Structural Engineering and Mechanics, *Vol. 50, No. 2 (2014) 231-240*
DOI: http://dx.doi.org/10.12989/sem.2014.50.2.231

Fatigue modeling of chopped strand mat/epoxy composites

M.M. Shokrieh*, M. Esmkhani[a] and F. Taheri-Behrooz[b]

Composites Research Laboratory, Center of Excellence in Experimental Solid Mechanics and Dynamics, School of Mechanical Engineering, Iran University of Science and Technology, 16846-13114 Tehran, Iran

(Received December 9, 2013, Revised February 7, 2014, Accepted March 2, 2014)

Abstract. In the present research, fatigue behavior of chopped strand mat/epoxy composites has been studied with two different techniques. First, the normalized stiffness degradation approach as a well-known model for unidirectional and laminated composites was utilized to predict the fatigue behavior of chopped strand mat/epoxy composites. Then, the capability of the fatigue damage accumulation model for chopped strand mat/epoxy composites was investigated. A series of tests has been performed at different stress levels to evaluate both models with the obtained results. The results of evaluation indicate a better correlation of the normalized stiffness degradation technique with experimental results in comparison with the fatigue damage accumulation model.

Keywords: fatigue; normalized stiffness degradation; damage accumulation; short fibers; chopped strand mat

1. Introduction

There are many applications for chopped strand mat (CSM) composites in various industries because of their intrinsic properties. In many applications, the CSM polymeric composites are under fatigue loading conditions. Three principal approaches are used to predict the fatigue life: residual strength (Whitworth 2000), residual stiffness (Whitworth 1997, Ye 1989, Whitworth 1987, Yang *et al.* 1990) and empirical methodologies (Epaarachchi and Clausen 2003).

The fatigue life of CSM polymeric composites has been investigated by some researchers (Mandell 1990, Sul *et al.* 2010, Caprino and D'Amore 1998). Sul *et al*. (2010) performed experimental and analytical investigations on the low cycle-fatigue life of glass-reinforced polymer (GRP) in CSM form at room temperature. Caprino and D'Amore (1998) investigated the flexural fatigue behavior of random continuous-fiber reinforced thermoplastic composites and the data obtained were used to assess a closed-form formula, aimed at the prediction of the fatigue response of a composite material, and explicitly accounting for the effect of the stress ratio (the ratio of minimum applied stress to maximum applied stress). Prusty *et al*. (2009) established a fatigue life prediction model to include both residual stiffness and strength degradation models together with thermal stresses.

*Corresponding author, Professor, E-mail: Shokrieh@iust.ac.ir
[a]Ph.D., E-mail: Esmkhani@iust.ac.ir
[b]Assistant Professor, E-mail: Taheri@iust.ac.ir

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

A set of sudden material property degradation rules, such as stiffness degradation, for various failure modes of a unidirectional ply under a multi-axial state of static and fatigue stress was developed by Shokrieh and Lessard (2000) for laminated composite materials. However, their model was not applied for CSM/epoxy composites.

In the present work, the normalized stiffness degradation method was utilized for CSM/epoxy composites to predict the fatigue life. Moreover, the fatigue damage accumulation model developed by Ye (1989), for E-glass fabric in CSM form with isophthalic polyester resin, was not applied for CSM/epoxy composites. So, in the present research, the capability of this model for epoxy matrix composites is also investigated. In the present research, a series of tests in tension–tension fatigue condition at room temperature is carried out at different load levels to evaluate the capabilities of both models with experimental observations.

2. Analytical models

2.1 Normalized stiffness degradation model

The residual stiffness of the material is also a function of the state of stress and number of cycles. Since residual stiffness can be used as a nondestructive measure of damage evaluation, stiffness degradation models have been developed by many investigators. The present study follows a normalization technique developed by Shokrieh and Lessard (2000) to predict the stiffness degradation of nanocomposite materials using micromechanics approaches. By using the normalization technique, all different curves for different states of stress can be shown by a single master curve. Polymeric composites under a constant uniaxial fatigue loading and under static loading, or equivalently at N=0.25 cycles (quarter of a cycle) in fatigue is considered. To present the residual stiffness as a function of number of cycles in a normalized form for polymeric composites in fatigue loading conditions, the following equation is developed (2000)

$$E\,(N,\sigma,R) = [1-(\frac{\log(N)-\log(0.25)}{\log(N_f)-\log(0.25)})^{\lambda}]^{\frac{1}{\gamma}}(E_s-\frac{\sigma}{\varepsilon_f})+\frac{\sigma}{\varepsilon_f} \tag{1}$$

where $E(N,\sigma,R)$= residual stiffness for polymeric composites under fatigue loading condition, E_s= static stiffness of polymeric composites, σ=magnitude of applied maximum stress, ε_f=the average strain to failure, N=number of applied cycles, N_f=fatigue life at σ, and λ,γ=experimental curve fitting parameters. By using the normalization technique (Shokrieh and Lessard 2000), all different curves for different states of stress collapse to a single curve as shown in Fig. 1.

