International Journal of Theoretical and Applied Mechanics.
ISSN 0973-6085 Volume 12, Number 4 (2017) pp. 863-872

http://www.ripublication.com

Development of a code to generate randomly distributed short fiber composites to estimate mechanical properties using FEM

Biju Balan[1], Babu Reddy[2] and K Badari Narayana[3]

[1] Aero Structures, UTC Aerospace Systems, Hoodi, White Field, Bengaluru-560048

[2] Asst. Professor, Department of Machine Design, VTU PG Centre,
Kalaburagi -585101, India.

[3]Professor, Department of Mechanical Engineering, BMSIT, Yelahanka,
Bengaluru-560064, India.
Corresponding Author

Abstract

Short fiber reinforced composites (SFC) emerged as a trade-off between continuous fiber composites, which are the secondary load bearing components in aerospace structures owing to their very high mechanical properties. The present work is aimed at developing a code to generate randomly distributed SFCs to estimation their mechanical properties using FEM. A close correlation was observed between the properties obtained by various empirical methods and by the present FE results obtained for random short fibers. This data should be a good starting point for the preliminary design of components manufactured using SFC.

1. INTRODUCTION

Specific stiffness and specific strength is always a premium for an aircraft. The lower the structural weight the higher payload it can carry, with lesser fuel consumption. This is the scenario in which Light weight alloys and composites become crucial for aerospace and other industries. Composite, a multi-phase material is a combination of two or more organic or inorganic components. One material with continuous phase called matrix, the other material with dispersed phase serves as reinforcement. The most common matrix materials are thermosetting materials such as Epoxy, Bismaleimide, or Polyimide. The reinforcing materials can be glass fibre, boron fibre, carbon fibre, etc.

It is very important to validate the component design before going for manufacturing, for this, the experimental data of the material in the form of its physical and mechanical properties are made available (unfortunately, these are not widely available). For this reason, an accurate prediction of mechanical physical properties of short fiber composites like strength and stiffness is very important. Empirical, mathematical & numerical models exist but the application of these to aerospace industry is very limited. The present work deals with the use of such models to predict the properties of SFC which can be used in FE simulations to evaluate the structural behavior of composite components made of short fibers.

The work has two major components of research, they are

- A thorough literature to identify close form solution for strength and stiffness for SFC with aligned and for non-aligned fibers
- Generate a VBA (Visual Basic for Applications) code for forming a unit volume of composite system with randomly oriented short fibers and validate its mechanical properties using FEM for either single fiber or certain fiber combinations in random orientations

2. PREVIOUS WORK

In the present work the literature related to mathematical models empirical relations and experimental methods for the evaluation stiffness and strength properties of randomly oriented SFC is given.

The simplest models developed by Voigt and Reuss are those which make use of the rule of mixtures. Voigt assumed that each component was subject to the same strain (iso-strain), giving an expression for E_c as

$$E_c = V_f E_f + V_m E_m \tag{1}$$

Reuss assumed that each phase was subject to the same stress (iso-stress), giving an expression for E_c as

$$E_c = E_f E_m / (V_f E_m + V_m E_f) \tag{2}$$

The in-plane modulus of a random fiber composite was proposed by Tsai and Pagano (1968) in the form

$$E = \frac{3}{8} E_{11} + \frac{5}{8} E_{22} \tag{3}$$

Where E11 and E22 are longitudinal and transverse modulus of unidirectional composite obtained from Halpin and Karados (1976). Eq.1 is very simple; the predictions are only good at low fiber volume fractions. At high fiber volume fractions, the predicted modulus is much higher than the measured ones. Blumentritt and Cooper (1975) explained that this is caused by the increase in concentration of defects within the composite as the fiber content increases.

Lavengood and Goettler (1987) established a general procedure for predicting the average Young's modulus for randomly oriented short fiber composites. For 2D oriented fibers, they derived an expression similar to the Reuss-type expression as

$$E = 24E_{11}E_{22}/(7E_{22} + 17E_{11}) \tag{4}$$

Where

$$E_{11} = E_m + V_f(E_f - E_m)$$

$$E_{22} = E_m[\frac{\{2V_f(R-1) + (R+2)\}}{V_f(1-R)}$$

$$+ (R+2)\}]$$

E_m and E_f are Young's moduli of the matrix and fiber, respectively. V_f is the volume fraction of the fiber; R is the ratio of transverse fiber modulus to matrix modulus.

