

ISSN 1996-3394

Asian Journal of  
**Materials**  
Science

## Effect of Corrosive Environment on Elasto-buckling Strength of GFRC Plate

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### ABSTRACT

This study reports the experimental investigation of the elastic, buckling and post-buckling response of unidirectional laminated and  $0^\circ$  oriented E-glass/epoxy composite rectangular plate subjected to compressive load and liquid environment exposure. The plates were exposed to liquid rocket propellants like kerosene oil, hydrogen peroxide and hydrazine hydrate for different duration. The effects of liquid fuels, moisture concentration, fiber damage and plate parameters on elastic, buckling and post buckling response of the plate were studied. The effect of corrosion on composite plate and reduction in properties like weight changes, elastic, buckling and post-buckling strength were observed and found as a time dependent. The theoretical evaluation using classical thin plate theory showed the significant buckling load variation with response to experimental observation. In addition, hydrogen peroxide and hydrazine hydrate are found more corrosive compared to kerosene oil and reduced one fourth of the total strength of the composite plate.

**Key words:** Unidirectional, thin plate theory, critical load, post-buckling load, corrosive environment

### INTRODUCTION

The structures like the propellant tank of the aircraft and spacecraft is having significant contribution towards the total weight of the vehicle. Low weight and high reliability are the requirement of these tanks (Korb, 1969; Kelly *et al.*, 1983). They must therefore, be fabricated from materials having high strength to weight ratios and uniform and reproducible mechanical properties such that unexpected failure cannot occur at stresses lower than the design operating conditions (Zhang *et al.*, 2008). Again, the behaviour of materials used in design of tank quietly depends on the fluid present inside as well as the fluid behaviour like corrosiveness, reaction and thermal nature. Therefore, there is a quest to obtain a suitable material for tank design with sufficient reliability (Chen and Soares, 2007).

In this line, the composite laminates not only provides lightweight and high strength but also have developed outstanding bending rigidity, low specific weight, superior isolating qualities, excellent vibration characteristics, good fatigue properties and ease to tailor-make and utilized (Srinivasan, 1974; Mumford *et al.*, 1983). The first two characteristics are the major reasons to make it use more often in aerospace vehicles that need high strength-to-weight ratio (Zhang and Yang, 2009). The composite laminate plates in service are commonly subjected to compressive forces

that may cause buckling. Abundant published papers present the structural analysis of composite plates. The effect of fibre angle, plate shape, boundary conditions, material properties and stacking sequence are investigated in general (Xu *et al.*, 2007). However, few of the studies consider composites under corrosive environments.

Abraham *et al.* (1984), Iyenger (1986), Kicher and Mandell (1971), Srinivasan (1974) and Swanson (1990) highlight the related properties study and practicable application of various composite for tank design of aerospace vehicles. One of them is the Glass Fibre Reinforced Composite (GFRC) which is used as potential materials for a variety of structural applications in aerospace and aeronautical industries because of the range of mechanical properties that possesses. In recent years, considerable amount of work on the buckling and postbuckling behavior of laminated composite plates subjected to mechanical, environmental or thermomechanical loadings has been reported (Sharma and Mittal, 2010; Kumar and Sundareswaran, 2010; Weaver and Nemeth, 2007; Onkar *et al.*, 2007; Civalek, 2007; Ridzwan *et al.*, 2006; Mahasneh, 2005; Shukla *et al.*, 2004; Shiau and Kuo, 2004; Zou and Qiao, 2002; Huang and Kardomateas, 1997; Librescu and Souza, 1993; Noor and Burton, 1992; Noor *et al.*, 1992; Gopalan and Ramesh, 1989). It is observed that relatively lesser attempts are made to study the effect of corrosive environment on buckling and postbuckling response of laminated composite plates incorporating moisture dependent properties using classical laminated plate theory, Whitney and Ashton (1971) presented the hydrothermal effects on bending, buckling and vibration of composite laminated plates. They used the Ritz method for analyzing symmetric laminates and equilibrium equations in the case of anti-symmetric angle-ply laminates based upon the classical laminated plate theory and effect of environmental degradation. Flagg and Vinson (1978) studied the hydrothermal effects on the buckling of laminated composite plates. Ram and Sinha (1992) presented the buckling of laminated composites plates under hydrothermal loading using first order shear deformation theory and linear kinematics, employing finite element method. The effects of moisture and temperature on critical load are presented for simply supported and clamped antisymmetric cross-ply and angle ply laminates using reduced lamina properties at elevated moisture concentration and temperature incorporating macro mechanical model. Chao and Shyu (1996) presented a micro to macro analytical model for estimation of buckling loads of composite laminated plates subjected to hydrothermal loading conditions. Shen (2001) studied the influence of hydrothermal effects on the post-buckling response of simply supported shear deformable laminated plates using Reddy's higher order shear deformation plate theory and employing perturbation technique. In most of the works, results are confined to uniaxial compression with hydrothermal loading and estimation of buckling load employing linear kinematics and macro mechanical model for evaluating lamina properties at increased moisture concentration and temperature. Analytical solutions are mainly limited to simply supported boundary conditions.

