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MICROMECHANICAL ANALYSIS OF HYBRID FRP COMPOSITE LAMINA FOR THERMAL LOADING

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ABSTRACT

The present research problem deals with the micromechanical analysis of a unidirectional continuous hybrid fiber-reinforced composite lamina. Three-dimensional models along with governing boundary conditions have been developed from the Representative Volume Elements (RVE) which are idealized as an array of square unit cells. The stress-strain relation in the finite element models takes place according to three-dimensional elasticity theory. The hybrid lamina consists of two different fibers of T300 and SGLASS materials, and epoxy matrix. The micromechanical analysis includes the evaluation of mechanical properties of the hybrid lamina at the fiber-matrix interface for perfectly bonded interfaces. In this phase of the work, the longitudinal Young's modulus (E1), Poisson's ratios (ν12 and ν13) are determined for a hybrid lamina for different volume fractions of fibers. In this case, the lamina is subjected to uniform pressure load in the In Plane Transverse direction of the composite lamina and no debond is considered at the fiber-matrix interfaces.

KEYWORDS: Key words: Finite Element Method, Unit Cell, Hybrid Lamin.

INTRODUCTION

In the recent period, there has been a tremendous advancement in the science and technology of fiber-reinforced composite materials. The low density, high strength, high stiffness to weight ratio, excellent durability and design flexibility of fiber-reinforced composites are the primary reasons for their use in many structural components, in aircraft, automotive, marine and other industries.Fiber-reinforced composites are now used in applications ranging from spacecraft frames to ladder rails, from aircraft wings to automobile doors, from rocket motor cases to oxygen tanks and from printed circuit boards to tennis rackets. Their use is increasing at such a rapid rate that they are no longer considered advanced exotic materials. The essence of fiber-reinforced composite technology is the ability to bond together of strong stiff fibers in the right place in the right orientation and right volume fraction.

DEFINITION

Fiber-reinforced composite materials consist of 'fibers' of high strength and modulus embedded in or bonded to a 'weak matrix', with distinct interface (boundary) between them. In this form, both fibers and matrix retain their physical and chemical identities, yet they produce a combination of properties that cannot be achieved with either of the constituents acting alone. In general, fibers are the principal load carrying members, while the surrounding matrix keeps them in the desired location and orientation, acts as a load transfer medium between them and protects them from environmental damages caused by elevated temperatures, humidity, etc. Thus even though the fibers provide reinforcement for the matrix, the latter also serves a number of useful functions in a fiber-reinforced composite material.

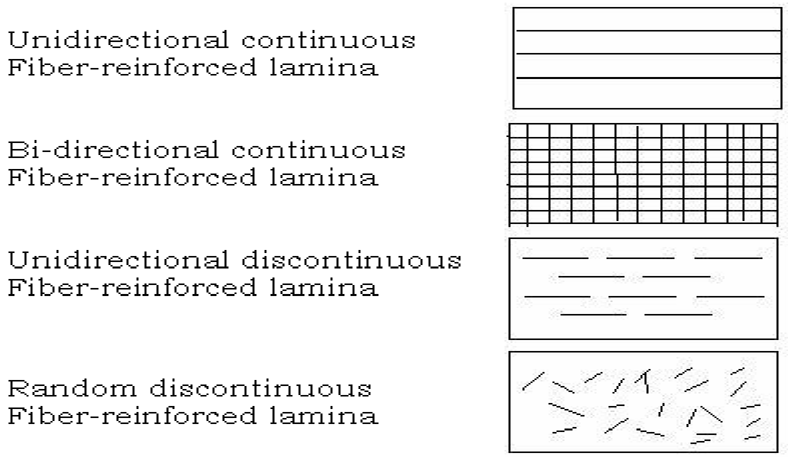

Fig. 1.1 Types of fiber-reinforcement

The fibers can be incorporated into a matrix either in continuous lengths or discontinuous forms (Fig. 1.1). The principal fibers in commercial use are various types of glass, carbon, Kevlar etc. fibers. Other fibers such as boron, silicon carbide, aluminum oxide are also used in limited quantities. The matrix material may be a polymer, a metal, or a ceramic.

