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Prediction of Post Underwater Shock Properties of Polymer - Clay/Silica Hybrid Nanocomposites through Regression Models

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***Abstract*—**Exploding concentrated underwater charges to damage underwater structures such as ship hulls is a part of naval warfare strategies. Adding small amounts of foreign particles (like clay or silica) of nanosize significantly improves the engineering properties of the polymers. In the present work the clay in terms 1, 2 and 3 percent by weight was surface treated with a suitable silane agent. The hybrid nanocomposite was prepared by the hand lay-up technique. Mathematical regression models have been employed for theoretical prediction. This will result in considerable savings in terms of project time, effort and cost.

***Keywords*—**ANOVA, clay, halloysite, nanocomposites, underwater shock, regression, silica.

I. Introduction

A major threat to ship structures and marine vessels is their exposure to severe shock loads which could be due to the underwater explosion of a mine or a torpedo or the structure striking a partially submerged object in water, and/or the slamming pressure that occurs at high sea states when the forefront of the vessel rises above the water surface and then rapidly re-enters the water. These shock waves generally generate impulses of very high pressures of short durations, resulting in extremely high strain rates, which may result in severe structural damages [2], [3]. Careful design of structures to withstand the shock loads still remains a challenge to structural designers. Hence, there is a continuing need to understand the structural behaviour of hull panels due to non-contact underwater explosion [1].

In order to with stand shock loads and to decrease weight of the empty ship and increase the payload, there is significant interest in developing lightweight structures for replacing conventional plate– beam metallic components in selected areas of a ship. For such structures to provide adequate protection against underwater blast, they must have high resistance to impulsive loads and good residual (post-impact) strength [4]. The absorption of energy in ballistic situations depends on the evolution of damage in the target that progressively degrades its material properties. Although several models have been developed to describe the deformation mechanisms of composites, no single model adequately characterizes the entire process. This is due to numerous factors like the difference in the behavior between the fiber types, fabric and composite constructions, the variation in thermomechanical properties, ductility, anisotropy, rate sensitivity of composite materials, and the fact that composite materials respond differently from monolithic materials (e.g., a metal) upon which fundamentals of the mechanics of high strain rate deformation are based [5].

The effect, if any, of temperature changes on the structure's response has been neglected, and the mechanical problem has been analyzed. 10 mm thick, 220 mm X 220 mm square, AS4/PEEK composite panel with the fiber volume fraction of 0.6 is considered for the analysis. These dimensions were chosen to match with those of the test specimen used by Turkmen and Mecitolu [6] who studied the dynamic response of a laminated composite subjected to air blast loads, and are of the same order of magnitude as those employed in other tests; e.g., Comtois et al. [7] used a 216 mm diameter, 2.1 mm thick circular plate, Langdon et al. [8] used a 220 x 220 mm (1.6–2.62 mm) plate, and Mouritz [4] a 270 mm X 70 mm X 6.1 mm rectangular plate.

Mouritz [4], [9] compared the damage resistance of stitched and unstitched GRP laminates loaded by an underwater shock wave produced by an explosion. It was found that unstitched and stitched laminates suffered the same types of damage that included cracking in the polymer matrix and glass fibers, small debonded lengths between the polymer and the glass fibers, and large delaminations between adjoining plies.

The shock factor is a measure of the severity of the attack and relates the charge weight to the distance between the point of ignition and the target plate. The shock wave pressure varies with the charge weight, the standoff distance, and the relative attack orientation. A higher value of the shock factor implies that a larger portion of energy of the underwater explosion is imparted to the ship. For submarines, this factor is called the Hull Shock Factor (HSF) [10], [11], [12], and is given by:

$$\boldsymbol{HSF} = \frac{w^{\frac{1}{2}}}{R} \qquad (1)$$

For a surface ship, it is necessary to correct the above equation for the angle at which the shock wave strikes the target; the corrected value, termed the Keel Shock Factor (KSF) [10], is given by:

$$\mathbf{KSF} = \left(\left(\frac{\mathbf{w}^{\frac{1}{2}}}{\mathbf{R}} \right) \left(\frac{\mathbf{1+COS\,(\theta)}}{\mathbf{2}} \right) \right) \qquad (2)$$

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The greatest threat during war is the explosion of underwater mines, which can cause severe structural damage to the hull. Despite the fact that FRP has been used in marine structures for many years, it is surprising that little work appears to have been performed to gain a detailed understanding of the response of FRP to the underwater shock loading produced by submerged mines [13], [14]