2.2 Fatigue damage accumulation model

Damage accumulation and cyclic degradation are critical issues for design and life prediction of composites under fatigue loading conditions. Several models for simulating damage accumulation have been developed in the last decade and can be categorized as follows (Ye 1989):

1- Models for dispersed defects, such as the application of fracture mechanics to transverse cracking and delamination (Crossman and Wang 1982, O'Brien 1982)

2- Phenomenological or macromechanical models (Poursartip and Beaumont 1983, Poursartip *et al.* 1986)

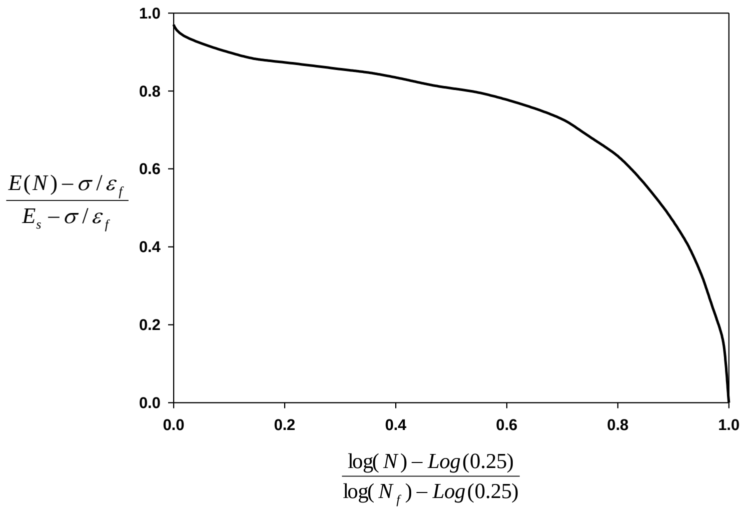

Fig. 1 Normalized stiffness degradation curve (Shokrieh and Lessard 2000)

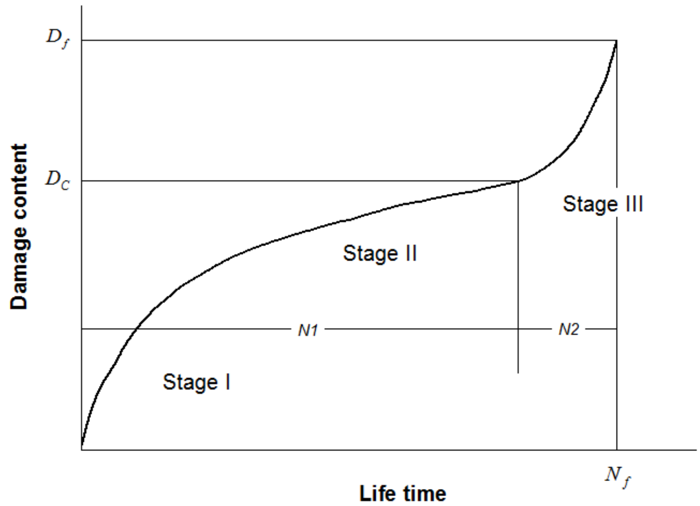

Fig. 2 Fatigue damage development in composite materials (Wang and Chim 1983, Highsmith *et al*. 1984)

3- Hybrid models (Ogin *et al*. 1985, Reifsnider 1986)

