Micro-Thermo-Mechanical Analysis of Glass-Fiber Reinforced Composite (GFRC) using COMSOL

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ABSTRACT

Composites can be defined as hybrid materials that can meet the current research demand. The composite is made by blended/mixed to obtain the desired properties, tailor-made for specific applications. Fiber reinforced composites are widely used for the various applications in construction and the aerospace, automotive, infrastructures and sporting goods industries. Mechanical and thermal properties are evaluated for accurate estimation of their structural response.

The mathematical modelling of the formation and testing of composite is a vast area of study for analyzing the mechanics and properties of composites. The paper studies the mechanics of mixing of two pack epoxy resin and glass fiber system and resultant properties of composite sheet. In this composite formed is analyzed by considering representative volumetric element (RVE) on which finite element analysis (FEA) was carried. The property of sheet was determined by the periodicity feature of COMSOL. Two types of studies were carried out one with thermal load and one without thermal load and using standard computation following mechanical properties were calculated Young's Modulus, Shear Modulus, Poisson's Ratio and Distortion energy variation along volume (von Miss Stresses Tensor). Then mechanical properties were employed in the estimation of thermal properties like-Coefficient of thermal expansion, thermal conductivity, thermal diffusivity, and specific heat capacity variation. Moreover, composites were formed by varying fiber volume fraction, using the principle of homogenization and results were compared with standard rule of mixing which shows good convergence with the data given by COMSOL.

Keywords: Composites, Micromechanical, Modelling, Epoxy, Glass fibres

1 Introduction

The current era of technology demands fast estimation and mathematical modelling before setting of any work at experimental level. With COMSOL it is very effective to model the real time systems and estimate the data set for achieving the bi-fold objective of developing mathematical model and estimating various parameters at certain boundary conditions. With this aim the current work is based on the estimation of thermo-mechanical properties of epoxy based glass fiber composite in COMSOL, using the concept of representative volumetric element (RVE) and finite element analysis (FEA) as used by [1].

The composites are the material having two distinct phases' matrix and reinforcement having distinct physio-chemical properties. These two phases are matrix (binder) and reinforcement (fiber) and based on fiber and matrix type, composites can be classified as (Figure 1).

Figure 1 demonstrate generic layout of the taxonomy of the composite which can be further extended, dimension of fiber can have micro-composites, nanocomposites, etc or look up over the type of material based on them bio-composites and smart composites are designated.

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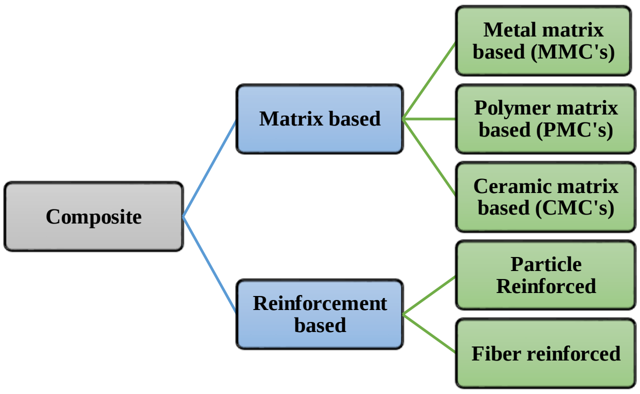

Figure 1: *Classification of composites*

Fiber reinforced composites hold a specific place in the taxonomy of the composites. It is having matrix as a continuous phase, matrix can be a metal matrix, or polymer matrix or a ceramic matrix and generally termed as epoxy resin. The dispersed phase is called filler or fiber and again it can be of a single fiber or combination of fiber. Materials generally used as fiber are synthetic and natural fibers. The objective of present work is analysis of Glass-Fiber Reinforced Composites (GFRC) as they constitute to very crucial application ranging from hybrid Portland cement to polycarbonate reinforced composite glass used in military and safety sectors [2]. Due to its application in the field of construction the estimation of thermal properties such as thermal conductivity, effective density, specific heat capacity, coefficient of thermal expansion and thermal diffusivity, becomes very important.

Fiber can classify the GFRC's in the following grades such as A-alkali glass C-corrosion glass and most popular E-glass. E-glass fiber also known as Electronic-Glass fiber possesses properties like high electrical resistivity and high durability. The constituent elements used in the production of E-type glass fiber composite are silica (SiO_2), calcium oxide (CaO), alumina (Al_2O_3), magnesium oxide (MgO), sodium oxide (Na_2O), boron trioxide (B_2O_3), and potassium oxide (K_2O). The significant characteristics that make E-glass a popular type of glass fiber is better strength, economical, higher stiffness, heat resistant, low density, fire-resistant, better endurance to chemicals, comparatively inert to wetness, better electrical isolation, and ability to uphold structural integrity in diverse circumstances. It finds the application of E-glass fiber ranging from marine application to airspace and industrial equipment designs [3].

Since the fabrication of composite is a time taking and tedious task and estimation of thermal properties requires sophisticated machinery, hence the simulation seems the only way to study variation of thermal properties with varying fiber volume fraction/fiber content. In present study epoxy (Araldite CY230) is reinforced with glass fiber (E-glass Fiber) to form glass fiber reinforced composite. The solid mechanics and heat transfer nodes were coupled together in a multiphysics node to carry out the finite element analysis of the representative volume element. The tensor yielded by COMSOL was used to calculate and analyze the data in a discrete way.