Micromechanics

Micromechanics is intended to study the distribution of stresses and strains within the micro regions of the composite under loading. This study will be particularized to simple loading and geometry for evaluating the average or global stiffnesses and strength of the composites. The properties of a lamina can be experimentally determined in the "as made" state or can be mathematically derived on the basis of the properties of the constituent materials. That is, used to predict lamina properties by the procedures of micromechanics and can be used to measure lamina properties by physical means and use the properties in a micromechanical analysis of the structure. Knowledge of how to predict properties is essential to constructing composites that must have certain apparent or micromechanics is a natural adjunct to micromechanics when viewed from a design rather than an analysis environment. Real design power is evidenced when the micromechanical predictions of the properties of a lamina agree with the measured properties. The results of micromechanics will help

- To understand load distribution, microscopic structure (arrangement of fibers), etc., of composites.
- To comprehend the influence of microstructure on the properties of composite,
- To predict the average properties of the lamina, and
- To design the materials, i.e., constituent and their distribution, for a given situation.

The properties and behavior of a composite are influenced by the properties of fiber and matrix, interfacial bond and by its microstructure. For a fiber of given cross-sectional shape, the size and quality of the surface directly influence the load transferring bond. The bond strength improves with the increase of ratio of surface area to the volume of reinforcement, for circular fibers of unit length and radius r, Surface area/volume=2/r. Hence the bond area increases with finer fibers. Other parameters that influence the surface bond are:

i) Adhesive bond, obtained by chemical binding, which in turn depends on resin, fiber and the size used on fiber surface, and
ii) Frictional bond, the shrinkage of the resin on to the fiber and a higher Poisson's ratio of matrix than that of fiber induces compressive normal stress on the interface. The coefficient of friction at the interface develops frictional force that acts as a bonding force.

Microstructure parameters that influence the composites behavior are grouped into:

i) Primary parameters such as length, volume fraction, packing and orientation of fiber, and

ii) Secondary parameters include fiber diameter and spacing, flaws, voids, inclusions, etc., and these marginally affect the composites behavior.

Lamina made of composites material is the building block of a laminate. The properties of individual layers are quite different from each other. In general each layer is a unidirectional, fibrous composite. Analysis and design of any structural element would require a full knowledge of the properties of individual plies. Thus it is only appropriate to first study the properties and behavior of unidirectional lamina.

Concept of unit cells

The distribution (or packing) of fibers in a plane normal to the axis of fibers is random (Fig.1.2). The analysis of any region of such a lamina is unwieldy. In order to tackle the problem by analytical tools, the microstructure of lamina is idealized. Idealization is done assuming that the fibers are straight and laid parallel to each other (Fig.1.3), and that their distribution cross-section follows regular pattern as shown in Fig1.4. The typical fiber packing pattern used for the lamina structural idealization is staggered square array (Fig. 1.5)

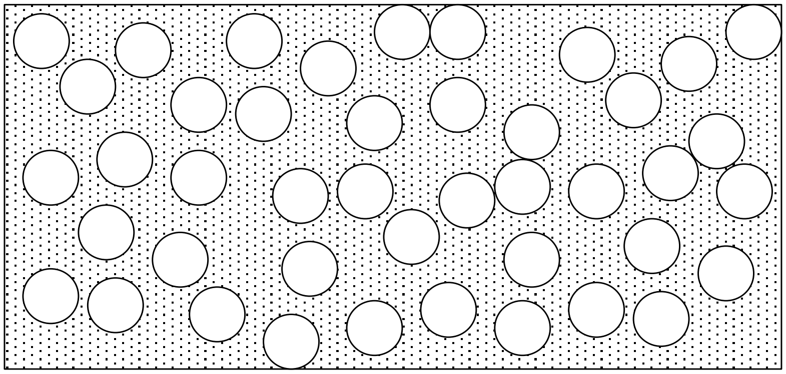

Fig. 1.2 Schematic diagram of cross section of fiber-matrix ply showing random distribution of fibers

