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Araştırma Makalesi

A manufacturing imperfection: fiber distortion and its effect on thermomechanical properties of polymer composites

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ABSTRACT

The aim of this study is to investigate the effect of a production imperfection, fiber distortions, on the resulting thermoelastic behaviour of composite materials in hexagonally packed Representative Volume Elements (RVEs) with finite elements micromechanical modelling. Instantaneous thermochemical and thermoelastic behavior of resin throughout the cure cycle is implemented into the model. This enables to calculate the resulting thermomechanical properties of composites, having fiber distortions from 0 to 18%, at the end of the cure cycle. It is found that the fiber distortion has great effect on the process induced residual stresses and Coefficients of Thermal Expansion (CTE) values. Equations expressing the variation of residual stresses and CTEs with fiber distortion are obtained. This study proves the importance of consideration of fiber distortions, a manufacturing defect, in finite element modeling of composite materials.

Keywords: *Composite materials, imperfection, fiber distortion, thermomechanical properties*

Bir üretim kusuru: fiber distorsiyonu ve polimer kompozitlerin termomekanik özellikleri üzerindeki etkisi

ÖZ

Bu çalışmanın amacı, bir üretim kusuru olan, lif bozulmalarının, kompozit malzemelerin ortaya çıkan termoelastik davranışı üzerindeki etkisini sonlu elemanlar mikromekanik modellemesi ile altıgen olarak paketlenmiş Temsili Hacim Elemanlarında (THE) araştırmaktır. Reçinenin kür çevrimi boyunca anlık termokimyasal ve termoelastik davranışı modele uygulanır. Bu, kürleme döngüsünün sonunda %0 ila %18 arasında fiber distorsiyonlarına sahip olan kompozitlerin termomekanik özelliklerinin hesaplanmasını sağlar. Fiber distorsiyonunun, proses kaynaklı artık gerilmeler ve Termal Genleşme Katsayıları (TGK) değerleri üzerinde büyük etkisi olduğu bulunmuştur. Fiber distorsiyonu ile artık gerilimlerin ve TGK'ların değişimini ifade eden denklemler elde edilir. Bu çalışma, kompozit malzemelerin sonlu elemanlar modellemesinde bir üretim kusuru olan fiber distorsiyonlarının dikkate alınmasının önemini kanıtlamaktadır.

Anahtar Kelimeler: *Kompozit malzemeler, imalat kusuru, fiber bozulması (distorsiyon), thermomekanik özellikler*

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I. INTRODUCTION

Fiber reinforced polymer composites have been one of the most remarkable materials of the last 50 years. Composites have two different constituents, that preserve the benefits of the separate constituents when combined. While one constituent, reinforcement, provides strength and stiffness for the overall material system, the other constituent, matrix, binds the reinforcements and transfers the applied load between them. High strength to low weight characteristics of composites is the most notable feature.

Computational analysis, specifically Finite Elements Modelling (FEM) is a very important tool for design and predict mechanical behavior of materials in engineering applications. It is always used for composite materials. Finite elements modelling of composites can be divided into three groups according to the scale of the model: Macro-meso-micro mechanical modelling. Finite elements micromechanical modelling is the only method that enables to investigate the interactions between the constituents. It provides to evaluate the effect of imperfections or defects of fiber and resin on the overall behavior of the structures [1]–[9]. Micromechanical analysis consist of Representative Volume Elements (RVEs) where the fibers are embbedded in the matrix with respect to regular arraying. However, the real life cannot be such perfect. Because, during the production of semi-products such as, carbon fabrics or pre-resin impregnated fabrics (prepregs), a distortion in a fabric yarn is highly possible and this can bring a decrease in mechanical properties of final composite parts.

While some authors prefer regular RVE arrays with respect to square and hexagonal geometries [1]–[17], some authors prefer randomly packed RVEs [18]–[28]. All of these studies preferred random arrayed RVEs to to approach the distributions of fibers in the matrix to more realistic view but not to investigate constituents' imperfectionsor defects. Some of them used statistical methods to distribute fibers randomly [20], [21], [24], [25], [28] or taking an example from a region inside a composite sample. High-tech optical observation techniques are used to detect fiber distribution from a cross section. These were enhanced by edge microscopy, X-Ray tomography or micro computed tomography equipments [26], [27]. Even though these observation techniques can enhance rich, accurate cross-sectional or volumetric views, they are time consuming and expensive methods. The aforementioned computational studies showed that the distance between the fibers have important effect on mechanical behavior [19], [21], [29], [30].