2 Materials and Methods (Simulation in COMSOL)

2.1 Geometry selection

A whole sheet is typical to analyze at once, concept of Representative Volumetric Element (RVE) say a sheet of 1m x 1m x 1mm then as a rule of thumb we will choose a RVE of a dimension 1mm x 1mm x 1mm. The assumptions were made and chosen a fiber configuration carefully to avoid complex model formation. The fiber configuration can be a localized isolated fiber imbedded in a matrix of a network of fibers or any random distribution even with the variation in fiber configuration the result varies as the RVE when repeated along the Cartesian (x, y, z) dimension will yield the sheet [4].

The fiber configurations can be selected from below mentioned configurations.

1. Geometry embedded along the other geometry: fiber can be a Cuboid, hexagonal cylindrical or elliptically cylinder.
2. A geometry localized inside geometry: sphere or elliptically closed figure type or any configuration like cube.
3. It can be a simple fiber distribution along length or a network of fiber or a random microfiber distribution.

In each case the geometry of RVE and the governing equations are different, for keeping the work simple the geometry here considered is a cylinder within a cube. Several RVE's considering different modelling aspects are created and evaluated regarding their effective composite stiffness [5].

The RVE chosen is almost like a unit cell with the cylindrical fiber at centre, the former configuration was done to avoid a statistical calculation. Analyzing layer-wise theory say a composite has n-layers of dx length each layer has same probability of finding the fiber at any point and lead to a heavy statistical calculation and hence it is very tough to devise a mathematical model for geometry variation with volumetric change of fiber (Figure 2 (a), Figure 2(b), and Figure 2(c)).

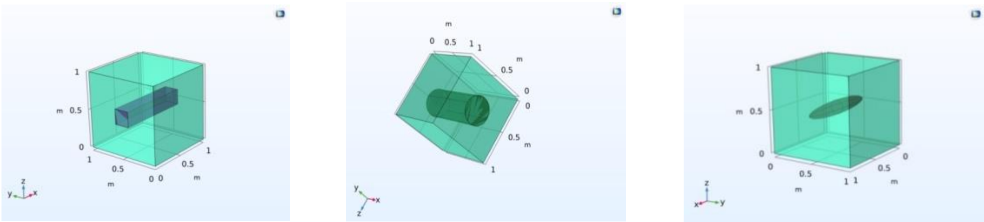

Figure 2(a): *Embedded geometry of fiber along single axis cuboid, cylindrical and ellipsoid*

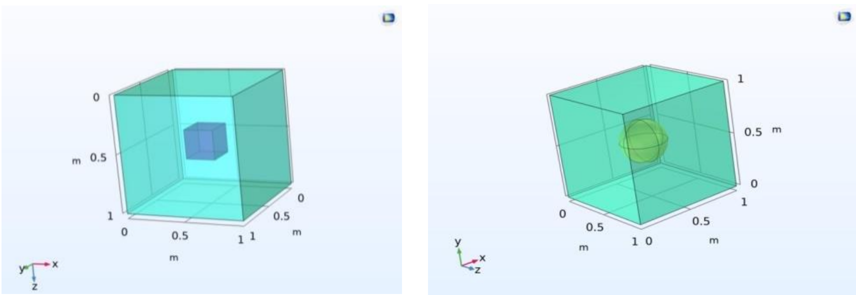

Figure 2(b): *Isolated geometry of fiber in form of cube (left) and sphere (right)*

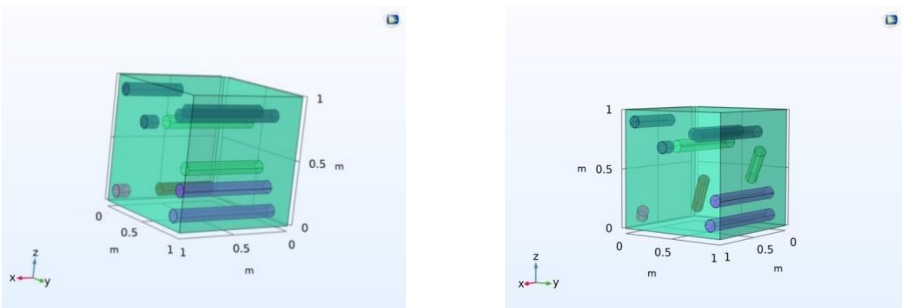

Figure 2(c): *Linearly distributed fiber in RVE (left) and randomly distributed fiber in RVE (Right)*

Simulation on a model with a random distributed fiber configuration is not easy to conduct, so a hypothetical system was considered (heterogeneity at micro scale). When a unidirectional fiber-reinforced composite is examined microscopically in a plane perpendicular to fiber it was for that distribution of fiber in matrix is fully random. The density probability of fiber in any direction is same [6].