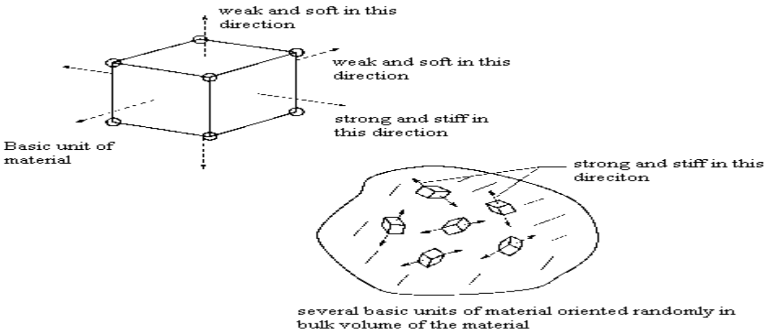

Fig. 1.3 Basic unit of a material

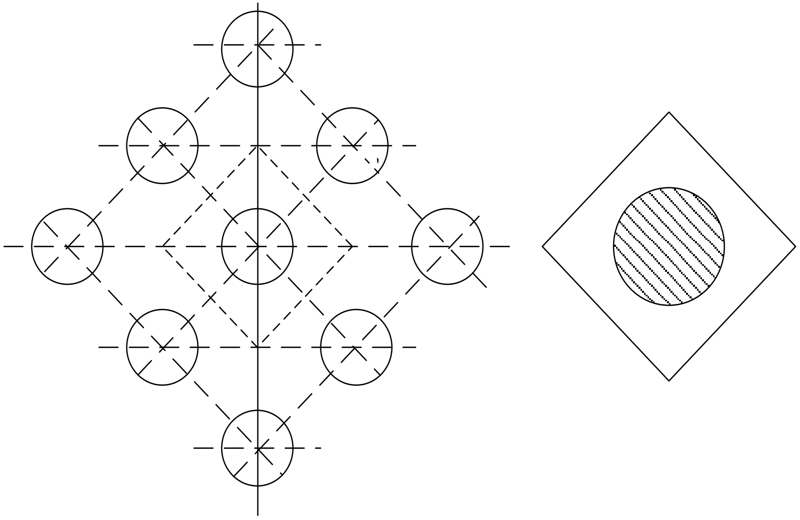

Fig. 1.4 Staggered Square array of circular fibers and representative volume element

EXPERIMENTAL PROCEDURE

Micromechanical behavior of the unidirectional continuous hybrid fiber-reinforced composite lamina subjected to in plane transverse loading (fiber directional loading) is discussed. A three-dimensional finite element model has been developed from the unit cells of staggered square pattern of the composite to predict the in plane transverse Young's moduli (E_2) and corresponding Poisson's ratios (ν_{21} and ν_{23}) of a hybrid fiber-reinforced lamina with combination of T300 and Sglass materials for various volume fractions. The finite element software ANSYS has been successfully executed to evaluate the properties at different volume fractions.

METHODOLOGY

The unidirectional continuous fiber reinforced composite lamina has been idealized as a large array of representative volume elements. Depending upon the arrangement of the fibers across the cross section of the lamina, different types of representative volume elements can be obtained such as square, hexagonal, staggered square patterns etc. In any pattern repetition of a particular volume of the lamina can be observed, which is called the representative volume element (RVE) or unit cell.

For the present analysis, the lamina is considered as an array of staggered square unit cells (Fig. 3.1) and one unit cell is adopted for the micromechanical analysis of the lamina. For the present problem, the unit cell is considered as a prism of square cross section embedded with four quarter cylinders at the four corners of the unit cell. This type of square unit cell is adopted in order to accommodate fibers of two different materials arranged in alternate rows. The cross sectional area of the fibers in the unit cell is governed by the fiber volume fraction, which is the ratio of the volume of the fiber to the total volume of the unit cell.