Piggott (1980) suggested the modulus for composites having fibers which are random in three dimensions as

$$E_c = \left(\frac{1}{5}\right) V_f E_f + V_m E_m \tag{5}$$

Cox (1952) who used a shear lag formulation to model the longitudinal elastic modulus showed that the modulus of short-fiber composites can be expressed as

$$E_c = (\frac{1}{5})E_{11} + (\frac{4}{5})E_{22} \tag{6}$$

where $E_{11}$and E_{22} are defined as in Voigt model (Eq. 1) and as in Reuss model (Eq. 2)

Hori and Onogi (1951) proposed the following equation for E_c

$$E_c = (E_{11}E_{22})^{1/2} \tag{7}$$

where E_{11} and $E_{22}$are defined as in Voigt model (Eq. 1) and as in Reuss model (Eq. 2)

Kelly and Tyson (1965) developed a theory to predict the strength of SFC. Basically, it is an extension of the "rule of mixtures" by taking into account the effects of both the fiber length and fiber orientation. It was based on the assumption that plastic flow will occur during stress transfer between matrix and fibers, this gives rise to

$$\sigma_c = \sigma_f V_f \left(1 - \frac{l_c}{2l}\right) + V_m \sigma_m \tag{8}$$

Where σ_c is ultimate tensile strength of composite σ_f, σ_m , strengths of fiber and matrix, respectively and *l, l_c*, fiber length and critical length of the fiber. One problem associated with Kelly and Tyson's theory is that the estimates of strength are higher than measured Peijs, et al. (1998).

Piggott (1980) accounted for both elastic and plastic effects in the matrix in his fiber theory. For composites having fibers which are random in 3D, he also suggested an upper strength bound critical length of fibers as

$$\sigma_c = \left(\frac{1}{5}\right) \sigma_f V_f + V_m \sigma_m \tag{9}$$

Riley (1968) considered interaction between fibers by taking into consideration of the stress transfer between fibers in a rationalized fiber array such as a hexagonal arrangement, and derived a strength equation as

$$\sigma_c = \left(\frac{6}{7}\right) \frac{\sigma_f V_f}{1 + \left(\frac{5l_c}{7l}\right)} + \sigma_m (1 - V_{f)} \tag{10}$$

Manera (1977) proposed approximate equations to predict the elastic properties of randomly oriented SFCs. The invariant properties of composites defined by Tsai and Pagano (1968) were used along with Puck's micromechanics formulation by Manera and made a few assumptions (including a) high fiber aspect ratio (>300), b) 2D random distribution of fibers and c) treatment of randomly oriented discontinuous fiber composites as laminates with an infinite number layers oriented in all directions) and obtained the approximate equations as

$$\begin{gathered} \bar{E} = V_f \left(\frac{16}{45} E_f + 2E_m\right) + \frac{8}{9} E_m \\ \bar{G} = V_f \left(\frac{2}{15} E_f + \frac{3}{4} E_m\right) + \frac{1}{3} E_m \\ \bar{\nu} = \frac{1}{3} \end{gathered} \tag{11}$$

where, V_f is the fiber volume fraction, ν_m is the Poisson's ratio of the matrix, E_m is the modulus of the matrix, E_f is the modulus of the fiber, $\overline{E}$ and $\overline{G}$ are the tensile (flexural) and shear moduli of the composite, respectively and $\bar{\nu}$ is Poisson's ratio of the composite. Predictions of composite modulus by Eq.11 were compared with test data, the constituent properties of the composites in the tests were 5 cm chopped glass fiber with E_f=73GPa, ν_f =0.25 and polyester resin with E_m = 2.25GPa and ν_m=0.40. The differences between the predictions and test data were less than 5%.

In the present work, Eqs. 3 to 11 are used to predict the properties of random SFC for v_f of 0.1 to 0.2 and the same is carried using FEM. The comparisons are made in Figures 3 and 4 for E and G of the SFC.

3. METHODOLOGY

The following steps are used in the current program

- The results of the existing empirical solutions are compared with the available experimental results from literature particularly for Peek Carbon Fiber
- In this work the closest empirical relations are chosen for further study
- Using the chosen empirical solution the elastic moduli for Peek carbon fiber composite is calculated for low fiber aspect ratio
- A VBA code is created to generate a block of composite with randomly oriented fibers for volume fraction varying from 0.1, 0.15 and 0.2.
- Discretization of the unit volume of SFC is executed in Patran and analysed to pull and torsion using Nastran
- The results from empirical solution and FE is compared for elastic modulus, If a close match is obtained then other elastic constants are also determined using the same FE model.
- As empirical relationships does not exist for randomly oriented short fiber composite, comparison is done with results for aligned fiber composites