The position of fiber also matters in the finite element analysis so fiber in cylindrical shape is placed the along the x-axis exactly in the middle of the RVE. RVE's dimension will follow equation 1 [7].

$$\frac{t}{a} \leq 1\,; where\ t = thickness\ of homogenious\ sheet\,; a = dimesnion\ of RVE \quad (1)$$

Since the thickness of final sheet, assumed to be 1 mm so the dimension of RVE of unit cell will be maximum 1 mm, according to equation 1. So, the total volume of the cell in total is V_t; Volume of matrix part is V_m and V_f be the volume of fiber (based on fiber fraction).

So, the total volume can be given as per equation (2 and 3).

$$V_t = V_m + V_f \quad (2)$$

$$\frac{V_t}{V_t} = \frac{V_m}{V_t} + \frac{V_f}{V_t} \quad (3)$$

Now the term V_m/V_t = volume fraction of matrix content (say v_m) in RVE and V_f/V_t= volume fraction of fiber content in RVE (say v_f) so equation three can be reduced to below in form of equation 4:

$$1 = v_m + v_f or v_f = 1 - v_m \quad (4)$$

So now we are intended to find the radius of cylindrical region of fiber,

$$V_f = V_t * v_f where V_t = a^3 where a is the dimension of RVE$$

If we are dealing with cylinder, then $V_f = \pi {r_f}^2 a$

So now

$$r_f = \sqrt{\frac{V_t * v_f}{\pi a}} = \sqrt{\frac{a^2 * v_f}{\pi}} \quad (5)$$

With the help of radius of the fiber region (as per equation 5) in terms of fiber volume fraction and we can design the RVE as shown in Figure 3.

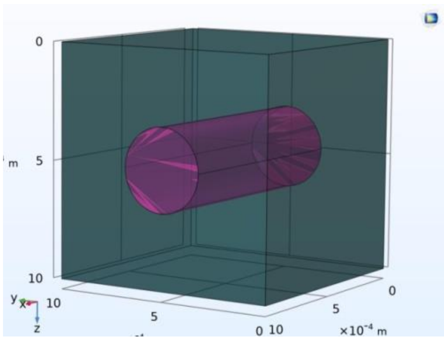

Figure 3: *RVE chosen for micromechanical analysis*

2.2 Data generation by Rule of Mixing:

E-glass and resin (matrix) as Epoxy (Araldite CY-230) is used in this study. The property data (Table 1) for the material were taken from vendor and web sources (a, b).

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Table 1: *Properties of resin matrix and fiber (a, b)*

Matrix (Epoxy)	***Reinforcement (Glass Fiber)***
Material Name: Araldite CY 230 , HY -951 *Nature of material :* Isotropic	*Material Name: E-glass fiber* *Nature of material : Orthotropic*
Mechanical properties : Young's Modulus → E_m= 4.14E+09 Pa Poisson's Ratio →υ_m =0.35 Shear Modulus →G_m = 1.65E+09 Pa Material Density →ρ_m=1100 kg/m^3	*Mechanical properties :* Young's Modulus →E_f =7.24E+10 Poisson's Ratio →υ_f =0.23 Shear Modulus →G_f = 2.96E+10 Pa Material Density →ρ_f=1800 kg/m^3
Thermal Properties: Coefficient of thermal expansion (CTE) α_m= 5.5E-05 (1/K) Specific heat Capacity (C_{pm})=930.5(J/kg .K) Thermal Conductivity(k_m) =0.85 (W/m .K)	*Thermal Properties* CTE (longitudinal) α_{xf}=6.00E-07 (1/K) CTE (Transverse) α_{zf}=8.50E-06 (1/K) Specific heat Capacity ($C_{pf)}$=1030(J/kg .K) Thermal Conductivity(k_f) =1.3 (W/m .K)

Using these data, data of rule of mixing was calculated and compared with the results that were produced by Finite Element Analysis (FEA) analysis using COMSOL. Rule of mixing is a widely used model for generic prediction of properties when the fiber and matrix and simple to apply [8].

Let

P_m=property of matrix ; P_f=property of fiber ;V_m = volume fraction of matrix ; V_f =volume fraction of fiber; $v_{i=}$Poisson's ratio of ith component; $E_{i=}$Young's Modulus of ith component $G_{i=}$Shear Modulus of ith component ; similarly, k= thermal conductivity C_p=Specific heat capacity ϱ=density at thermal and elastic load and so on Then by rule of mixing we can determine the resultant properties in longitudinal and transverse direction. The suffix 1 and 2 denotes longitudinal and transverse direction as.

In longitudinal direction any property can be calculated as per equation 7

$$P_{1t} = P_{1f}V_f + P_mV_m \tag{6}$$

In Transverse direction the formulation changes to equation 8

$$P_{2t} = \frac{1}{(\frac{V_f}{P_{2f}} + \frac{V_m}{P_m})} \tag{7}$$

Since the rule of mixing formulation takes only account the data of fiber volume fraction and the given property and it does not consider the effects of other parameters so it will be evident to devise Shapery's Model to get data of Coefficient thermal expansion and Caruso's Model to derive data of Thermal Conductivity [9].