The researches on the buckling in the literature were mostly focused on different aspects of composite laminates and most of the works were carried out on laminated structures made up of high performance composite materials such as carbon epoxy or Kevlar epoxy. However, several studies have dealt with the elastic and buckling behaviour of E-glass fibre reinforced laminated composite materials. For this reason, in the present study, the effects of the corrosive liquid propellants on the critical buckling load and ultimate failure load of E-glass/epoxy composite laminates with various duration of environmental exposure are studied. The effects of the typical aerospace fuels like kerosene oil, hydrogen peroxide and hydrazine hydrate are selected as the liquid chemicals for the investigations. For elastic, buckling and post-buckling experiments, the

unidirectional,  $0^\circ$  oriented E-Glass/epoxy composite rectangular plates are produced by using hand lay-up technique. Theoretical analysis of buckling load has been carried out using simple thin laminated plate theory and variations of experimental and theoretical results have been found out.

## ANALYSIS

Out of several plate theories which have been developed depends upon the level of sophistication; the most popular categories are linear and non-linear theories. Within each of these categories, there are three distinct levels. These are:

- Thin plate analysis
- Moderately thick plate analysis
- Classical elasticity theory

The thin plate analysis is the most popular due to its simplicity. However, this type of analysis has two subclasses: (a) simplicity correctly applicable only to a plate laminated symmetrically with respect to its middle plane and (b) complete analysis including laminated bending-stretching coupling and thus applicable to arbitrarily laminated plates, i.e., either symmetrical or unsymmetrical laminated ones.

When the magnitude of the load on a structure is such that the equilibrium changes from stable to neutral, the load is called the critical load and the phenomenon of change of equilibrium is called the buckling of structure. The term 'buckling load' is used synonymously with 'critical load'. However, there is a subtle difference between the two terms. The latter defines the load; obtained theoretically for an ideal structure, whereas the former is the load obtained experimentally for a real structure and differ depending on the idealisation.

Using thin plate analysis (Sharpe and Helenbrook, 1979), the governing differential equation for the deflection ' $\omega$ ' for a thin, flat orthotropic laminated rectangular plate simply supported along the edges  $x = 0, a$  and  $y = 0, b$  as shown in Fig. 1 and subjected to a uniform uniaxial load  $N_x$  along the X-direction is given by:

$$D_{11} \frac{\partial^4 \omega}{\partial x^4} + 2(D_{12} + 2D_{66}) \frac{\partial^4 \omega}{\partial x^2 \partial y^2} + D_{22} \frac{\partial^4 \omega}{\partial y^4} + N_x \frac{\partial^2 \omega}{\partial x^2} = 0 \quad (1)$$

Solving for the boundary conditions, the nontrivial solution of Eq. 1 is:

$$N_x = \frac{\Pi^2}{a^2} \left[ D_{11} m^2 + 2p^2 (D_{12} + 2D_{66}) n^2 + D_{22} p^4 \frac{n^4}{m^2} \right] \quad (2)$$

where, 'm' and 'n' define the number of half waves that plate buckles in X and Y direction respectively and 'p' is the aspect ratio. The smallest value of ' $N_x$ ' is obtained when  $n = 1$  and Eq. 2 reduces to:

$$N_x = \frac{\Pi^2}{a^2} \left[ D_{11} m^2 + 2p^2 (D_{12} + 2D_{66}) + D_{22} \frac{p^4}{m^2} \right] \quad (3)$$

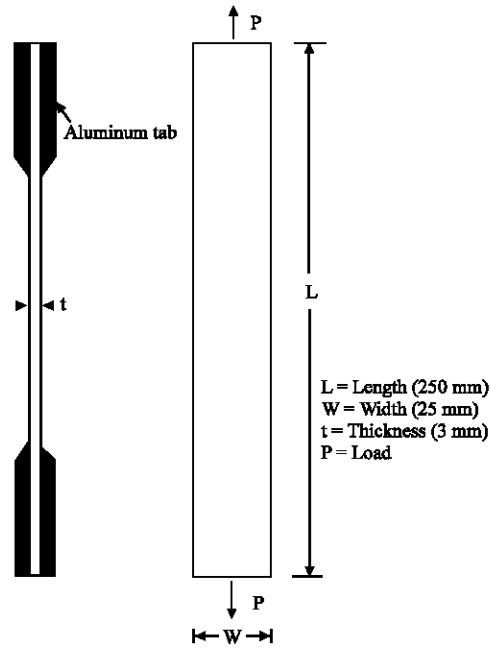


Fig. 1: Dimensions of tensile specimen

The minimum value of ' $N_x$ ' depends on the stiffness, aspect ratio and for given value of ' $m$ '. Solving the Eq. 3 for different values of ' $m$ ', ' $n$ ' and ' $p$ ', the theoretical buckling load can be derived as:

$$N_x = K \frac{\Pi^2 D_{22}}{a^2} \quad (4)$$

For unidirectional,  $0^\circ$  oriented composite plate:

$$D_{22} = \frac{1}{3} \left[ \frac{E_T}{1 - \gamma_{LT}\gamma_{TL}} \right] \left( \frac{t}{2} \right)^3 \quad (5)$$