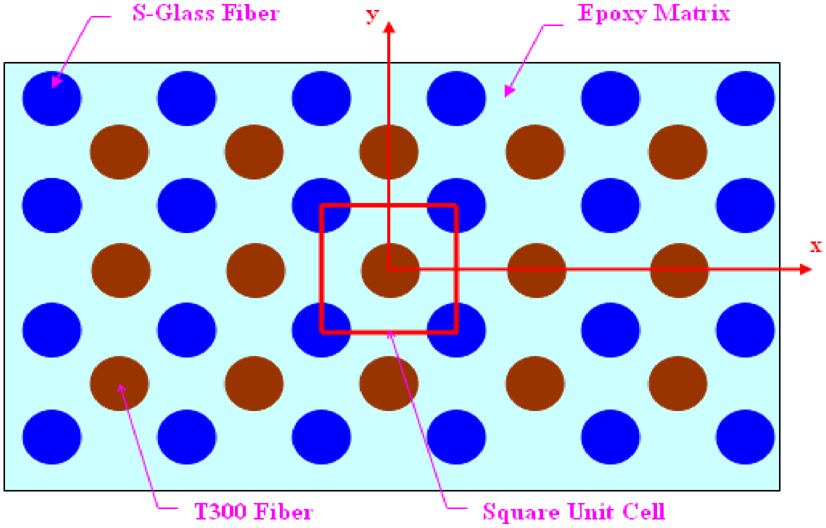

Fig. 3.1 Hybrid composite lamina

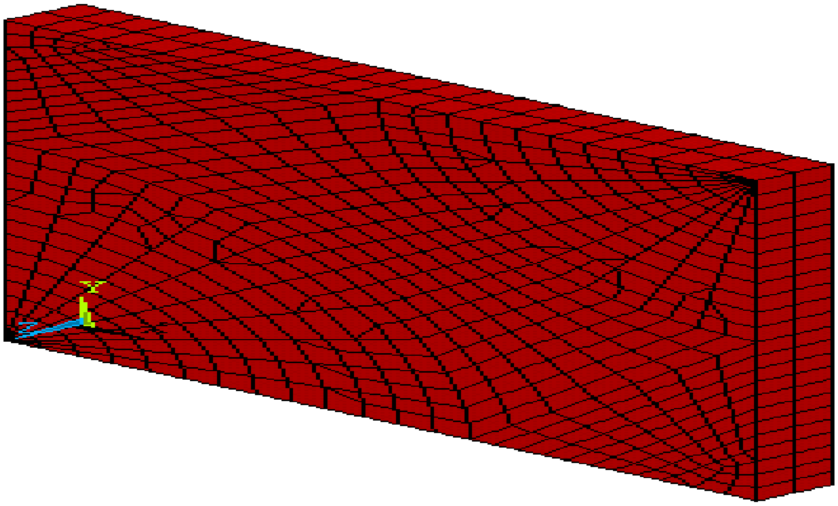

Fig. 3.2 Finite Element mesh showing uniform temperature load on eighth portion of the unit cell

Loading

Uniform tensile load of 1 MPa is applied in the longitudinal direction (along 1- or z- axis) on the area at Z=10 units.

Boundary conditions

Due to the symmetry of the problem, the following symmetric boundary conditions are used

- On the surface at x=0, U_x=0
- On the surface at y=-100, U_y=0
- On the surface at z=0, U_z=0

In addition the following multi-point constraints are used.

- The U_x of all the nodes on the area at x=100 is same
- The U_y of all the nodes on the area at y=100 is same
- The U_z of all the nodes on the area at z=10 is same

RESULTS

The mechanical properties of the lamina are calculated using the following expressions.
Young's modulus in fiber direction

$$E_2 = \frac{\sigma_1}{\varepsilon_1}$$

Poisson's Ratio $\nu_{12} = \frac{-\varepsilon_2}{\varepsilon_1}$

Poisson's Ratio $\nu_{13} = \frac{-\varepsilon_3}{\varepsilon_1}$

Where

σ_1=Stress in 1-direction (z-direction).
ε_1=Strain in 1-direction (z-direction)=displacement of the FE model in z-direction/10)
ε_2=Strain in 2-direction (x-direction)=displacement of the FE model in x-direction/100)
ε_3=Strain in 3-direction (y-direction)=displacement of the FE model in y-direction/100)

Sufficient number of convergence tests are made and the present finite element model is validated by comparing the Young's modulus of T300-Epoxy lamina predicted with the value obtained from exact elasticity theory (102) and found close agreement (Fig. 3.3). Later the finite element model is used to evaluate the properties E_1, ν_{12}, ν_{13} of a hybrid composite with T300 and Sglass fibers. Figs. 5.4-5.6 presents the mechanical properties predicted from the present analysis for different combinations of volume fractions.