Shapery's Model depicts the coefficient of thermal expansion as function of Young's Modulus of fiber and matrix, fiber volume fraction and CTE's of matrix and fiber. The equations 8 represents longitudinal loading condition and equation 9 represents transverse direction estimation.

$$\alpha_{1t} = \frac{E_{1f}\alpha_{1f}V_f + E_m\alpha_mV_m}{E_{1f}\alpha_{1f} + E_m\alpha_m} \tag{8}$$

$$\alpha_{2t} = V_{1f}\alpha_{1f}(1 + v_f) + V_m\alpha_m(1 + v_m) - \alpha_{1t}v_t \tag{9}$$

Caruso's Model models the transverse thermal conductivity as function of thermal conductivity of matrix and fiber phases and volume fraction in a more sophisticated way as per equation 10:[10]

$$k_{eff} = 1 - k_m\sqrt{v_f} + \left(\frac{k_m\sqrt{v_f}}{1-\sqrt{v_f}\left(1-\frac{k_f}{k_m}\right)}\right) \quad (10)$$

Also notice that 1 corresponding to x direction 2 corresponds to y direction and 3 corresponds to z direction and 1 also represents longitudinal direction and 2 and 3 are transverse direction as orthotropic direction is considered. Using excel we can generate the data corresponding to fiber volume fraction. Above equations from 6 to 10 can be used to generate the rule of mixing (ROM) data, which was later used for comparison with FEA analysis using COMSOL.

3 Theory and Calculation

3.1 Mathematical Modeling of Composites in COMSOL

The mathematical model of the current works revolve around two domains of the COMSOL multiphysics namely

- Solid mechanics module and physics: For the estimation of solid mechanics node and the longitudinal and transverse mechanical properties of homogenized RVE that is later on used to carry out the thermal analysis.
- Heat Transfer module: This module utilizes the heat flux equations and the elastic force nodes together to calculate thermal properties of the homogenized RVE.

Governing equation of each of these modules are:
Solid mechanics node uses generalized form of Hook's Law and yield 6*6 tensor in general in COMSOL which can be used for the calculation of rest of mechanical properties of homogenized material such as Young's Modulus, Shear Modulus, Poisson's Ratio and Density.

Generalized form of the Hooks Law: Stress is directly proportional to strain within a elasticity limit, mathematically former can be expressed as per equation 11.

$$\sigma = E.\epsilon \quad (11)$$

Where E is called as Young's Modulus, σ =stress and ε=strain; but this form of law only holds in 1D deformation and stress in different direction is ignored. As move towards 3D tensors get involved and hence the law takes the form of matrix formulation and now 9 different moduli are to be dealt with. Say if on assuming x to be direction 1, y to be direction 2 and z to be direction 3; stresses and strains can be formulated as equation 12 and 13 respectively [11].

$$\begin{Bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \epsilon_{12} \\ \epsilon_{23} \\ \epsilon_{13} \end{Bmatrix} = \begin{Bmatrix} \epsilon_{XX} \\ \epsilon_{yy} \\ \epsilon_{zz} \\ \epsilon_{xy} \\ \epsilon_{yz} \\ \epsilon_{xz} \end{Bmatrix} \quad (12)$$

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{23} \\ \sigma_{13} \end{Bmatrix} = \begin{Bmatrix} \sigma_{XX} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{xz} \end{Bmatrix} \quad (13)$$

Now
The equation in the form of

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$$\sigma = C\epsilon where \begin{cases} \sigma = Stressmatrixofunitvalue\ (6*1) \\ \epsilon = Strainmatrix\ (6*1) \\ C = Stiffnessmatrix\ (6*6) \end{cases}$$

The dual of the similar equation is in the form of

$$\epsilon = S\sigma where \begin{cases} \sigma = Stressmatrixofunitvalue\ (6*1) \\ \epsilon = Strainmatrix\ (6*1) \\ S = Compliancematrix\ (6*6) \end{cases}$$

Now in the terms of tensor formulation the combined equations are :

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{xz} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\vartheta_{yx}}{E_y} & -\frac{\vartheta_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{\vartheta_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\vartheta_{zy}}{E_z} & 0 & 0 & 0 \\ -\frac{\vartheta_{xz}}{E_x} & -\frac{\vartheta_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{xy}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{yz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{xz}} \end{bmatrix} * \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{xz} \end{bmatrix}$$

The above equation is now in the form.

$$\epsilon = S\sigma whereS = Compliancematrixoforder\ 6*6$$

The Stiffness matrix C will be yielded by COMSOL when it applies FEA analysis over RVE and using that matrix and using the Stiffness Matrix S , compliance matrix is generated after using the relation using the relation $S = C^{-1}$. The calculation were done after inverting the matrix [5].

The Heat Transfer Module in COMSOL works on the following equations.

$$\rho C_p \boldsymbol{u}.\boldsymbol{\nabla T} + \nabla.\boldsymbol{q} = Q + Q_{ref} \tag{14}$$

$$k\nabla T = q \tag{15}$$

The equation 14 &15 is the flux equation in general, the heat distribution according to the meshing and the internal distortion energy tensor yielded by COMSOL together will yield different parameters of this equation.To estimate the heat flux a reference temperature is provided in COMSOL and hence Q_{ref} is calculated then 'q' is calculated on the basis of the thermal conductivity of fiber and matrix data provided in COMSOL. All the basic nodes were balanced and hence the Fourier Law of heat transfer yield us the 3*3 thermal conductivity matrix as per equation 16 [12].

$$k_{eff} = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \tag{16}$$

The other properties like Specific heat and Coefficient of thermal expansion were calculated by COMSOL itself by the load constraints groups defined in COMSOL.