In present observation, the theoretical buckling load for a rectangular plate is calculated by taking the constants  $a = 75$  mm,  $t = 3$  mm and  $p = 2$ . The  $K$  value is calculated for minimum buckling load and it is equal to 8.5 when  $m = 1$ . Therefore, the critical buckling load is:

$$(N_x)_{cr} = 1.2603 \left[ \frac{E_T}{1 - \gamma_{LT}\gamma_{TL}} \right] \quad (6)$$

Using Eq. 6, the theoretical buckling is determined and presented in Table 2.

## EXPERIMENTAL PROCEDURE

**Materials and specimens:** In this investigation, all the specimens with unidirectional fibre orientation were cut from the rectangular panels which were made up with E-Glass roving and a

resin composition with Araldite LY556 and Hardener HY951 at the ratio of 10:1 by weight. The panels were fabricated by hand-layup technique developed in the laboratory with special interest on  $0^\circ$  fibre orientation. A rectangular mild steel frame was used for winding the fibre in unidirectional and  $0^\circ$  orientation form. The thickness of the panels was controlled by controlling the number of lamina impregnated into the fabrication. Ample precaution was taken to minimize voids in the material and maintain homogeneity.

These panels were cured at  $80^\circ\text{C}$  and at a pressure of 85 psi ( $586 \text{ KN m}^{-2}$ ). After two hours, the fabricated panels cooled and were posts cured at  $60^\circ\text{C}$  for 4 h. The resulting panels had average thickness of 3 mm and had a fibre volume fraction of 45% ( $\pm 1\%$ ).

The specimens with ASTM Standard (D-3039) dimensions, as shown in Fig. 1, were prepared from the fabricated Glass fibre reinforced composite panel using a sharp edge diamond blade Marvel Cutter. Similarly for the buckling test, the rectangular plate of dimension  $150 \times 75 \text{ mm}$  as shown in Fig. 2, were cut from the same panel with unidirectional,  $0^\circ$  oriented glass fibre presents. After specimens for all tests were cut, they were numbered, weighed and measured to obtain accurate dimension. The tensile and buckling tests conducted for both virgin specimens (without liquid chemicals exposure) and chemicals exposed specimens with different durations of exposure. Minimum of five specimens were tested from each group.

**Liquid chemicals:** Based on liquid fuels used in aerospace industries, three types of liquid chemicals were selected for studying the effect over the GFRC specimens. These were Kerosene oil, Hydrogen peroxide and Hydrazine hydrate. The specimens were immersed in these chemicals for different durations, namely 24, 72, 120 and 168 h in room temperature conditions and final weight of the specimens were measured after schedule exposure. The amount of liquid chemicals absorption is calculated as percentage of weight gain by using following equation:

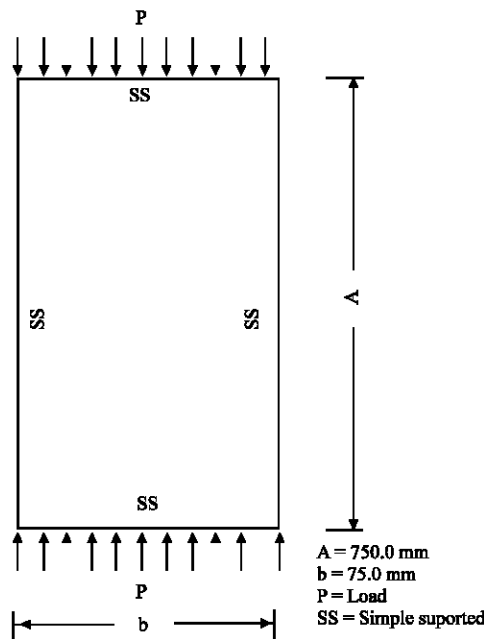


Fig. 2: Rectangular plate for buckling test

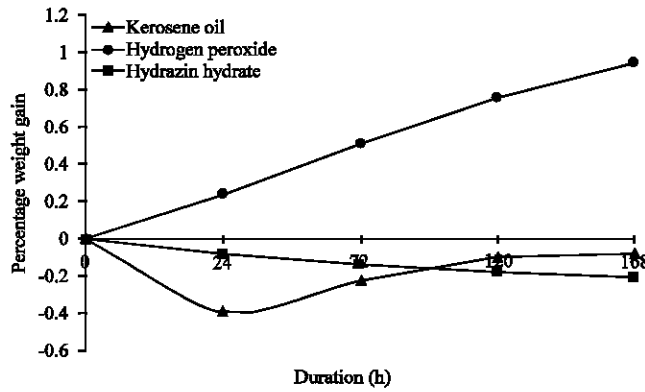


Fig. 3: Percentage of weight gain unidirectional, 0° oriented glass/expoxy composite after exposure to various liquid chemicals for different durations

$$\% \text{Weight gain} = \frac{M_f - M_i}{M_i} \times 100 \quad (7)$$

where,  $M_f$  was the final weight of the specimen after removing from liquid chemicals and  $M_i$  was the initial weight measured after specimen preparation. The average of percentage weight change of the specimens in treated chemicals for different durations were calculated and shown in Fig. 3.