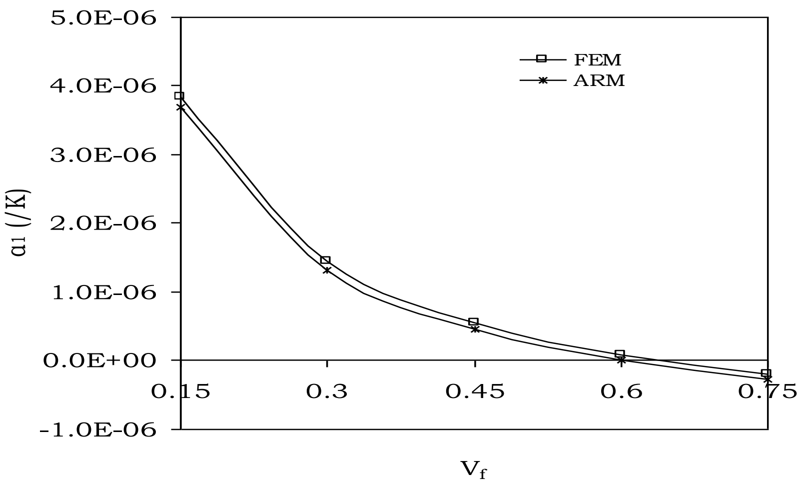

Fig.34 Validation for α1 with Alternate Rule of Mixtures

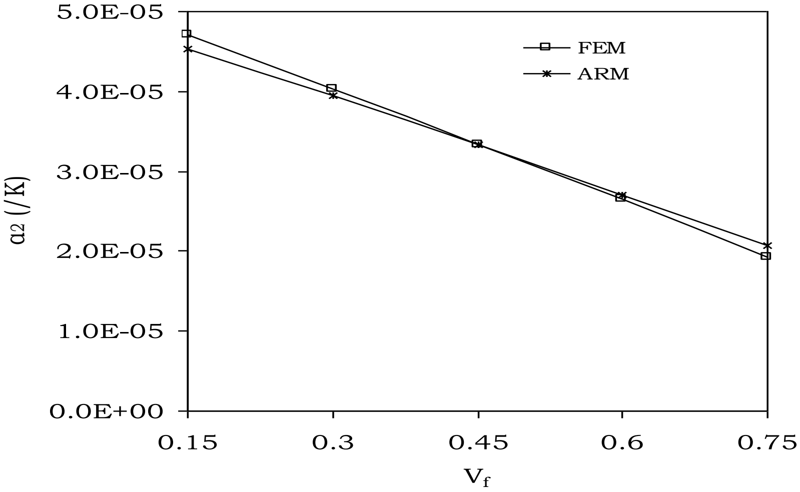

Fig.34 Validation for α2 with Alternate Rule of Mixtures

ANALYSIS OF RESULTS

Variation of α_1 with respect to V_f:

It is observed that there is a linear increment of the young's modulus with respect to volume fraction for all the three combinations. This is because the longitudinal stiffness of the composite increases with increase in volume fraction (V_f), which is equally distributed among the two fibers in case of hybrid composite. The young's modulus of T300 epoxy at all the volume fractions is observed to be maximum followed by hybrid epoxy and Sglass epoxy, due to the less value of Sglass fiber longitudinal modulus when compared with T300 fiber modulus.

M1= T300 EPOXY: M2 = HYBRID EPOXY: M3 = SGLASS EPOXY

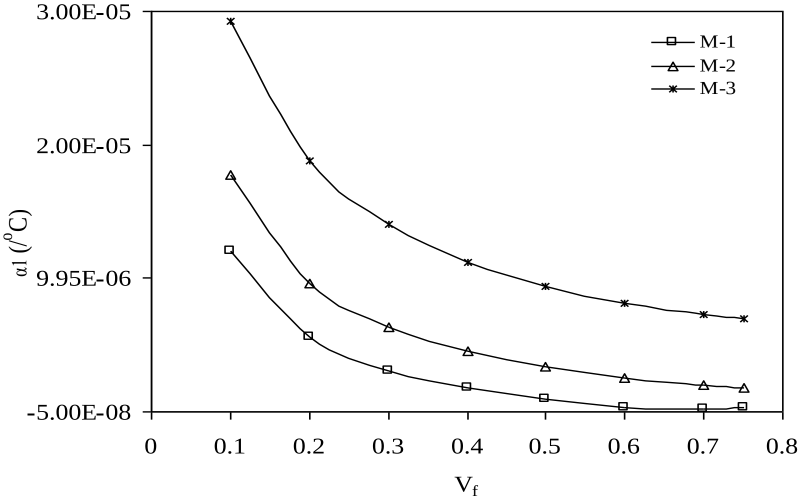

Fig.3.4 Variation of α1 with respect to Vf:

Variation of α_2 with respect to V_f

Poisson's Ratios ν_{12} and ν_{13} decreases almost linearly with increase in volume fraction (V_f) for all the three combinations. This is because the longitudinal stiffness of the composite decreases with increase in volume fraction (V_f) which is equally distributed among the two fibers in case of hybrid composite. The Poisson's Ratios of T300 epoxy at all the volume fractions is observed to be maximum followed by hybrid epoxy and Sglass epoxy, due to the less value of Sglass fiber longitudinal modulus when compared with T300 fiber modulus. However, there is no considerable variation of Poisson's Ratios with respect to the fiber material.