The combined effect of the heat transfer module and solid mechanics module was modeled by multiphysics node. The governing equation of periodicity and homogenization was as follow:

$$-\boldsymbol{n}.\boldsymbol{q} = \boldsymbol{0}; \boldsymbol{where} \begin{cases} \text{q} = \text{parameter to be estimated} \\ \text{n} = \text{elemental tensor} \end{cases} \tag{17}$$

With these equations COMSOL calculates the desired parameters. The value of 'n' is derived by COMSOL itself, after used has meshed RVE. The meshing will decide number of independent variable and convergence of the equation while running the simulation, so it is important to user define the correct mesh. Since rigorous analysis of the x direction is required and the same equations can be propagated in y and z direction, so we choose triangular mesh in yz plane and swept it along x. The meshed RVE looks like somewhat figure 4.

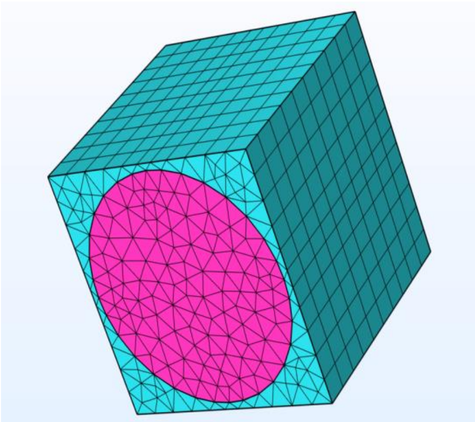

Figure 4: *RVE after meshing*

3.2 Setting up of parametric study

The parametric study was conducted in the simulation at two different boundary conditions one with thermal load and one without thermal load. Moreover, the parametric sweep node was used to vary fiber volume fraction from 0.1 to 0.7, The reason that the simulation is not going beyond 0.7 is that the set of equation form a highly stiff system, hence beyond 0.7 the current model is unable to yield correct result. Excel solver and Microsoft excel 2007 has been linked to COMSOL to store the solution in Excel and corresponding calculation were carried out by the following function.
MINVERSE() function will calculate the Compliance matrix S in excel.

The required function is defined in Excel as follows:

$$MINVERSE(< Ref1 >:< Ref2 >)where \begin{cases} Ref\ 1\ denotes\ the\ address\ of first\ cell\ of matrix \\ Ref\ 2\ denotes\ the\ address\ of\ last\ cell\ of matrix \end{cases}$$

Comparing the same with the standard compliance matrix in the same order and then manual calculation is carried out using excel with standard functions. The other function often used to loop over and retrieve the value of a cell repeatedly in different matrix for calculation, OFFSET () function is defined somewhat like

$$OFFSET(\$i\$j, (ROW(I1) - 1) * N, 0)$$

Where ij = initial reference of the cell that is used; N = after how many values we must capture the value. ROW (ij) = represent what will be the number of row; second argument tells us the number of repetition. Third argument talks about column iteration; here is set to 0 it means we have no column iteration.
The data generated were plotted in Excel and conclusions were drawn:

4 Results and Discussion

The FEA was conducted over RVE for the analysis of micromechanical properties and cell periodicity node was used for determination of property of homogenized sheet, the basic elastic properties that were studied for homogenized sheet in COMSOL.

4.1 Von Misses Stress Tensors

Once we have run the simulation the general 3D surface of stress tensors will be displayed by COMSOL. Since we have 7 different cases so fiber volume fraction ranging from 0.1 to 0.7 so we have 7 different stress tensors [13]. These stress tensor shows that on increasing the fiber content the internal stress will increase. Now these stress values briefly describe the fracture limits and in COMSOL® we can simulate by the concept of FEA that how it will look in the different section of RVE, in a nutshell the plot shows variation of distortion energy along RVE per square meter. Different plots achieved in these cases are depicted below in figure 5(a) to 5(g).

