The impact energy absorbed by the composites has been calculated using FEA (Finite Element Analysis) of the standard strength specimen. For the various materials impact energy absorbed has been tabulated and compared. To assess the energy absorbing capacity of the plate, change in internal energy of the plate during the impact need to be found out.

In the present study, the fibres selected from the nonmetallic composite materials used for hull construction are Carbon(C), Glass (G) and Aramid (A) and the matrices selected are Epoxy (E), Vinyl Ester (VE) and Polyester (P). In this study composites made of above three fibres and three matrices are considered. All the combinations of above fibres and matrices are selected. Accordingly nine types of nonmetallic hull materials are studied. They are Carbon fibre and Epoxy matrix (CFRP-E), Carbon fibre and Vinyl Ester matrix (CFRP-VE), Carbon fibre and Polyester matrix (CFRP-P), Glass fibre and Epoxy matrix(GFRP-E), Glass fibre and Vinyl Ester matrix (GFRP-VE), Glass fibre and Polyester matrix (GFRP-P), Aramid fibre and Epoxy matrix (AFRP-E), Aramid fibre and Vinyl Ester matrix (AFRP-VE), Aramid fibre and Polyester matrix (AFRP-P). Energy absorbing capacity of above materials has been evaluated. These composite materials are used in laminate or panel form in ship hull construction.

V. Material Properties Of Constituents And Laminates

Composite materials consist of reinforcing fibres and a matrix. The reinforcing fibres give strength to the composites and the matrix made of resin transfer the stresses developed and act as a barrier to corrosion. Material properties like Elastic modulii (E_1, E_2, E_3), poisson's ratio ($\nu_{12}, \nu_{23}, \nu_{13}$) and shear modulii ($G_{12}, G_{23}, G_{13}$), of the lamina can be calculated, using the material properties of constituents using analytical formulae. In the present study the analytical method, rule of mixtures [5] has been used to predict material properties of composites.

For the analysis of specially orthotropic material the engineering constants required are E_1, E_2, E_3, ν_{12}, ν_{21}, ν_{23} ,G_{12}, G_{23} and G_{13}. Material properties like E_1, E_2, ν_{12}, and G_{12} are found out using rule of mixtures and other material properties are made available by assuming $E_2= E_3$, $\nu_{12}= \nu_{23}= \nu_{13}$, and $G_{12}= G_{23}=G_{13}$[5] . The values of the material properties of the constituents E_f, E_m, G_f ,G_m, ν_m and ν_f are available in literature. From literature it has been found that use of 60% as percentage volume of fibres is a good value to produce a strong laminate encompassing the virtues of both fibre and matrix. Therefore V_f is taken as 60% [5].

Elastic modulus, poisson's ratio and shear modulus of the three fibres selected are given in Table 1[9].

TABLE 1. Material Properties Of Fibres

Fibre	E_f (GPa)	ν_f	G_f(GPa)
Glass	72	0.09	33
Carbon	234	0.26	93
Aramid	124	0.45	43

Elastic modulus, poisson's ratio and shear modulus of the three matrices selected are given in Table 2. [9]

TABLE 2. Material Properties Of Matrices

Matrix	E_m(GPa)	ν_m	G_m(GPa)
Epoxy	3.4	0.35	1.25
Vinyl Ester	3.2	0.3	1.23
Polyester	3.3	0.25	1.32

Elastic modulus of laminate in the longitudinal direction, Elastic modulus of laminate in transverse direction, Inplane shear modulus and Poisson's ratio when inplane load is applied parallel to longitudinal direction of laminates are calculated using rule of mixtures. Thus material properties of the FRP's under study are evaluated and are given in Table 3.