M1= T300 EPOXY: M2 = HYBRID EPOXY: M3 = SGLASS EPOXY

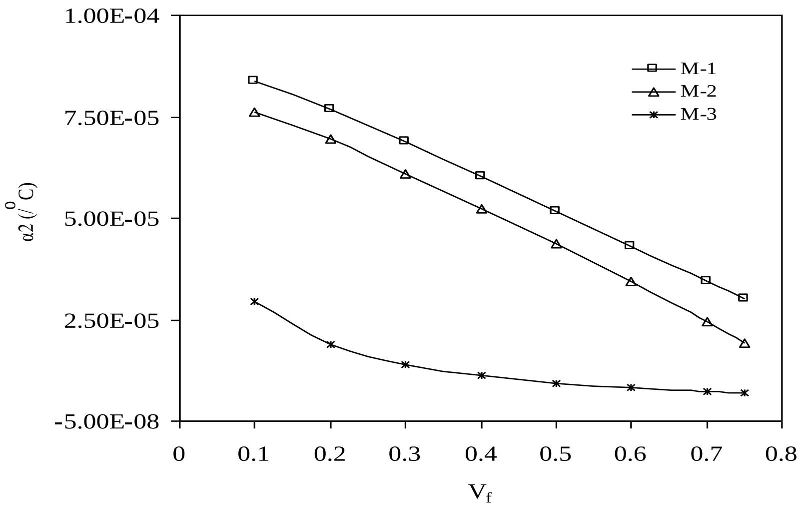

Fig 3.5: Variation of α_2 with respect to V_f

Variation of α_1 with respect to V_f
(V_f for lower fiber is constant):

It is observed that there is a linear increment of the young's modulus with respect to volume fraction for all the three combinations. This is because the longitudinal stiffness of the composite increases with increase in volume fraction (V_f), which is equally distributed among the two fibers in case of hybrid composite. The young's modulus of T300 epoxy at all the volume fractions is observed to be maximum followed by hybrid epoxy and Sglass epoxy, due to the less value of Sglass fiber longitudinal modulus when compared with T300 fiber modulus.

M1= T300 EPOXY: M2 = HYBRID EPOXY: M3 = SGLASS EPOXY

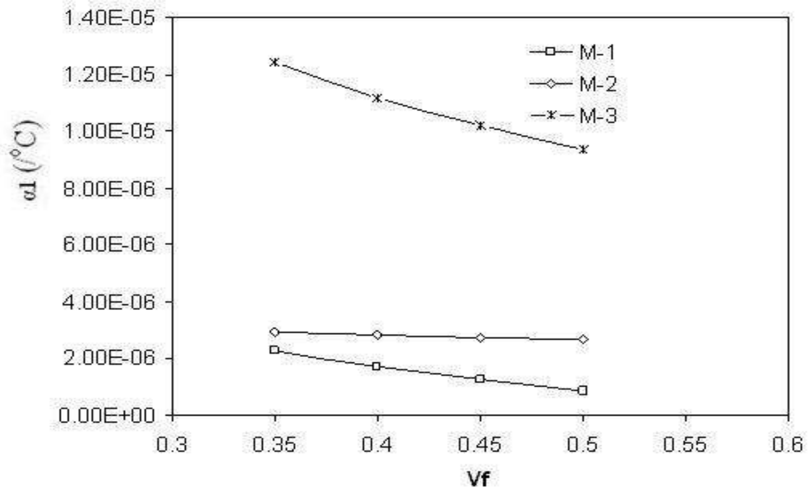

Fig 3.6: Variation of α_1 with respect to V_f

Variation of α_2 with respect to V_f

The Poisson's Ratios ν_{12} and ν_{13} decreases almost linearly with increase in volume fraction (V_f) for all the three combinations. The reason given for the variation of E1 is valid for this case also. However, there is no considerable variation of Poisson's Ratios with respect to the fiber material.

M1= T300 EPOXY: M2 = HYBRID EPOXY: M3 = SGLASS EPOXY

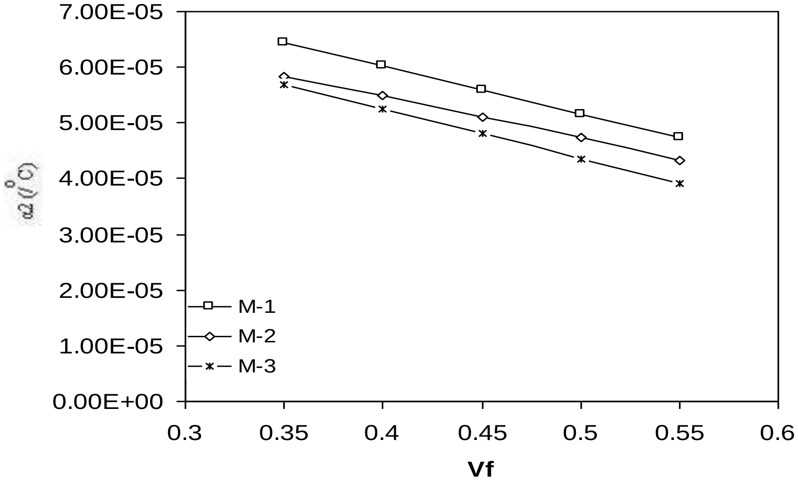

Fig 3.7: Variation of α_2 with respect to V_f

Variation of α_1 with respect to Non-uniform V_f:
(upper fiber is constant)