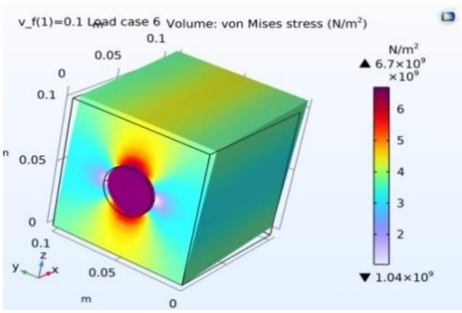

Figure 5(a): *Stress tensor at v_f=0.1*

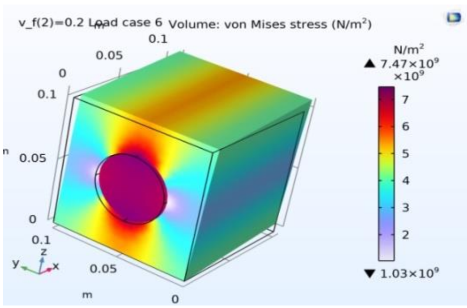

Figure 5(b): *Stress tensor at v_f=0.2*

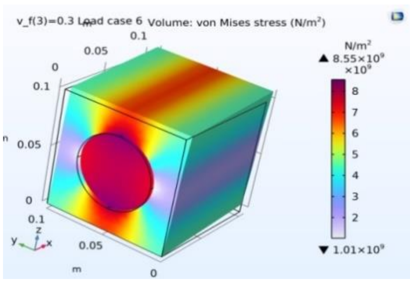

Figure 5(c): *Stress tensor at v_f=0.3*

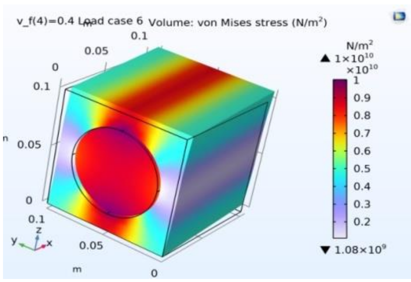

Figure 5(d): *Stress tensor at v_f=0.4*

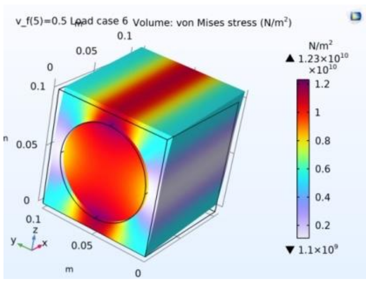

Figure 5(e): *Stress tensor at v_f=0.5*

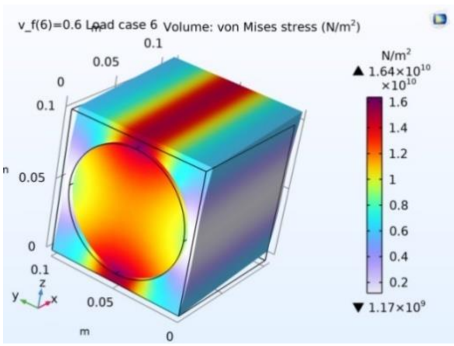

Figure 5(f): *Stress tensor at v_f=0.6*

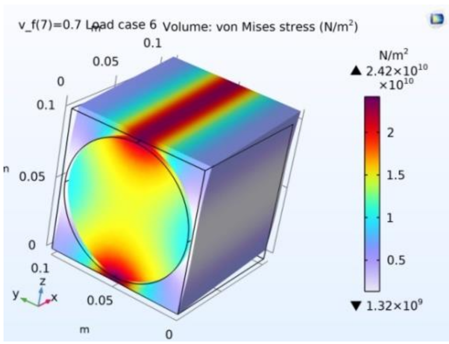

Figure 5(g): *Stress tensor at v_f=0.7*

4.2 Coefficient of thermal expansion (CTE)

Coefficient of thermal expansion shows the tendency of the material to change its dimension under temperature gradient. The CTE will tend to decrease on increasing the fiber volume fraction as the glass fiber makes the sheet a bit stiff. Rule of mixing model shows a bit of divergence with the data yielded by COMSOL and Shapery's Model converges as we increase the fiber volume fraction and gives a good data trend as per figure 6 and by work of [14].

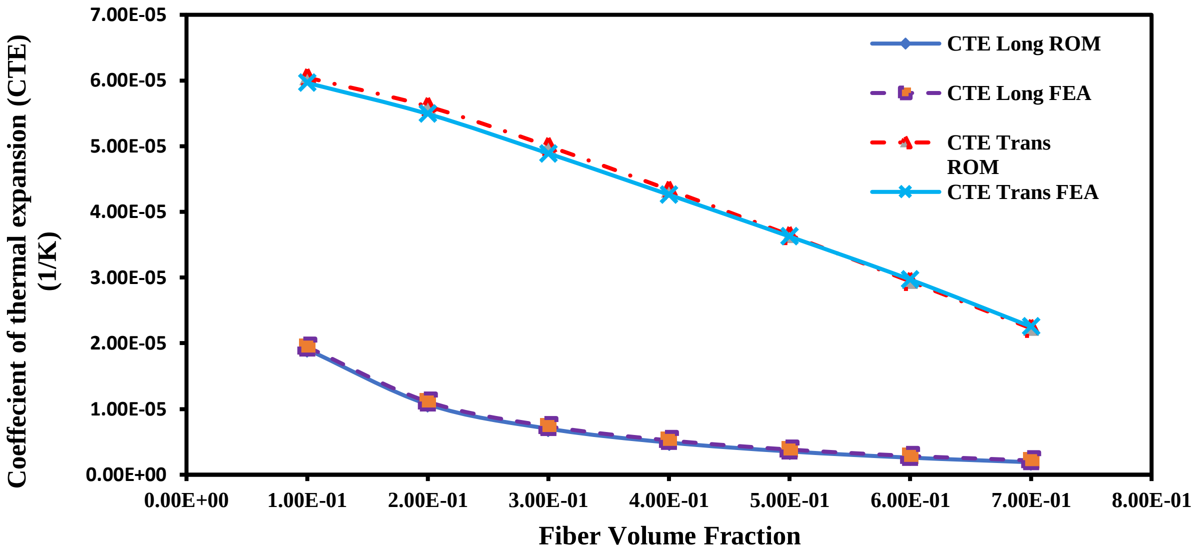

Figure 6: *Variation coefficient of thermal exapansion with fiber volume fraction*