**Tensile test and elastic properties measurement:** The tensile tests were conducted on ASTM D 3039 Standard specimens (Fig. 1) both dry and wet stage. The servo hydraulic UTM machine having a maximum capacity of 10000 Kgf load was used for measuring the ultimate tensile strength, tensile modulus of longitudinal and transverse axis and major and minor Poisson's ratio. Minor Poisson's ratio was calculated using simple relationship:

$$\frac{\gamma_{LT}}{E_T} = \frac{\gamma_{TL}}{E_L} \quad (8)$$

Electrical rosette strain gauges and electrical balanced stain indicator supplied by Rohit and Co., Roorkey (India), were used to measure the strain of the glass fibre reinforced composite specimens. Minimum of five specimens were tested from each group of liquid chemicals exposed and virgin samples for elastic properties determination and average results were presented in Table 1.

**Buckling test:** Similarly, buckling tests were conducted for both liquid chemical exposed specimens and virgin specimens. A universal testing machine with modified support fixtures with four side simple condition were used for the test. Deflections were observed putting dial gauges at the centre of the plate. As the load was gradually increased, the dial gauge needle started moving and at the onset of buckling, there was a sudden large movement of the needle. The load corresponding to this point was taken as the initial buckling load. The process was further continued until the plate was unable to carry any more loads and results were recorded as post buckling load.

Table 1: Elastic properties of unidirectional,  $0^\circ$  oriented glass fibre reinforced composite after exposing to various liquid chemicals for different durations

Types of chemicals	Duration of exposure (h)	$E_L$ ( $10^6 \text{ kg cm}^{-2}$ )	$E_T$ ( $10^6 \text{ kg cm}^{-2}$ )	$\gamma_{LT}$	$\gamma_{TL}$	UTS ( $\text{kg mm}^{-2}$ )
Virgin	0	0.470	0.132	0.2649	0.0744	4.539
Kerosene oil	24	1.176	0.058	0.053	0.0026	3.824
	72	0.995	0.161	0.102	0.0165	3.558
	120	0.778	0.202	0.270	0.0701	3.468
	168	0.645	0.251	0.340	0.1318	2.908
	24	0.360	0.149	0.450	0.1863	2.5163
Hydrogen peroxide	72	0.456	0.159	0.330	0.1151	1.827
	120	0.516	0.163	0.252	0.0800	1.339
	168	0.840	0.175	0.246	0.0512	0.9316
	24	0.950	0.1005	0.115	0.0122	2.673
Hydrazine hydrate	72	0.750	0.156	0.137	0.0285	1.808
	120	0.590	0.2057	0.165	0.0575	1.091
	168	0.508	0.2317	0.242	0.1104	0.774

Table 2: Buckling properties of unidirectional,  $0^\circ$  oriented glass fibre reinforced composite after exposing to various liquid chemicals for different durations

Types of chemicals	Duration of exposure (h)	Experimental buckling load (kg)	Theoretical buckling load (kg)	Experimental post-buckling Load (kg)
Virgin	0	1382	1478	1670
Kerosene Oil	24	1067	731	1293
	72	1184	2031	1400
	120	1263	2593	1534
	168	1343	3296	1624
	24	1280	2048	1582
Hydrogen peroxide	72	1214	2081	1560
	120	1164	2095	1455
	168	934	2232	1350
	24	1354	1267	1600
Hydrazine hydrate	72	1247	1972	1497
	120	1182	2615	1407
	168	1044	2998	1364

The experiments were conducted for five numbers of specimens from each group of liquid chemical exposed specimens and for virgin specimens. The average results of buckling tests and calculated theoretical buckling load are shown in Table 2 for ready reference.

## RESULTS AND DISCUSSION

**Liquid chemical effect:** Figure 3 shows changes of weight gain of the specimens immersed in three different chemicals, i.e., kerosene oil, hydrogen peroxide and hydrazine hydrate at room temperature for different durations. The results shown in the figure are average of five specimens measured by an electronic digital balance having 0.001 mg minimum least count. Percentage of weight gain after various environmental exposures for different durations was calculated by using Eq. 7. The negative values indicate the loss of weight.