It is observed that there is a linear increment of the young's modulus with respect to volume fraction for all the three combinations. This is because the longitudinal stiffness of the composite increases with increase in volume fraction (V_f), which is equally distributed among the two fibers in case of hybrid composite. The young's modulus of T300 epoxy at all the volume fractions is observed to be maximum followed by hybrid epoxy and Sglass epoxy, due to the less value of Sglass fiber longitudinal modulus when compared with T300 fiber modulus.

M1= T300 EPOXY: M2 = HYBRID EPOXY: M3 = SGLASS EPOXY

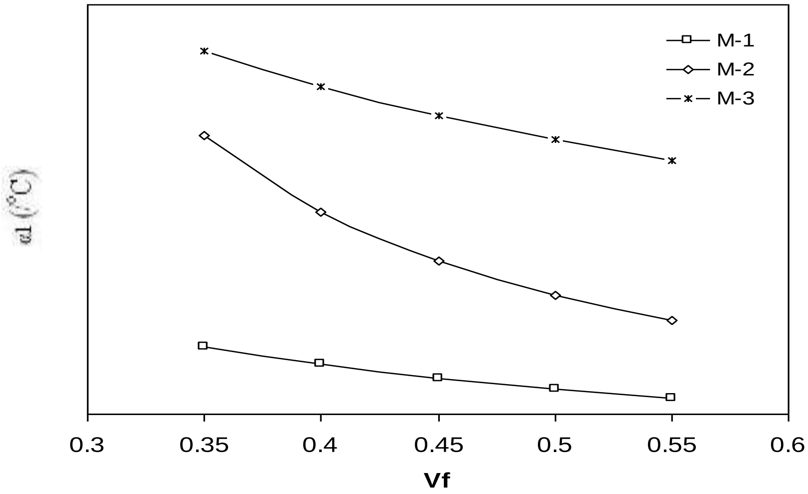

Fig 3.8: Variation of α_1 with respect to V_f
Variation of α_2 with respect to V_f

The Poisson's Ratios ν_{12} and ν_{13} decreases almost linearly with increase in volume fraction (V_f) for all the three combinations. The reason given for the variation of E_1 is valid for this case also. However, there is no considerable variation of Poisson's Ratios with respect to the fiber material.

M1= T300 EPOXY: M2 = HYBRID EPOXY: M3 = SGLASS EPOXY

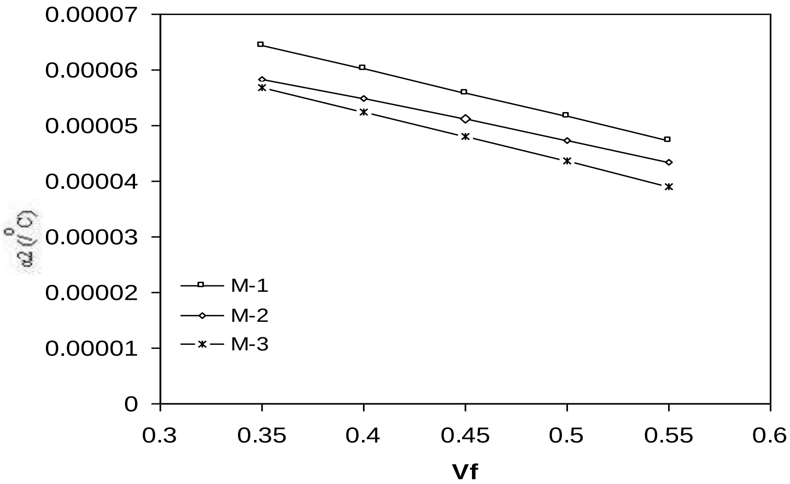

Fig 3.9: Variation of α_2 with respect to V_f

Variation of α_1 with respect to Non-uniform V_f
(V_f for various combinations)

It is observed that even if the volume fractions are not uniform, as long as the total volume fraction is same, there will be no change in the Young's modulus(E1) for T300 and S-glass fibers. For hybrid epoxy the Young's modulus increases for increase in T300 content in the total volume fraction.