TABLE 3. MATERIAL PROPERTIES OF LAMINATES

FRP	V_f	E_1(GPa)	E_2(GPa)	G_{12}(GPa)	v_{12}
CFRP(E)	60%	141.76	8.32	3.06	0.3
CFRP(VE)	60%	141.68	7.84	3.02	0.28
CFRP(P)	60%	141.72	8.08	3.23	0.26
GFRP(E)	60%	44.56	7.94	2.97	0.19
GFRP(VE)	60%	44.48	7.5	2.91	0.17
GFRP(P)	60%	44.52	7.72	3.11	0.15
AFRP(E)	60%	75.76	8.16	2.99	0.41
AFRP(VE)	60%	75.68	7.70	2.95	0.39
AFRP(P)	60%	75.72	7.93	3.15	0.26

VI. DESCRIPTION OF SPECIMENS USED

For attaining uniformity between the nine laminates, laminates of same thickness and with same number of plies and same stacking sequence are considered for all materials. Specimen selected for the impact analyses is a rectangular plate 1000mm x 500mm. The plate consists of 8 plies of 0.5mm thick each. The stacking sequence of the plies used is [45/0/-45/90]s. The total thickness of the plate is 4mm.

The impact study was conducted using commercially available softwares like LS-PrePost and LS-DYNA. Modelling of the plate and ball has been done in LS-PrePost and the solver LS-Dyna has been used for solution. LS-PrePost is an advanced pre- and post-processor and model editor from Livermoore Software Technology Corporation, preparing input data and processing the results from LS-DYNA analyses [12]. LS-DYNA is a general-purpose finite element program capable of simulating highly nonlinear and transient dynamic problems.

In impact study, a steel ball has been dropped from a known height and has been made to impact the plate. For impact analysis the ball has been modelled as rigid body and plate has been modelled as elastic material. On impact, the plate will absorb the kinetic energy possessed by the ball and total internal energy of the plate gives the impact energy. As the laminates studied are orthotropic and elastic, the plate has been modelled using the element '4N SHELL' having 'orthotropic elastic' properties. The ball has been modelled using the element 'SOLID SPHERE' having 'solid' properties. The material properties used as input is given in Table 3 and Table 4. Impact load has been applied as a steel ball of 50 mm diameter falling from a height of 60 mm. The initial velocity of the steel ball was taken as 10mm/milli second [12]. While meshing the aspect ratio of the mesh has been maintained as 2.

TABLE 4. MATERIAL PROPERTIES OF STEEL BALL

Specimen	Diameter (mm)	Density (kg/m^3)	Poisson's ratio
Steel	50	7800	0.3

VII. IMPACT ANALYSIS OF LAMINATES

The plate i.e. composite laminate and the impactor i.e. steel ball has been modelled in LS Pre Post as shown in Fig. 1.

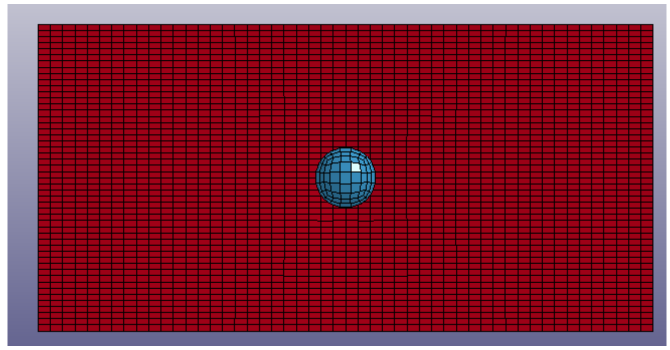

Figure 1. LS – Pre Post model of impactor and plate

The simulated model of the plate and impactor in LS DYNA has been shown in Fig.2. The front view of the model has been shown in the figure.

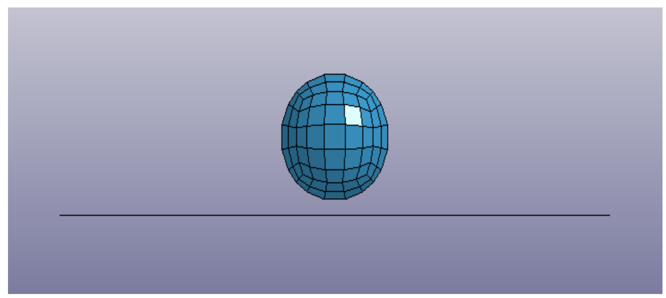

Fig. 2. LS-DYNA simulated model (front view)

The front view of the deformed model in LS-DYNA has been shown in Fig. 3.