Generation of random oriented short fibre composite for FEM: An Excel based VBA code is developed to generate random locations and orientations of the fiber. A unit cube of the composite is constructed using these fibers in the matrix using Patran as Geometric model. This model is meshed and converted into FE model using Patran. Interface between fibers and matrix is modelled using Nastran's glued contact. Mechanical properties of fiber and matrix are separately fed to the FEM. This model is analysed in Nastran using the control volume procedure given in Reference (Sun and Vaidya, 1996, Li, 2000 and Kim and Lee, 2009) to obtain the deformation and stresses and from which mechanical properties are calculated. The flow chart of VBA code for generating random locations and orientations for fibers is shown in Figure 1. The Figure A-1in the Appendix A, shows the typical SFC generated using the code.

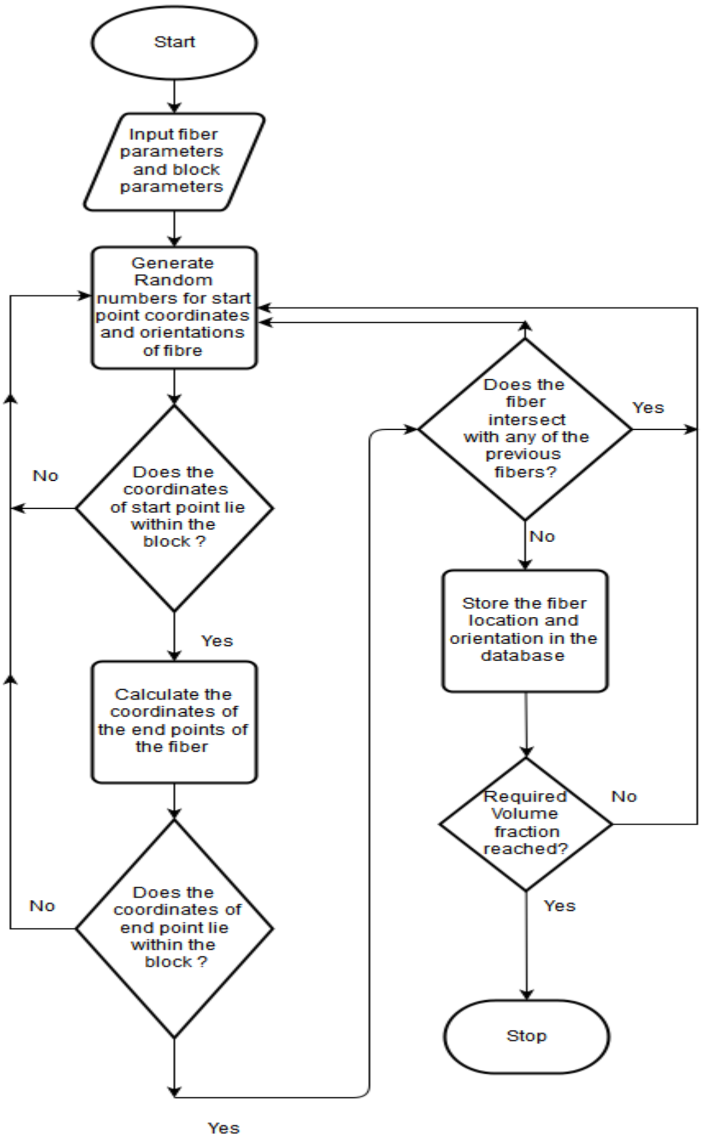

Figure 1. Flow chart for Random fiber generation code

4. RESULTS

Comparison of empirical relationships with Test results: In this section details of the mechanical properties of random oriented shot fiber composites are estimated and compared with the results from Tsai and Pagano solutions and also results from present FEM. Out of all the available empirical solutions a comparison is made with experimental results to choose the best solution. Test results are available for high aspect ratio shot fiber composite; however, as the present study is about short fiber composite a low aspect ratio composite was used. Figures 2 (a) and (b) give the comparison of empirical and experimental results for stiffness and strength. Out of all the different methods considered, the one that closely matches with the experimental results is considered in this study. Tsai and Pagano model is the best suited for comparison with FE modelling for stiffness estimation. This is the reason why this model is considered with different aspect ratio (with a low aspect ratio up to 0.2) as a parameter.