4.3 Density Variation

The density variation shows a good data trend with the standard rule of mixing and with work of [15]. Three components mainly contribute in density; Epoxy (CY-230), Hardener (HY-591) and glass fiber, out of these glass fiber has highest density so as we increase the volume fraction of glass fiber so the density of the homogenized material will increase in linear fashion as per figure 7.

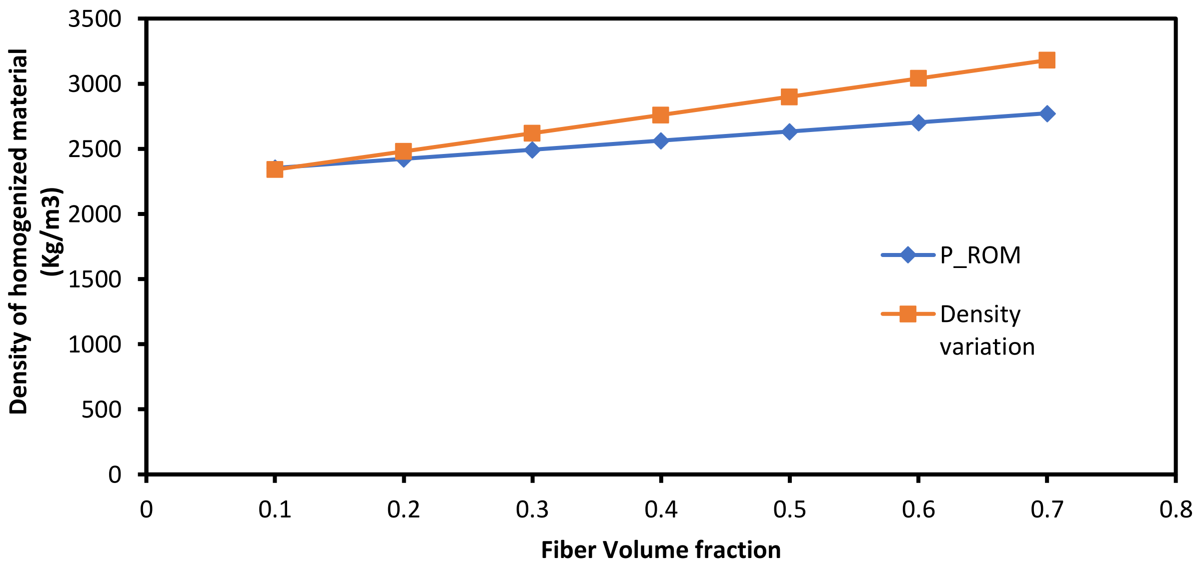

Figure 7: *Density Variation with fiber volume fraction*

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4.4 Thermal Conductivity Variation

Thermal Conductivity of E-glass fiber is greater than that of Epoxy so on increasing the fiber volume fraction a slight increase in thermal conductivity can be seen. Rule of mixing is somewhat inconsistent with the data, so a better model was needed to validate the result and hence Caruso's Model was used which takes into account the action of thermal conductivity of matrix and fiber and fiber volume fraction in volumetric fashion [16], [17]. Figure 8 below shows the variation of thermal conductivity along with respect to the change in the volume fraction of glass fibers. As stated earlier the E-glass fiber was used as a material in simulation, E-glass fibers have good optical and thermal properties hence it can be clearly seen that thermal conductivity will tend to increase as the fraction of E-glass fiber increases in the composite system.