The fatigue damage theory for the CSM composites based on phenomenological aspects of damage accumulation in composite materials has been assessed by Ye *(1989)*. They assumed that the residual stiffness is a monotonically decreasing function of the fatigue cycle and depends on the damage variable as follows

$$D = 1 - \frac{E}{E_s} \tag{2}$$

where E is the current stiffness and E_s is the initial static stiffness of the material. The characteristics of fatigue crack growth and a damage accumulation law for composites can be defined as

$$\frac{dD}{dN} = C(\frac{\sigma^2_{\max}}{D})^n \tag{3}$$

where C and n are material constants that can be determined by testing specimens at various applied stresses. From the definition of the damage variable in Eq. (2) the damage development in the composites is shown in Fig. 2 (Wang and Chim 1983, Highsmith *et al*. 1984). Due to the inherently heterogeneous microstructure of the chopped fiber-reinforced composites, various kinds of stress concentrators exist in the materials, including fiber/matrix interfaces, fiber ends, process-induced defects, laminate stress-free edges or discontinuities, and residual stress concentrations developed during the curing process (Ye 1989). The presence of these stress concentrators results in a significant energy storage. The energy storage tends to approach an energy balanced state, as indicated by the feature of entropy in nonlinear irreversible thermodynamics (Ye 1989). In the early stage (stage I) of fatigue damage development, rates of energy dissipation and material degradation are rapid. In this stage, fatigue damage appears predominantly in the form of matrix cracking along fibers in plies of composite laminates (Reifsnider *et al*. 1983) and additionally, fiber-matrix interface debonding in the case of chopped fiber composites. The fibers aligned ahead of a matrix crack are obstacles to the crack growth. Therefore, it is more difficult to break a fiber than to break the matrix. Hence, during the stage II of fatigue damage development, energy dissipation and material degradation rates decrease when the matrix cracks reach fibers aligned at some angle in front of them. In the final stage (stage III) of fatigue damage development, sudden coalescence of micro-cracks and severity of interaction, in addition to rapid growth of the most favorable cracks, lead to the catastrophic fracture of composites (Ye 1989).

By combination of the damage parameter (Eq. (2)) and damage accumulation law (Eq. (3)) a material degradation model can be obtained as

$$\frac{dE}{dN} = -E_s C (\frac{\sigma^2_{\max}}{1 - E/E_0})^n \tag{4}$$

After integrating Eq. (4), the predicted modulus after N cycles can be expressed by the following expression

$$E = [1 - \{NC(n+1)\}^{1/n+1} \ \sigma_{\max}^{2n/(n+1)}]\, E_s \tag{5}$$

Eq. (5) can be used to predict the number of cycles required to reach a given stiffness reduction for a known fatigue maximum applied stress. In this relation, C and n, as material constants have to be identified by testing specimens after measuring stiffness reduction at various applied stresses.

3. Experimental procedure and test method

3.1 Material

The ML-526 epoxy resin is based on Bisphenol-A. The ML-526 epoxy was selected because of its low viscosity and extensive applications in composites industries. The curing agent was HA-11

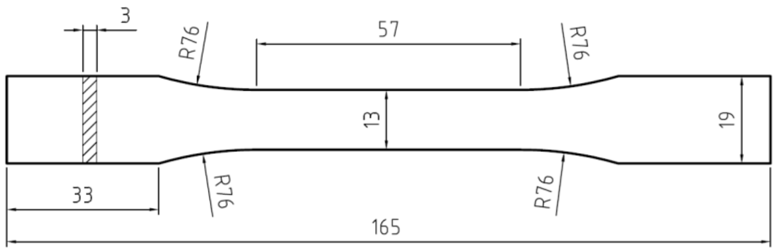

Fig. 3 Drawing of the specimen (dimensions in mm)

Table 1 Specification of the E-glass CSM fiber

Parameter	Value
Fiber diameter (μm)	10-20
Nominal weight (g/m^2)	450
Density (kg/m^3)	2500
Poisson's ratio	0.27
Tensile strength (MPa)	3300
Tensile modulus (GPa)	71

Table 2 Properties of ML-526 epoxy resin

Physical Properties		Mechanical Properties	
Viscosity at 25℃ (Centipoise)	Glass temperature (℃)	Tensile modulus (GPa)	Tensile strength (MPa)
1190	72	2.6	60

(Polyamine). The ML-526 epoxy resin and polyamine hardener HA-11 were supplied by Mokarrar Engineering Materials Company, Iran. The E-glass fabric in form of chopped-strand mat (CSM) was supplied by Taishan Fiberglass Inc., China. The random distributed fibers have an average diameter of approximately 13 micron; around 5 mm length and an area density of 450 g/m^2.