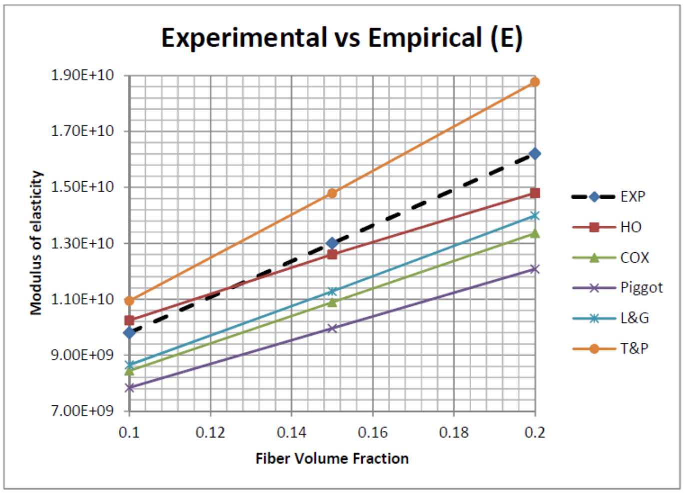

Figure 2 (a). Comparison of empirical and experimental results for stiffness

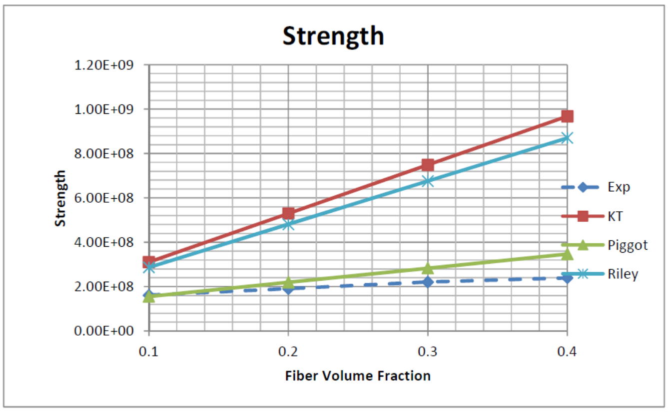

Figure 2 (b). Comparison of empirical and experimental results for Strength

As shown in Figure 2 (b), estimating strength by FEM is not possible for all failure modes of random SFC. All the empirical models predict higher strength than shown by experimental results. Piggot predicts the closest result which again deviates from the test results at higher fiber volume fractions.

Using the VBA code we can generate, a Patran session file which can be executed with in Patran to obtain the geometric model of SFC from which a 3D FEM mesh is generated. The BCs & loads are (Sun and Vaidya, 1996, Li, 2000 and Kim& Li, 2009 and) applied accordingly. Patran Session file for creating random fibers of volume fraction 0.1, 0.15 and 0.2 and respective FE models are generated and solved for estimating mechanical properties. The results of the analysis and comparison with available reference solutions are shown in Figures 3 and 4.

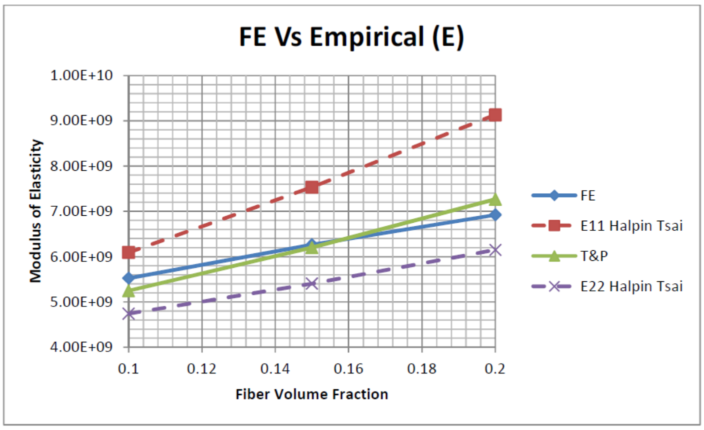

Figure 3. Comparison of empirical model results vs. FE results for Young’s modulus (E)

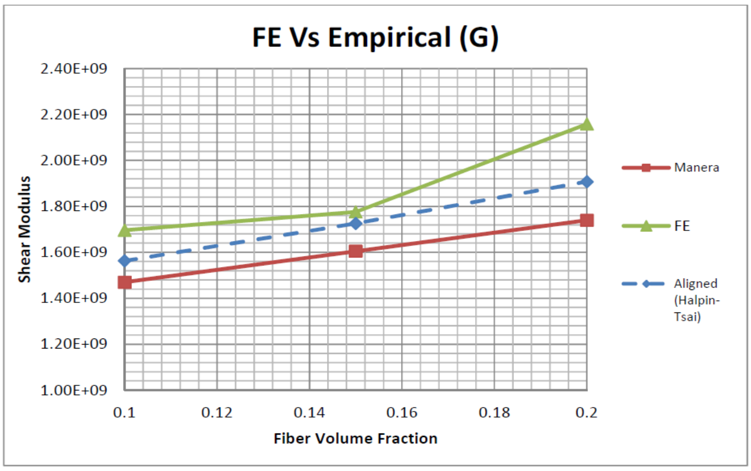

Figure 4. Comparison of empirical model results vs. FE results for Shear modulus (G)

5. CONCLUSION

Extensive literature survey is carried out to identify the various empirical models available for estimating stiffness and strength of randomly oriented short fiber composites (SFC). A FE based random oriented fibers in matrix was adopted to obtain the mechanical properties of SFC. The results obtained from the present studies give a decent comparison.