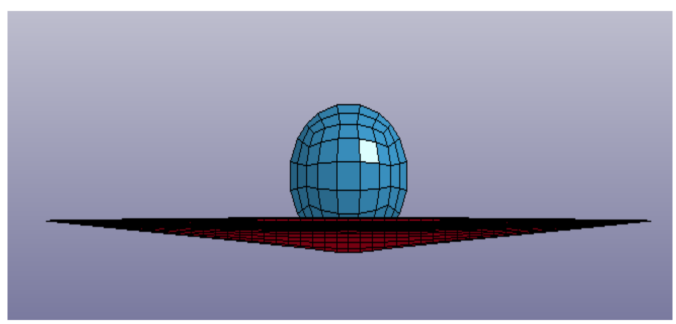

Figure 3. LS-DYNA deformed model (front view)

Change in internal energy of composite plates during the impact with respect to time has been found out for all the nine composites. Maximum internal energy of the plate or the energy absorbed for all the specimens are given in Table 5.

TABLE 5. MAXIMUM INTERNAL ENERGY DEVELOPED IN THE PANEL DURING IMPACT

Specimen	**CFRP(E)**	**CFRP(VE)**	**CFRP(P)**	**GFRP(E)**	**GFRP(VE)**	**GFRP(P)**	**AFRP(E)**	**AFRP(VE)**	**AFRP(P)**
Maximum Internal Energy (AE-F) (kNmm)	179.3	179.2	179.1	172.4	172.8	172.5	179.4	177.1	176.3

The time taken by each specimen to reach the maximum internal energy has been tabulated in Table 6.

TABLE 6. TIME TAKEN FOR MAXIMUM ABSORPTION OF IMPACT ENERGY

Specimen	**CFRP(E)**	**CFRP(VE)**	**CFRP(P)**	**GFRP(E)**	**GFRP(VE)**	**GFRP(P)**	**AFRP(E)**	**AFRP(VE)**	**AFRP(P)**
Time (AE-F) (millisec)	3.7	3.8	3.8	4.4	4.4	4.4	4.2	4.1	4

'Internal Energy' vs 'Time' curve of CFRP(E), GFRP(E) and AFRP(E) has been superimposed and given in Fig.4.

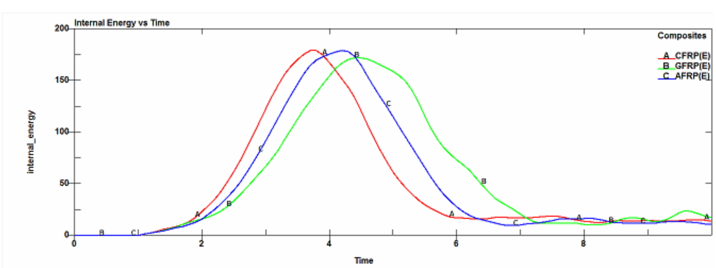

Figure 4. Internal Energy vs Time

In Fig. 5. 'Internal Energy' vs 'Time' curves of CFRP(VE), GFRP(VE) and AFRP(VE) has been superimposed and in Fig.6. 'Internal Energy' vs 'Time' curves of CFRP(E), GFRP(E) and AFRP(E) has been superimposed.

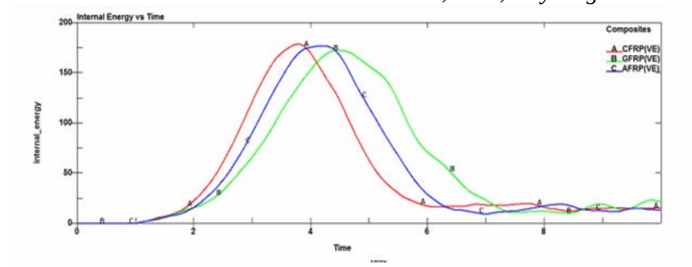

Figure 5. Internal Energy vs Time

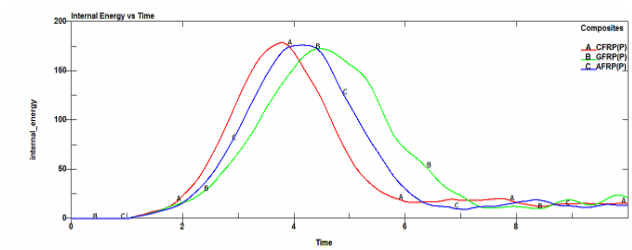

Figure 6. Internal Energy vs Time

'Internal Energy' vs 'Time' curves of CFRP(E), CFRP(VE) and CFRP(P) has been superimposed and given in Fig.7. In Fig.8, 'Internal Energy' vs 'Time' curves of GFRP(E), GFRP(VE) and GFRP(P) has been superimposed and in Fig. 9. 'Internal Energy' vs 'Time' curves of AFRP(E), AFRP(VE) and AFRP(P) has been superimposed.