3.2 Specimen preparation

To fabricate specimens, the hardener was added to the epoxy resin at a ratio of 15:100 and stirred gently by using a mechanical stirrer (Heidolph RZR2102) for 5 min at 100 rpm. Stirring at low speed was very important to avoid any undesirable bubble formation. The CSM/epoxy composite specimens were manufactured using the hand layup process. Six layers of E-glass CSM were cut into a sheet of dimensions as follows: 210×200×3.5 mm. Then, layer by layer were stacked with ML-526 epoxy resin and impregnated at room temperature. To release the trapped air and voids, using a roller was required. Later, samples were kept under 500 N static loading to get trapped bubbles out. The fabricated sheet was also pre-cured under loading conditions for 48 hr. In order to do the post-curing process, it was placed into an oven for 2 *hr* at 80 *℃* and further 1 *hr* at 110℃. Finally, the test specimens, shown in Fig. 3, were cut in accordance with type 1 in ISO 527-4 by water jet cutting process. The specifications of both the E-glass CSM and the resin are presented in Tables 1 and 2.

Fig. 4 Servo hydraulics Instron 8802 uni-axial fatigue test machine

3.3 Test setups

A universal testing machine, STM-150 made by Santam Co. was utilized to perform the tensile tests in accordance with DIN EN ISO 527-4. A cross-head speed for the tensile test was set at 2 *mm/min*. For fatigue loading, the servo hydraulics Instron 8802 uni-axial fatigue test machine was used (see, Fig. 4).

4. Tests results and models evaluation

4.1 Static tests

A series of tests in static loadings are carried out to determine tensile properties of fabricated composites as isotropic fiber-reinforced composites. The stress-strain relationship of a sample is presented in Fig. 5 and the tensile tests results of all specimens are presented Table 3. In order to evaluate the fiber weight fraction, the burn-off test was performed to obtain the glass fiber content. In order to maintain statistical reliability, a minimum of four samples were tested in each step. The mean tensile strength of four samples was achieved equal to 158 MPa. The Young's modulus of fabricated composites was around 8.9 GPa (Table 3).

4.2 Cyclic tests

The tension-tension fatigue test was conducted at three different stress levels. The maximum stresses were chosen to be 50, 60 and 70% of the ultimate tensile strength of the specimen. The fatigue tests were carried out under load-control condition at a frequency of 2 Hz. During all fatigue tests, the stress ratio (minimum applied stress/maximum applied stress) was set at 0.1 under room temperature condition. The applied maximum stress and number of cycles to failure

Table 3 Properties of CSM/epoxy composites

Mechanical Properties			
Young's modulus (GPa)	Ultimate tensile strength (MPa)	Strain to failure (%)	E-glass CSM weight fraction (%)
8.9±0.2	158±2.7	1.9	50.5

Table 4 Sample of experimental results of CSM/epoxy composites under tension-tension fatigue loading at room temperature condition, R= 0.1, Strain to failure= 0.0187

Stress level (%)	Applied stress (MPa)	Number of cycles to failure (cycles)
70	111	6121
60	95	19398
50	79	36481

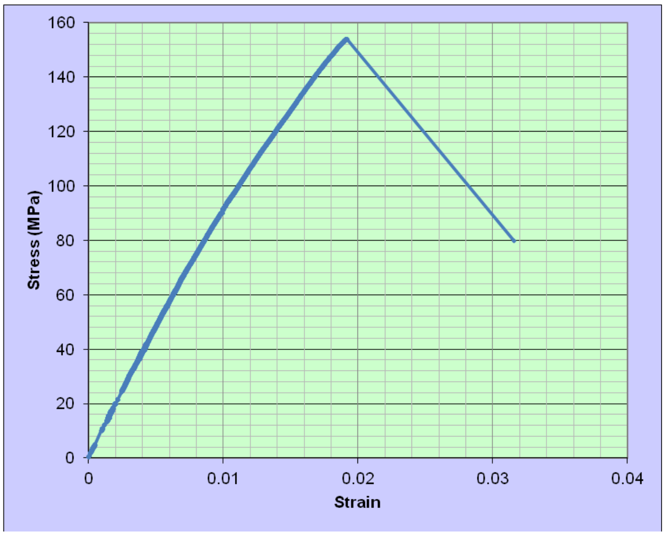

Fig. 5 Stress-strain curve of CSM/epoxy composites

from experiments for CSM/epoxy composites under the load control fatigue loading are demonstrated in Table 4.