As a part of future work, a) the results obtained can be used to simulate the structural responses of randomly oriented SFC secondary structures b) The present VBA code can be further extended to generate composites with high aspect ratio (high fiber volume fraction), c) a better contact modelling to replicate the fiber matrix interaction can be done d) complexities like curved fibers, fibers with variable length, fibers sticking to each other etc. can be studied by improving the VBA code e) the methodology can be extended to particulate composites and metal matrix composites and f) testing the manufactured SFC material and components to study the response of materials and the structural configuration.

REFERENCES

1. Tsai, S. W., and Pagano, N. J.,“Invariant properties of composite materials”, In Composite Materials Workshop, Stamford, Conn: Technomic Publishing Co. 233-238, 1968.
2. Halpin, J., and Kardos, J., “The Halpin-Tsai Equations”, A Review. Polym Eng Sci, 16, 344-52,1976.
3. Lavengood, R. F., and Goettler, L. A., Contract Report, ONR/ARPA Contract No.NOOO14-67 C-0218, 1987.
4. Piggott, M. R, “Load Bearing Fiber Composites”, Pergamon Press, 1980.
5. Cox, H, “The elasticity and strength of paper and other fibrous materials”, Brit J Appl phys, Vol. 72, 1952.
6. Hori, M., and Onogi, S, “Dynamic Measurements of Physical Properties of Pulp and Paper by Audio frequency Sound”, J. Appl. Phys, Vol. 22., No. 7,971-977,1951.
7. Kelly, A., and Tyson, W. R, Journal of Mechanics and Physics of Solids, Vol. 13, 1965, 329-336,1965.
8. Peijs, T.et.al, “Thermoplastic composites based on flax fibers and polypropylene: Influence of fiber length and fiber volume fraction on mechanical properties,” Macro-mol. Symp, 193-203,1998.
9. Riley, V. R.,”Fiber/Fiber Interaction”, J. Compo. Mater., Vol. 2, 436-446,1968.

10. Manera, M, “Elastic properties of randomly oriented short fiber-glass composites”, Journal of Composite Materials, Vol. 11, 235-247,1977.
11. Sun C. T and Vaidya S.R, “Prediction of Composite Properties from a Representative Volume Element,” Composites Science and Technology, Vol. 56, No. 2, 171-179, 1996.
12. Li S., “General Unit Cell for Micromechanical Analyses of Unidirectional Composites,” Composites Part A , Vol. 32, No. 6, 815-816,2000.
13. Kim B.R and Lee H. K, “An RVE-Based Micromechanical Analysis of Fiber-Reinforced Composites Considering Fiber Size Dependency,” Composite Structures, Vol. 90, No. 4, 418-427, 2009.
14. MSC Patran and Nastran Software: www.**msc**software.com

APPENDIX –A

VBA code for random fiber generation: Figures A-1 shows a typical fibers in unit volume of composite systems, while the VBA code generated for random fiber generation is given figure A-1. A copy of the VB code can be obtained from the corresponding author.

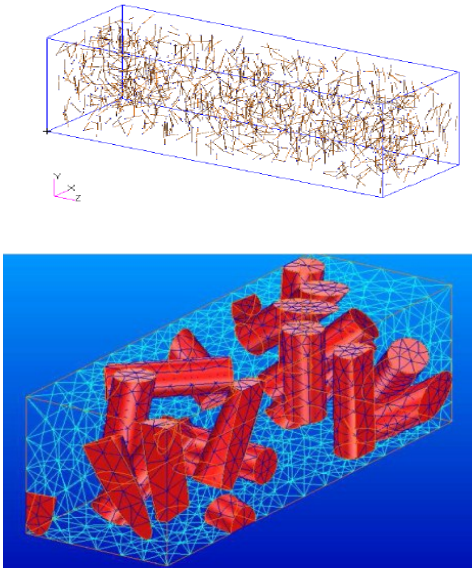

Figure A-1.Typical random SFC specimen generated and it FE idealization