The explosive charges were made from Plastic Explosive type 4 (PE4), which is composed of about 88% ROX (cyclotrimethylenetrinitramine) and 12% of a non-explosive binder, and it produces an underwater shock wave pressure which is about 15% higher than that of TNT (trinitrotoluene)[15]. The maximum pressure of the shock wave is related to the charge weight and stand-off distance by the expression:

$$\mathbf{P_{max}} \approx \mathbf{53.9}\left(\frac{\mathbf{W^{0.33}}}{D}\right)^{\mathbf{1.33}} \quad (3)$$

where W is in kgf, D is in m and P_{max} is in MPa.

Therefore, in the experiments shock waves were generated with maximum pressures between 8 and 133 MPa. The unreinforced polymer specimens were tested with PE4 charges weighing 5.8 g and the stand-off distance was varied between 0.3 and 1.3 m, this produced maximum shock wave pressures between 8 and 31 MPa [15].

Ramajeyathilagam et al. studied the experimental and numerical investigations on clamped rectangular plates subjected to underwater explosion loading. Experiments were conducted on rectangular plates of size 0.55 x 0.45 x 0.004 m using a box model set-up under air-backed conditions in water tank detonating small charge weights of PEK-I explosive. Corresponding plastic deformation of the plates were measured for different charge weights and stand-off distances [16].

Exploding concentrated underwater charges to damage underwater structures such as ship hulls is a part of naval warfare strategies. Careful design of structures to withstand the shock loads still remains a challenge to structural designers. Hence, there is a continuing need to understand the structural behaviour of hull panels due to non-contact underwater explosion. The structural analysis is quite complex involving large deformation, high strain rates, material non-linearity and fluid-structure interaction [17].

A. Composite Laminate Preparation

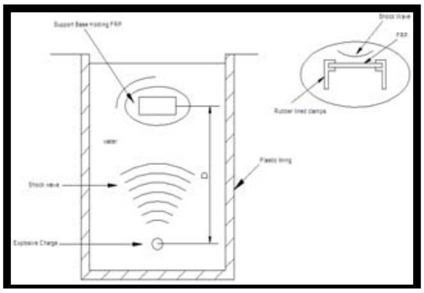
The synthesis of glass fiber reinforced epoxy with particle reinforced hybrids consists of mixing epoxy resin with nanoparticle by sonication process and then placing the mixture in the vacuum oven to remove the air bubbles at room temperature. This procedure results in a well dispersed state of nanofillers in the epoxy resin. The 50wt% of E-glass fiber woven rove mat, together with 50wt% of epoxy resin (pure, 1wt%, 2wt% and 3wt% of nanofillers) are used for preparation of hybrid composite by the hand-layup technique. The laminates are cured at room temperature and left in the mould for 24hrs for complete curing.

B. Experimentation

The inside steel lining of the pit was covered with a thin plastic sheet containing small air bubbles, which was used to minimize the internal reflection of shock waves from the pit wall following the explosion. The pit has a diameter of 5m and a depth of 5m. Hybrid nanocomposites laminates were cut into square specimens of 850mm side for testing. The laminates were placed at the top of the fixture and were clamped on all sides at their ends which allowed the FRP to bend under shock loading. The laminates were backed with either water or air and the experimental setup is shown in Fig. 1.

Fig. 1 FRP laminate fixing to the underwater shock test setup fixture

In the present investigation underwater shock tests were performed to simulate the conditions experienced by the GRP hull of a naval vessel when subjected to an underwater blast from an exploding mine, bomb or torpedo. The tests were performed in a water-filled pit as shown schematically in Fig. 2. This small-scale shock testing facility consists of a steel cylinder confined within a concrete slab.