M1= T300 EPOXY: M2 = HYBRID EPOXY: M3 = SGLASS EPOXY

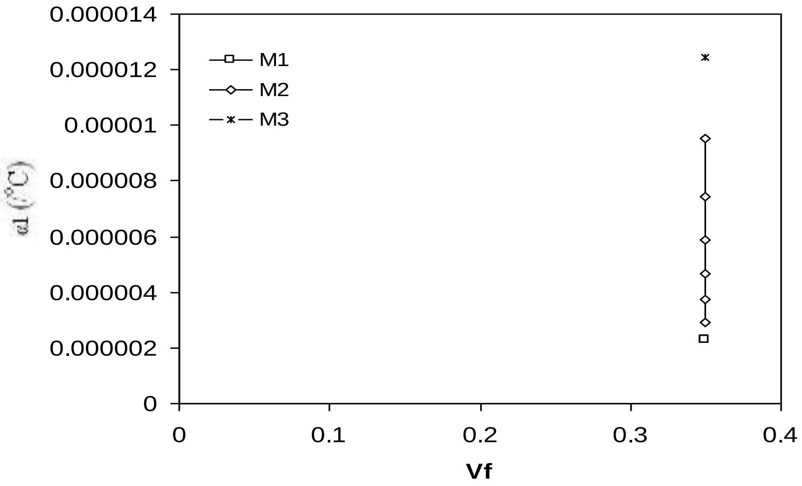

Fig 3.10: Variation of α_1 with respect to V_f

Variation of α_2 with respect to Non-uniform V_f:
(V_f for various combinations)

It is observed that even if the volume fractions are not uniform, as long as the total volume fraction is same, there will be no change in the Poisson's Ratios (ν_{12} and ν_{13}) for T300 and S-glass fibers. For hybrid epoxy the Poisson's Ratios (ν_{12} and ν_{13}) increases for increase in T300 content in the total volume fraction.

M1= T300 EPOXY: M2 = HYBRID EPOXY: M3 = SGLASS EPOXY

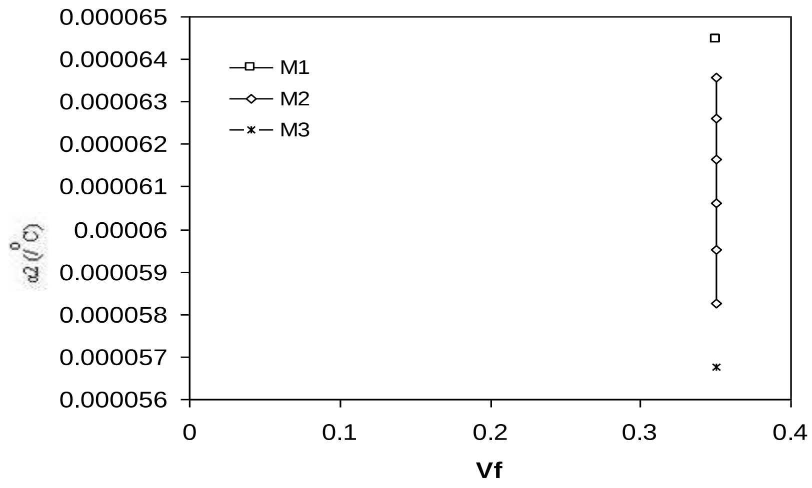

Fig 3.11: Variation of α_2 with respect to Non-uniform V_f:

CONCLUSION

Micromechanical analysis of a hybrid fiber-reinforced composite due to thermal loading is studied using FEM. The coefficients of thermal expansion of the T300-SGlass-epoxy hybrid composite are predicted using three-dimensional finite element method. The following conclusions are drawn.The coefficient of thermal expansion (α_1) is found to be decreasing with increase of volume fraction (V_f) for all the three composites. The value of coefficient of thermal expansion is maximum for the S-glass epoxy. The coefficient of thermal expansion (α_2) is found to be decreasing with increase of volume fraction (V_f) as the value of coefficient of thermal expansion is more for the T300 material.The coefficients of thermal expansion are found to be constant for T300 and S-glass for various combinations of volume fractions (V_f). For hybrid epoxy the coefficient of thermal expansion (α_1) is decreasing and the coefficient of thermal expansion (α_2) is increasing.

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