In kerosene oil, there is highest amount of weight loss in 24 h and that loss gradually reduced as the time of immersion increased. Chemical reaction of kerosene and glass fibre reinforced composite dissolved matrix phase of composite. Reverse effect found for hydrogen peroxide immersed specimens. The specimens have gained the weight after immersing into the liquid and that weight gain was accelerated with increase in duration of exposure. However, the rate of diffusion of chemicals reduced as the duration of exposure is increased.

Again, in case of hydrazine hydrate, there was marginal weight loss or low rate of dissociation of composite at initial period of immersion. However, the dissociation rate was gradually increased, as the immersion time was increased. Therefore, there is a minor weight loss at initial period of immersion, i.e., 24 h and increased to a higher value as the duration of exposure increased to 168 h. It can be noted that the rate of chemical reaction reduced as the duration of immersion increased and that is due to the dilution of the chemicals by dissolving elements of the composite.

**Elastic properties:** The percentage variation in elastic modulus at longitudinal axis ( $E_L$ ) of unidirectional,  $0^\circ$  oriented glass fibre reinforced composite after exposure to various liquid chemicals for different durations are shown in Fig. 4. It was found that the values of  $E_L$  for Kerosene oil exposed specimens are higher than the values of virgin (without chemical effect) specimens. This is attributed to low value of strain obtained for kerosene oil exposed specimens compared to virgin specimens at same stress. In addition to weight loss in form of matrix loss, the composite properties are controlled by the fibre presence. The fibres contribute high rigidity and produce less elongation at the high stress value. It caused the higher elastic modulus at longitudinal axis. However, for longer duration of exposure, the continue diffusion of liquid chemicals into the penetrated surface area of composite caused the swelling of the specimens. The ductility of the composite is increased and resulted reduction in  $E_L$  value for kerosene oil exposed specimens. Similar types of behaviour are recorded for the hydrazine hydrate exposed specimens. The possible cause of these higher values is related in same line like kerosene oil exposed specimens. Whereas, the specimens exposed in hydrogen peroxide have continuous increase in weight with respect to immersion duration. The liquid particles diffused to the composite caused the swelling due to osmotic pressure and reaction of liquid with polymer. This might increased the ductility of the matrix. This is resulted a higher strain on same stress value as applied for kerosene and hydrogen peroxide exposed specimen and a low elastic modulus ( $E_L$ ). It has been observed that the duration of exposure and rate of chemical reaction have sufficient influence over the elastic modulus  $E_L$ .

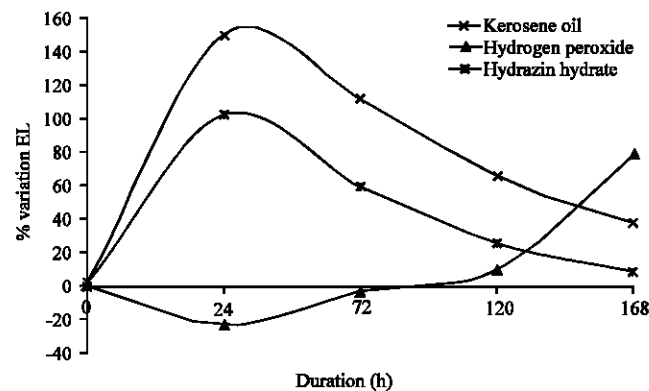


Fig. 4: Percentage variation of young's modulus ( $E_L$ ) of unidirectional,  $0^\circ$  oriented glass/epoxy composite after exposure to various liquid chemicals for different durations

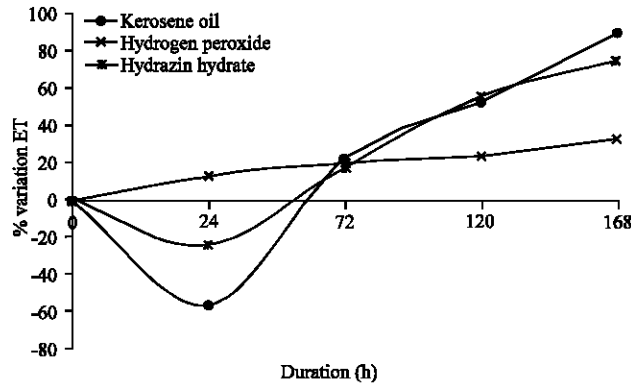


Fig. 5: Percentage variation of young's modulus ( $E_T$ ) of unidirectional,  $0^\circ$  oriented glass/epoxy composite after exposure to various liquid chemicals for different durations