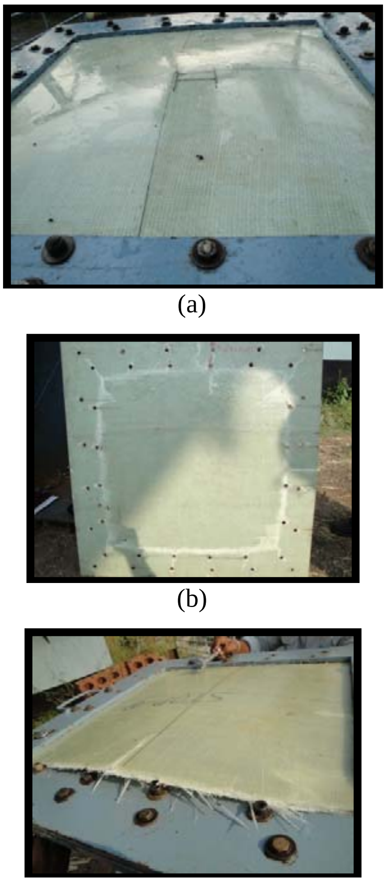


(a)

(b)

Fig. 2 (a) Schematic representation of the facilities for the underwater explosive shock testing of FRP laminates;
(b) Experimental assembly before dipping into the water pit

Under water shock tests of 15gms of explosive charge is taken for the study. An explosive PEK-1 at 0.46 m was taken as the stand-off distance (D) from the laminate. The rapid rise in pressure at the start of the profile represents the front of the shock wave striking the FRP. In this case the maximum pressure of the shock wave was measured to be 31 MPa. Calculated Shock factor is 0.122, where standoff distance (D) is 0.46meters and Charge weight (W) is 0.015kgf. The post shock hybrid laminates are shown in Fig. 3(a-c).



(a)

(b)

(c)

Fig. 3 (a) Deformed laminate after underwater shock test; (b): 1wt% nanoclay reinforced hybrid nanocomposites after underwater shock test; **(c):** Pure FRP composite laminate after underwater shock test

The shock factor is a measure of the severity of the attack and relates the charge weight to the distance between the point of ignition and the target plat. The shock wave pressure varies with the charge weight, the standoff distance, and the relative attack orientation. A higher value of the shock factor implies that a larger portion of energy of the underwater explosion is imparted to the ship.

III. Regression Analysis

Regression is the process of fitting models to data. The process depends on the model. If a model is parametric, regression estimates the parameters from the data. If a model is linear in the parameters, estimation is based on methods from linear algebra that minimize the norm of a residual vector. If a model is nonlinear in the parameters, estimation is based on search methods from optimization that minimize the norm of a residual vector. Categorical predictors are the subject of Analysis of Variance. Mathematical regression models have been built to estimate mechanical properties on line Statistical Package for the Social Sciences (SPSS, a registered product of SPSS Inc., Chicago).

Several influencing measurable parameters wt% of nanoclay, wt% of nanosilica considered for the regression analysis and are used as the independent factors and post underwater shock tensile strength is considered dependent factors. The general model to predict the post underwater shock Tensile strength over the experimental region can be expressed in the equitation.

Post underwater shock tensile strength = $((1.473*x) + (8.072*x^2) - (2.625*x^3) + (7.744*y) - (4.897*y^2) + (0.807*y^3) + (164.194))$

where x = wt% of nanoclay and y = wt% of nanosilica

Multiple linear regression, carried out for the linearized terms using SPSS, postulates a functional dependence between the independent and dependent variables minimizing the modeling error.

A linear function problem reduces to finding the coefficients V1, V2, V3, V4, V5, V6, V7 and constant. In the present analysis, these constants were found to be 1.473, 8.072, -2.625, 7.744, -4.897, 0.807 and 164.194 respectively. Experimental data was obtained to build the model and validation with 0, 1, 2 and 3wt% of nanoclay and nanosilica.

A. Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) is a powerful statistical technique used to confirm the effect of several simultaneously applied factors on the response variable [18]. A null hypothesis, postulating ‘no dependence’ of the applied factors & response variables are considered and is checked for its validity. Degrees of Freedom (DF) and sum of the squares (SS) are computed for the considered data. F-statistic (variance ratio) is computed as the ratio of sums of squares denoting influence of factors and their interdependence. The computed value of variance ratio (F) is compared with the standard ANOVA table and the hypothesis is accepted or rejected at a particular (1% or 5%) confidence level. If the hypothesis is rejected at 1% confidence level, it also stands rejected at 5% confidence level.

In the present work, the degrees of freedom were found to be 6 and 19; F-statistic was obtained as 140.896 from SPSS. The tabulated critical value of F distribution for the obtained degrees of freedom at 1% significance level was 4.10. Hence the proposed null hypothesis advocating no dependence of wear rate on the taken parameters was rejected at 1% significance level. Hence the choice of parameters is justified.