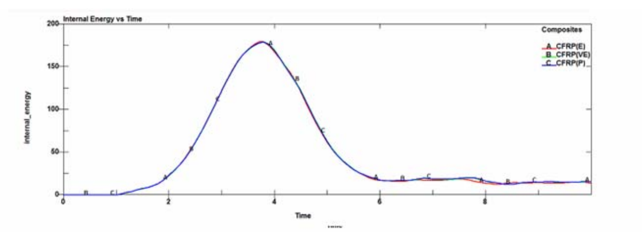

Figure 7. Internal Energy vs Time

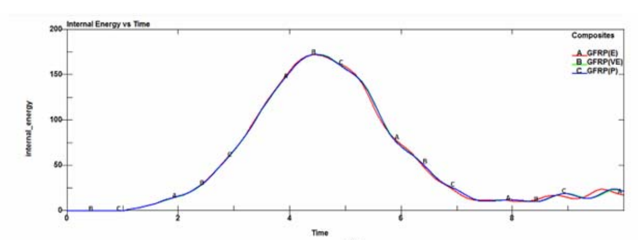

Figure 8. Internal Energy vs Time

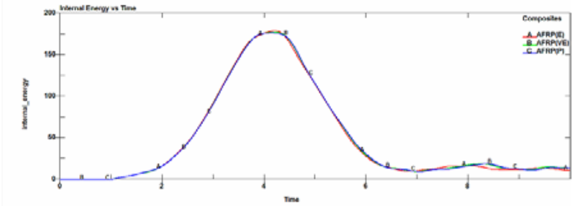

Figure 9. Internal Energy vs Time

VIII. Results And Discussions

Impact analyses had been conducted on the above nine composites with all the edges fixed. Maximum internal energy developed in the plate during impact and the time taken to develop this internal energy has been found out for all the cases are given in Table 5 and Table 6. Maximum internal energy was developed in CFRP and least internal energy was developed in GFRP in all the specimens. It has been found that time taken to reach the maximum internal energy is least for CFRP and highest for GFRP in all the specimens.

'Internal Energy' vs 'Time' curves of CFRP(E), GFRP(E) and AFRP(E) has been superimposed and given in Fig. 4. In Fig.5 'Internal Energy' vs 'Time' curves of CFRP(VE), GFRP(VE) and AFRP(VE) has been superimposed and in Fig.6 'Internal Energy' vs 'Time' curves of CFRP(P), GFRP(P) and AFRP(P) has been superimposed. All the curves are bell shaped. It can be seen that the curve is more flat at top for GFRP and less flat for CFRP. A plateau of maximum internal energy exists at the top for AFRP, a sharp variation of internal energy exists at the top for CFRP and a stage between the two exists for GFRP. The time taken to reach the maximum internal energy value is highest for GFRP and least for CFRP. Therefore although CFRP can absorb maximum energy, GFRP is more advantageous in composite construction when impact loading is considered. The flatter top portion of AFRP shows the capacity of such composites to absorb high energies for a longer time than CFRP.

'Internal energy vs Time' curve has been drawn for all the three CFRP composites, three GFRP composites and three AFRP composites respectively in Fig.7, Fig.8 and Fig.9. Comparison of Fig.7, Fig.8 and Fig.9 shows that change in matrices in the laminates does not produce much change in the energy absorbing characteristics. Comparison of Fig.4, Fig.5 and Fig.6 shows that change in fibres in the laminates affect their energy absorbing characteristics. Therefore it can be concluded that impact resistance is more of a fibre dominated property than a matrix dominated one.

By combining the above findings and on comparing the maximum internal energy developed and the time taken to reach the maximum internal energy in laminates on being impacted, it can be concluded that when impact value of various laminates are considered AFRP(E) is the best choice among the nine laminates and CFRP(E),CFRP(VE) and CFRP(P) rates as the last choice for the construction of ship hulls.

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