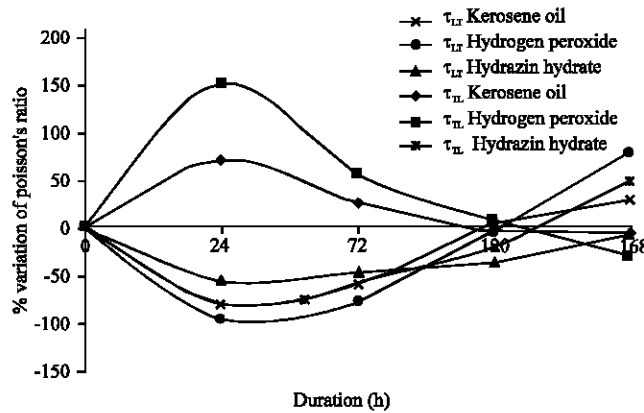


Fig. 6: Percentage variation of poisson's ratio ( $\tau_{TL}$  and  $\tau_{LT}$ ) of unidirectional,  $0^\circ$  oriented glass/epoxy composite after exposure to various liquid chemicals for different durations

In Fig. 5, the percentage variation of elastic modulus ( $E_T$ ) in transverse axis of unidirectional,  $0^\circ$  oriented glass fibre reinforced composite specimens are shown after exposing to various liquid chemicals for different durations. As the elastic modulus in transverse axis is matrix dependent properties, the elastic modulus of matrix is reduced due to high value of weight loss in kerosene oil at initial immersion period and further increased above the virgin result after long duration of exposure. This is due to the continue reaction of liquid medium with the matrix which resulted the change in stiffness of matrix in composite. Similar trend found in hydrazine hydrate exposed specimens. However, the specimens exposed to hydrogen peroxide have shown an insignificant change in  $E_T$  values. This may be correlated with weight gain of the specimens inside the chemicals which resulted low yield strength and increased ductility of the resin.

Figure 6 shows the percentage variation of both major and minor Poisson's ratio ( $\gamma_{LT}$  and  $\gamma_{TL}$ ) of unidirectional,  $0^\circ$  oriented glass fibre reinforced composite after immersing to various liquid chemicals for different durations with respect to virgin test results. The Poisson's ratio is generally related to factors like longitudinal and lateral strain of the specimens. The causes of variation of strain values after exposing to various liquid chemicals are already discussed in above paragraphs. The properties measured have significant effect over theoretical buckling load.

The percentage variation of ultimate tensile strength of unidirectional,  $0^{\circ}$  oriented glass fibre reinforced composite are shown in Fig. 7 after exposing to various liquid chemicals for different durations and comparing with ultimate tensile strength of virgin specimen. It is approximately 36% reduction after 168 h immersion in kerosene oil. However, there is 80% reduction of ultimate tensile strength of same composite when it is immersed in hydrogen peroxide and 83% in hydrazine hydrate. It is indicating that the chemical reaction over composite and development of stress corrosion. In addition, the trend indicates that there is constant reduction of material tensile strength under these liquid chemicals and this is in higher order for hydrogen peroxide and hydrazine hydrate exposed specimens, whereas in kerosene oil, the reduction of tensile properties of composite is marginal. Possible cause of reduction can be attributed to following events:

- Loss of strength of the reinforcing fibres by stress corrosion
- Loss of adhesion and interfacial bond strength by chemical reaction
- Strength loss of matrix due to permeation of liquid chemicals
- Accelerated degradation of material properties due to prolong immersion in liquid chemicals and
- Failure due to different chemical reaction with constituent phases

**Buckling properties:** The percentage variation of experimental determined buckling loads of unidirectional,  $0^{\circ}$  oriented glass fibre reinforced composite plates after exposing to various liquid chemicals for different durations with respect to virgin buckling loads are shown in Fig. 8. The figure shows the percentage variation is initially 22.8% for 24 h kerosene oil exposed specimens and that value reduced to 2.8% as the duration of exposure increased to 168 h. Whereas the specimens exposed to hydrogen peroxide and hydrazine hydrate have shown an increasing trend as the duration of exposure increased and that is maximum of 32.4% for hydrogen peroxide exposed specimens and 24.5% for hydrazine hydrate after 168 h exposure. Possible causes are attributed to chemical reaction effects on fibre-matrix composition, liquid inflow by osmotic pressure and swelling resulted weak bond strength of the specimens. The kerosene oil may produce some initial reaction with composite that dissociate the outer core of the bonded matrix present. With prolong exposure, the reaction was reduced and more kerosene oil penetrated into the material and provided high stiffness.

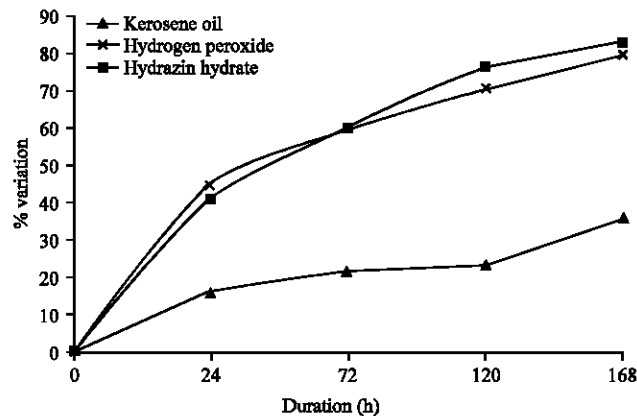


Fig. 7: Percentage variation of ultimate tensile strength for unidirectional 0-deg. Oriented glass/epoxy composite after exposure to different liquid chemicals for various duration