Table I summarizes the results from regression analysis. The first column gives the values of constant and coefficients of the variables in the formulated model. Standard Error Coefficients (SE Coef) obtained in the model give the significance of each independent variable. T-value gives the ratio of the parameter estimate and its standard error. P value denotes the probability of null hypothesis to be wrongly reject.

TABLE I
PREDICTION MODEL FROM REGRESSION ANALYSIS (HARDNESS)

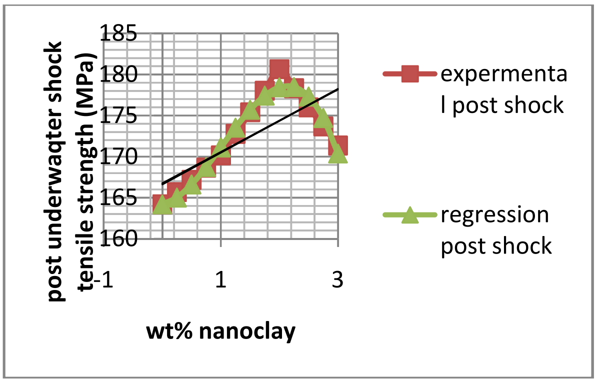
Predictor const	**Coef**	**SE Coef**	**T**	**P**
Constant	164.194		332.355	0.000
V1	1.473	0.312	0.843	
V2	8.072	4.419		0.000
V3	-2.625	-3.926		0.000
V4	7.744	1.640	4.433	
V5	-4.897	-2.681	-3.279	
V6	0.807	1.208	2.392	

R^2 = 0.978, R^2 (adjusted) = 0.971

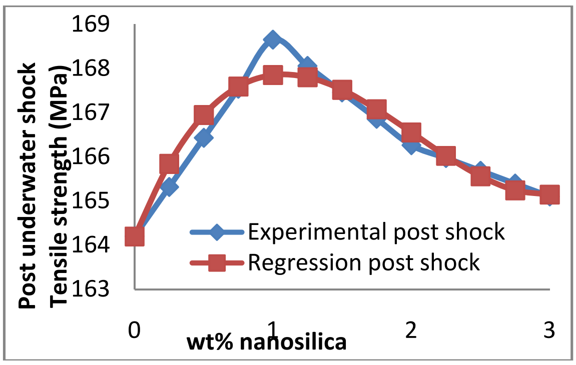
ANOVA

Source	**SS**	**DF**	**Mean Square**	**F**	**P**
Regression	566.819	6	94.450	140.890	0.000
Residual Error	12.739	19	0.67		
Total	579.559	3725			

Both the high adjusted-R^2 and P values are close to zero, in the analysis of variance (ANOVA), showing that the postulated model has satisfactory goodness of fit. Error from regression analysis is shown in Figure-4c. Experimental and regression analysis of post underwater shock tensile strength along with wt% of nanoclay and wt% of nanosilica is shown in Fig.4 (a&b). Regression analysis gives good agreement with experimental data and shows error less than 1.2% in all the conditions.



(a)



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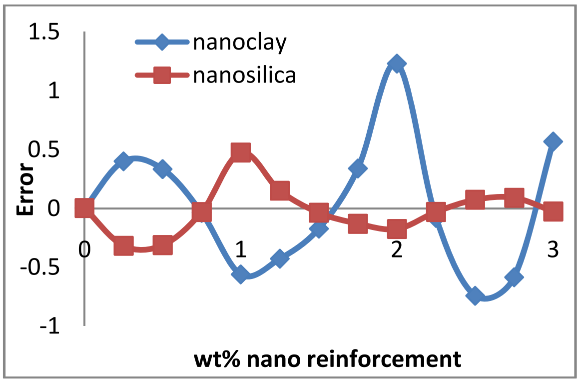

(c)

Fig. 4 (a-c) Regression results for hybrid nanocomposites in post underwater shock tensile test

The experiment concludes that nanoclay reinforced hybrid nanocomposites give better impact shock for underwater explosives. Pure FRP laminate shows less post shock strengths when compared with nanoclay reinforced hybrid nanocomposites. The experiment concludes that, nano reinforcement of clay upto 2wt% will give better properties in underwater explosive conditions. Post underwater shock tensile strength increased by 3.9%, 10% and 4% over pure FRP for 1wt%, 2wt% and 3wt% of nanoclay reinforcement respectively.

IV. CONCLUSION

Polymer hybrid nanocomposites have attracted a great deal of interest because they exhibited remarkable improvement of physical properties when compared with those of pure polymer or conventional composites.

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