4.3 Fatigue models evaluation

In the normalized stiffness degradation approach for CSM polymeric composites under fatigue loading to predict the fatigue life of CSM/epoxy composites, λ, γ (experimental curve fitting parameters from Eq. (1) have to be determined. By using the normalization technique and obtaining parameters as discussed in the previous sections, all different curves for different states of stress collapse to a single curve as shown in Fig. 6. The obtained value of λ, γ are 7.348 and 0.852, respectively. Moreover, the empirical parameters of C and n for the fatigue damage accumulation approach (Ye's Model) are founded from experiments equal to 2E-43 and 8.1256, respectively.

Finally, during the stage II of fatigue life (4000-24000 cycles) the normalized stiffness

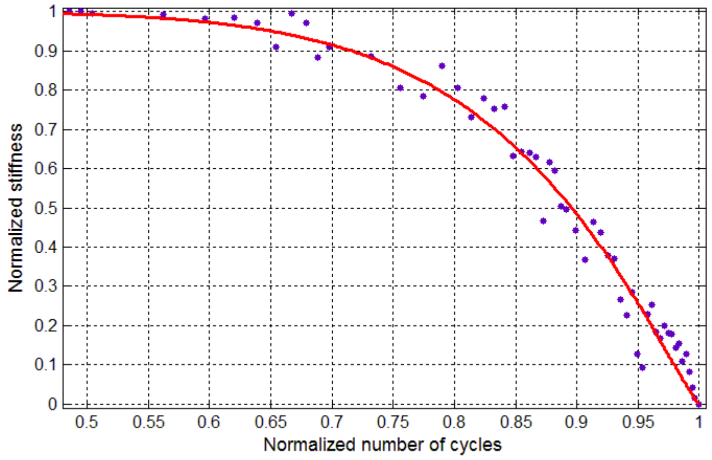

Fig. 6 Normalized stiffness degradation curve for CSM/epoxy composites, λ=7.348, γ=0.852, ε_f=0.0187

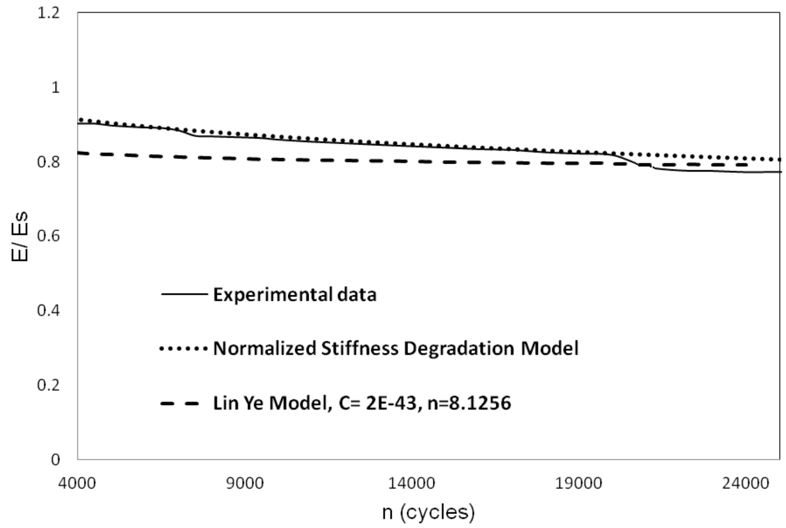

Fig. 7 Stiffness reduction of CSM/epoxy composites, stress level 50% of UTS, (comparison between models and experimental data)

reduction of CSM/epoxy composites at 79 MPa stress loading or 50% of the ultimate strength has been achieved and demonstrated. Then, the obtained behaviors of both models have been compared with experimental results and represented in Fig. 7. Evaluation of models indicates that there was a better correlation between the normalized stiffness degradation technique with experimental results in comparison with the fatigue damage accumulation model. In addition, the results show that the normalized stiffness degradation approach is properly applicable for CSM/epoxy composites and the application of this approach is not limited to unidirectional ply composites.

5. Conclusions

In the literature, the normalized stiffness degradation model for a unidirectional ply in a normalized form was studied and application of this model for CSM manufactured composites was not taken into account. Therefore, in this research, the normalized stiffness degradation method has been applied for CSM/epoxy composites to predict the fatigue life. A series of tests has been performed at different stress levels to evaluate both models. Also, reliability of the fatigue damage accumulation (called Ye's model) for an epoxy based matrix is investigated. Then, the obtained results have been compared with Ye's model and experimental observations. Evaluations indicate that there is good correlation between the normalized stiffness degradation technique with experimental results in comparison with fatigue damage accumulation model for CSM/epoxy composites. In addition, it is demonstrated that the normalized stiffness degradation model is not limited only to unidirectional ply composites but is also valid for CSM composites. Therefore, the defined scope and application area can be extended.