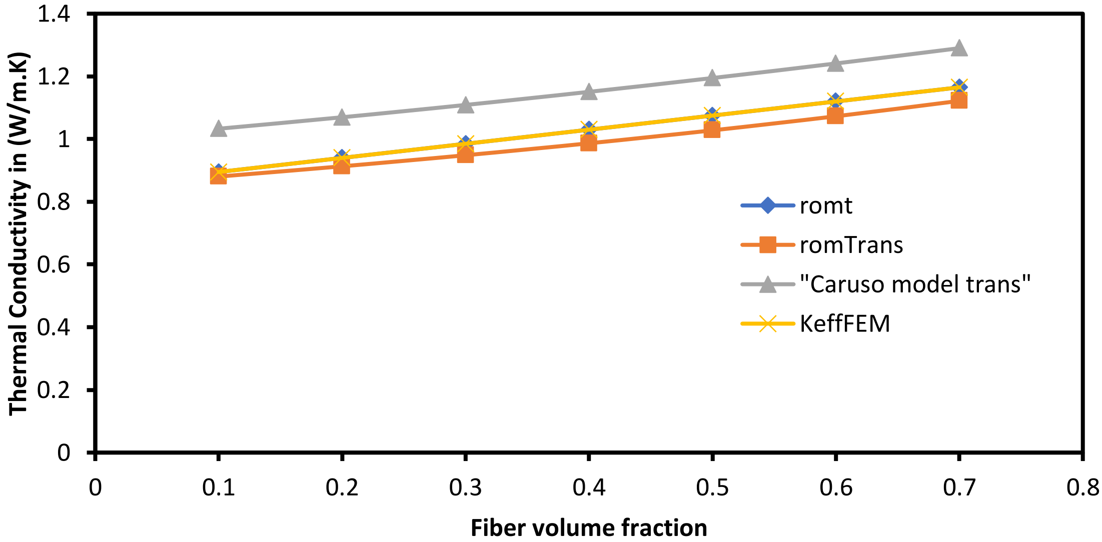

Figure 8: *Thermal Conductivity variation with fiber volume fraction*

4.5 Specific heat Capacity

Specific heat capacity shows sharp increase on increasing the fiber volume fraction in composites which is also concluded in recent research works [18]. The sharp increase shows that the glass fiber reinforced composite infact has high heat storage capacity and hence can be used for thermal insulation and in construction and interior application. This argument can be graphically shown as in figure 9.

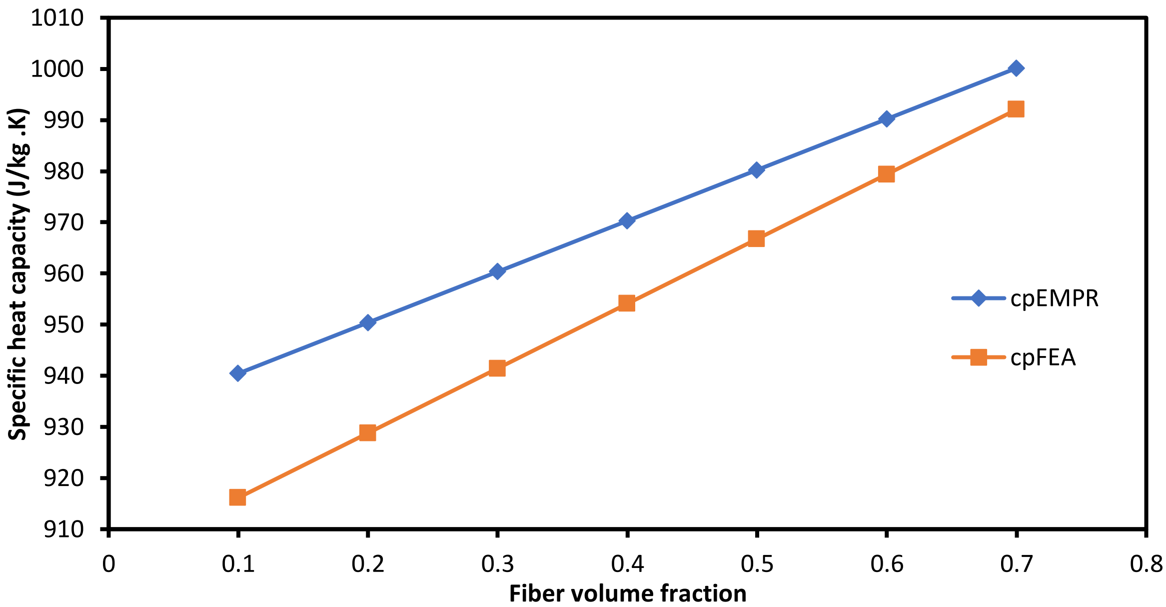

Figure 9: *Specific heat Variation with fiber volume fraction*

5 Conclusions

1. The von miss stresses tensor or distortion energy surface shows that as the fiber volume fraction is increased the curing of the fiber and matrix will become tough and due to this agglomeration chances are there to occur hence internal stress shows increase as we can infer by seeing the surface.
2. On the application of longitudinal and transverse thermo-mechanical load and increasing fiber volume the coefficient of thermal expansion tend to decrease. The decreasing nature of the curve is observed due to the fact that the glass fibers shows a bit of thermoplastic properties and hence on increasing fiber volume fraction they tend to decrease in both longitudinal and transverse direction. Along fiber the evaluation shows a linear decrease and along transverse direction it show exponential decrease.
3. Similarly on increasing the fiber volume fraction or fiber content of the composite a bleak increase can be seen in the thermal conductivity, which is due to the fact that the thermal conductivity of E-glass fiber is higher than that of epoxy. Caruso's Model is the best fit approximation for prediction of thermal conductivity.
4. As we increase the fiber volume fraction the amount of glass fiber will increase and hence the material will become stiffer and hence density will increase a bit. The epoxy comes with hardener which has its own density which is also taken into account while calculating effective density. Though density is purely a mechanical property but in the current simulation thermal action has also been considered.
5. Since the specific heat capacity of the glass fiber is more than that of epoxy so on increasing the fiber volume fraction the specific heat capacity tends to increase in sharp linear fashion. Since the specific heat is a volumetric property so it was evaluated on average volume basis not on basis of longitudinal and transverse direction separately.

6 Declarations

6.1 Competing Interests

There is no potential conflict of interest exist.

6.2 Publisher's Note

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