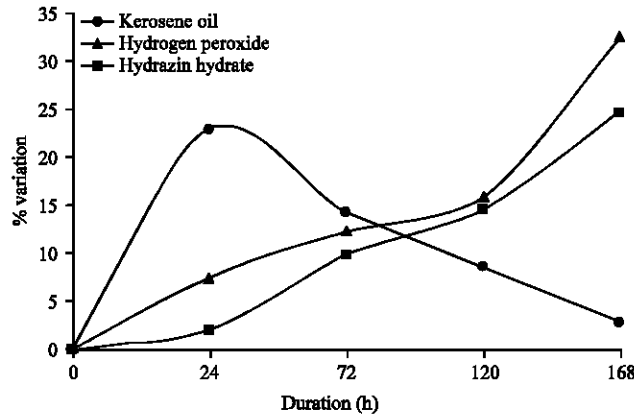


Fig. 8: Percentage variation of experimental buckling load of unidirectional,  $0^0$  oriented glass/epoxy composite after exposure to various liquid chemicals for different duration

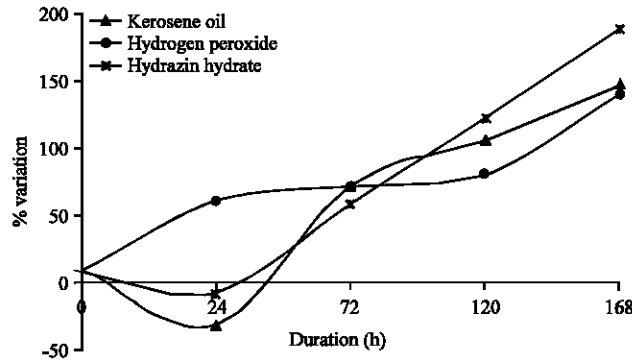


Fig. 9: Percentage variation of theoretical and experimental buckling load of unidirectional,  $0^0$  oriented glass/epoxy composite after exposure to various liquid chemicals for different duration

In hydrogen peroxide, there is gradual increase in weight of the specimens as the duration of immersion increased and indicated the maximum absorption of liquid. The fibres bonded with the resin expanded in the process by moisture absorption which resulted the interfacial debonding between fibres and matrix and micro cracks development near the interface in the matrix. The strength of a unidirectional oriented composite depends on the interlaminar strength, fibre-matrix bonding and the strength of the resin and fibres. Immersion of liquid particles into composite phases has lowered the bonding strength of the interface and weakened the strength of composite. Also, prolong immersion inside the liquid hydrazine hydrate resulted the debonding, fibre corrosion and weakening the specimen strength. Here, the weight loss was found and the weight loss was completely depended on duration of exposure. There were continuous diffusion of liquid particles into matrix, corrosion of fibres and reduction of bond strength and development of micro cracks. Thus, the virgin buckling strength was reduced significantly with respect to duration of exposure.

The percentage variation of theoretical buckling load in comparison to experimental buckling load was shown in Fig. 9. A lowest theoretical buckling load was found for 24 h exposed specimens in kerosene oil and it is about 31.5% less than the experimental buckling load. However, for other

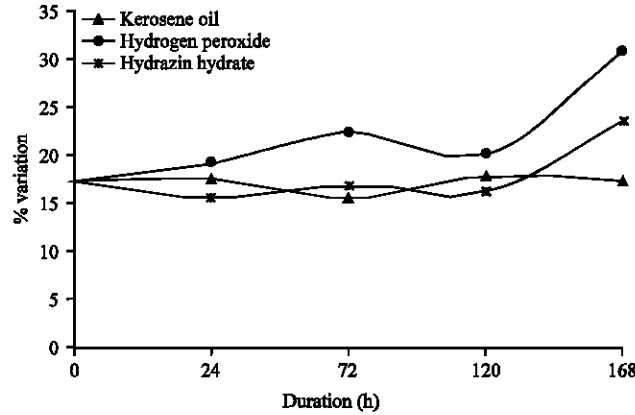


Fig. 10: Percentage variation of post-buckling load of unidirectional,  $0^{\circ}$  oriented glass/epoxy composite after exposure to various liquid chemicals for different duration

exposed specimens, the theoretical buckling loads have higher value compared to experimental buckling load and it is about 145.4% more for 168 h exposed specimens in same kerosene oil. Similar type of trend was found for Hydrazine hydrate exposed specimens. However, the specimens exposed to hydrogen peroxide has shown different trend. For 24 h exposed specimens, the theoretical buckling load is 60% more than experimental buckling load and that variation increased to 139% for 168 h exposed specimens. The cause of variation of theoretical buckling load and experimental buckling load can be related to following factors:

- The calculation of theoretical buckling load depends on flexural stiffness  $D_{22}$  which is a derivative of elastic properties like  $E_T$ ,  $\gamma_{LT}$  and  $\gamma_{TL}$ . These properties have been significantly affected due to chemical reaction
- By hand-lay-up technique, it is almost impossible to fabricate a plate with equal distribution of fibres and the matrix material everywhere and impossible to obtain complete homogeneity
- The in-plane load applied may not be exactly axial to the fibre
- The presence of void also reduces the experimental buckling load

Figure 10 shows the percentage variation of post-buckling load of unidirectional,  $0^{\circ}$  oriented glass fibre reinforced composite with respect to critical buckling load. It has been found that there are reasonable variations of post-buckling load in comparison to critical buckling load. The results are also indicating that the composite has sufficient residual strength after exposure to various liquid chemicals for different durations.

The possible cause of variation of buckling and post buckling load is attributed to the coupling between bending and extension in a laminate which increased the deflections of the specimen. Hence, the coupling decreased the effective stiffness of a laminate. At the same time, that coupling reduced the buckling load capability. For laminate with twist-curvature coupling, the deflections of composite specimen were found to increase and reduced the load bearing capacity of the specimens. Finally, these effects produced the failure on the specimens and decreased the amount of load carrying capacity of the specimens. Further, chemical effect could not be ignored which decreased sizably the post-buckling strength of the composite.

## CONCLUSIONS

Based on the experimental observations and discussion following important conclusions can be drawn:

- Used liquid chemicals has shown both weight gain and loss of composite specimens and depended on immersion duration. But, rate of chemical reaction differed with respect to duration of immersion
- High value of elastic modulus in longitudinal axis ( $E_L$ ) was observed for specimens which has shown weight loss after immersion in liquid chemicals and that depended on nature of the chemicals and type of the reactions. In case of more absorption, similar trend noted and related to debonding, matrix swelling, matrix cracking and micro buckling of fibre in due course of exposure
- Unidirectional,  $0^\circ$  oriented glass/epoxy composite, elastic modulus in transverse axis ( $E_T$ ) depended on matrix properties. The specimen, who has shown weight gain, has produced high elastic modulus in transverse axis. There is no physical loss of matrix materials. However, in case of weight loss specimens, there is initial loss in elastic modulus value in transverse axis and that was recovered and exceed than original value as the duration of exposure increased
- Similar trend was observed for determination of both major and minor Poisson's ratio. Initially it has shown low value than virgin results for weight loss specimens (specimen exposed to Kerosene oil and Hydrazine hydrate) and gradually increased above than virgin test results. Reverse results was obtained in case of weight gain specimens, i.e., the hydrogen peroxide exposed specimens and is related to diffusion rate of liquid into matrix, chemical reaction and corrosion of composite
- Ultimate tensile strength reduced significantly after liquid chemicals reaction over the specimen and it is highest in case of Hydrogen peroxide exposed specimens
- Experimental buckling load reduced marginally after exposing to three different liquids and it is within the range of 32% maximum after 168 h exposure
- Theoretically, determined buckling load has shown significant deviation in comparison to experimental determined buckling load for liquid chemical exposed plates and it is due to flexural stiffness value used in determination of theoretical buckling load
- Experimental determined post-buckling loads have shown almost equal difference against experimental determined buckling loads except to some cases, like for specimens exposed for 168 h in hydrogen peroxide and hydrazine hydrate. It justifies that the process of experiment is error less

Thus, the unidirectional,  $0^\circ$  oriented glass fibre epoxy composite has shown a significant changes in buckling strength after exposure to liquid chemicals like Kerosene oil, Hydrogen peroxide and Hydrazine hydrate for various durations. The chemicals have reduced elastic properties in a sizeable margin. This can be prevented by application of advance fabrication technique, so that there will be better void control; applying corrosion resistance coating over the material, controlling the hygroscopic nature of matrix and selecting better matrix to prevent chemical reaction. No doubt, fibre composite is a better pursuit for tank design for future aerospace vehicles.

## **NOMENCLATURES**

$D_{11}$ ,  $D_{12}$ ,  $D_{22}$  and  $D_{66}$  = Bending stiffness of the plate  
 $E_L$  = Young's modulus in longitudinal direction  
 $E_T$  = Young's modulus in transverse direction  
 $K$  = Constant values for different aspect ratio  
 $M_f$  = Weight of the specimen after exposure to environment  
 $M_i$  = Weight of the specimen at virgin condition  
 $N_x$  = Buckling load  
 $a$  = Length of the plate (mm)  
 $b$  = Width of the plate (mm)  
 $m$  = n-Number of half waves that the plate buckles in the x and y direction, respectively  
 $p$  = Aspect ratio of the plate  
 $t$  = Thickness of the plate (mm)  
 $w$  = Deflection of the point on median surface of plate in direction normal to the undeformed plate  
 $cr$  = Critical condition

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