References

Caprino, G. and D'Amore, A. (1998), "Flexural fatigue behavior of random continuous-fiber reinforced thermoplastic composites", *Compos. Sci. Tech.*, **58**, 957-965.

Crossman, F.W. and Wang, A.S.D. (1982), "The dependence of transverse cracking and delamination on ply thickness in graphite/epoxy laminates", Damage in Compos Mater, ASTM STP-775, 118-139.

Epaarachchi, J.A. and Clausen, P.D. (2003), "A model for fatigue behavior prediction of Glass Fibre-Reinforced Plastic (GFRP) composites for various stress ratios and test frequencies", *Compos. A: Appl. Sci. Manuf.*, **34**, 313-326.

Highsmith, A.L., Stinchcomb, W.W. and Reifsnider, K.L. (1984), "Effect of fatigue induced defects on the residual response of composite laminates", Effects of defects in Composite Materials, ASTM STP-836, 194-216.

Mandell, J.F. (1990), *Fatigue of Composite Materials*, Ed. Reifsnider, K.L., Elsevier Science Publishers B.V.

O'Brien, T.K. (1982), "Characterization of delamination onset and growth in a composite laminate", Damage in Composite Materials, ASTM STP-775, 140-167.

Ogin, S.L., Smith, P.A. and Beaumont, P.W.R. (1985), "Matrix cracking and stiffness reduction during the fatigue of a (0/90) GFRP laminate", *Compos. Sci. Tech.*, **22**, 23-31.

Whitworth, H.A. (2000), "Evaluation of the residual strength degradation in composites laminates under fatigue loadings", *Compos. Struct.*, **48**, 261-264.

Whitworth, H.A. (1997), "A stiffness degradation model for composite laminates under fatigue loading", *Compos. Struct.*, **40**, 95-101.

Ye, L. (1989), "On fatigue damage accumulation and material degradation in composite materials", *Compos. Sci. Tech.*, **36**, 339-350.

Poursartip, A. and Beaumont, P.W.R. (1983), *A damage approach to the fatigue of composites*, Mechanics of Composite Materials, Recent Advances, Ed. Hashin, Z. and Herakovich, C.T., Pergamon Press, New York.

Poursartip, A., Ashby, M.F. and Beaumont, P.W.R. (1986), "The fatigue damage mechanics of a carbon fiber composite laminate, I - Development of the model", *Compos. Sci. Tech.*, **25**, 193.

Prusty, B.G., Pan, J.W. and Sul, J. (2009), "Characterization of temperature-dependent behavior of chopped strand mat GRP during low cyclic fatigue", *Conference of Composites or Nano Engineering*, Honolulu, Hawaii.

Reifsnider, K.L. (1986), "The critical element model: a modeling philosophy", *Eng. Fract. Mech.*, **25**, 739-

749.

Reifsnider, K.L., Henneke, E.G., Stinchcomb, W.W. and Duke, J.C. (1983), “Damage mechanisms and NDE of composite laminates”, Mechanics of Composite Materials, Recent Advances, Ed. Hashin, Z. and Herakovich, C.T., Pergamon Press, New York.

Shokrieh, M.M. and Lessard, L.B. (2000), “Progressive fatigue damage modeling of composite materials Part I: modeling”, *J. Compos. Mater.*, **34**, 1056.

Sul, J.H., Prusty, B.G. and Pan, J.W. (2010), “A fatigue life prediction model for Chopped Strand Mat GRP at elevated temperatures”, *Fatig. Fract. Eng. Mater. Struct.*, **33,** 513-521.

Wang, S.S. and Chim, E.S.M. (1983), “Fatigue damage and degradation in random short-fiber SMC composite”, *J. Compos. Mater.*, **17,** 114-131.

Whitworth, H.A. (1987), “Modeling the stiffness reduction of graphite/epoxy composite laminates”, *J. Compos. Mater.*, **21**, 362-372.

Yang, J.N, Jones, D.L., Yang, S.H. and Meskini, A. (1990), “Stiffness degradation model for graphite/ epoxy laminates”, *J. Compos. Mater.*, **24**, 753-769.