Composite materials are exposed to high temperature cure cycles. Mismatch in Coefficients of Thermal Expansion (CTE) of constituents results with process induced residual stresses at the end of cooling down to room temperature. Specifically, tension residual stresses generate in the matrix, whereas compressive residual stresses generate in fibers and this is unavoidable. However, few of these studies considered residual stresses only on the mechanical behavior of composites [4]–[7], [11], [13]–[16], [21], [22]. Only two of them used random fibre arrays [21], [22]. None of the studies used micromechanical modelling to evaluate the effect of fiber distortions on the thermomechanical properties of composites at the end of cure cycle, like process-induced residual stresses and CTEs. It is an important gap in literature.

During the production of composite raw materials or semi-products, an important quality problem is distortion of yarns during weaving or pre-resin impregnated fabric (prepreg) processes. While it brings visual defects on the surface, more importantly it can cause degradation in mechanical properties in final products. This is not desired by composite customers, since these materials are used for luxury cars or advanced engineering structures. While a visual defect can degrade the value of a luxury car or yacht, on the other hand, a quality defect can be the reason of catastrophic failure in an aeroplane in aerospace industy. Thus, it is important to investigate the effect of fiber distortions on the thermomechanical behaviour. Moreover, simple and quick tools are required in composite industry to provide quick solutions to problems. Even though, random fiber arrayed RVEs with complex statistical calculations are developed in literature, simple finite elements micromechanical analysis are important prediction tools to investigate and predict the effect of fiber distortion on the mechanical behavior of composite materials.

The aim of this study is to investigate the effect of a production imperfection, fiber distortions, on the resulting thermoelastic behaviour of composite materials in hexagonally packed RVEs with finite elements micromechanical modelling. Instantaneous thermochemical and thermoelastic behavior of resin throughout the cure cycle is implemented into the model. This enables to calculate the resulting thermoelatic properties of composites in different RVEs having fiber distortions from 0 to 18%. It is found that the fiber distortion has great effect on the process induced residual stresses and Coefficients of Thermal Expansion (CTE) values. Equations are obtained to represent the variation of process-induced residual stresses and CTEs with fiber distortion. This study provides a simple but robust prediction method for the effect of the fiber distortions on the thermomechanical properties of composites with simple RVEs.

II. MATERIAL

The material in this study is Hexcel's UD AS4/8552 prepreg [31]. HexPly® 8552 is an amine cured, toughened and high-performance epoxy resin system reinforced with UD AS4 carbon fibres for use in primary aerospace structures [31]. Fibre diamaeter, fibre volume fraction (Vf) and cured laminate thickness are 8 μm, 57.4 % and 0.184 mm respectively. Constituents' properties are given in Table 1 and Table 2. Subscripts 1-2-3 represent longitudinal and transverse directions respectively. In Table 2, subscript "r" stands for resin, while superscripts "T" and "C" stand for tension and compression respectively.

Table 1. Material properties of AS4 fiber [32], [33]

E_1	(GPa)	228
E_2=E_3	(GPa)	17,2
G_{12}=G_{13}	(GPa)	27.58
G_{23}	(GPa)	5,73
$\nu_{12}= \nu_{13}$		0.2
ν_{23}		0.5
α_1	(10^{-6}/ºC)	-0.9
α_2=α_3	(10^{-6}/ºC)	7,2
σ_{f1}^T	(MPa)	4150

Table 2. Material properties of 8552 resin [31], [32]

E	(GPa)	4,67
ν		0,37
α	(10^{-6}/ºC)	65
σ_r^T	(MPa)	121
σ_r^C	(MPa)	270

III. FINITE ELEMENTS MODEL

A. REPRESENTATIVE VOLUME ELEMENTS

In this study, ABAQUS® is used for finite elements analysis. 3D hexagonally packed RVE is considered in this study. Planar dimensions of RVEs are determined with respect to the fiber diameter and fiber volume fraction. 1 μm through-the-depth thickness to is given to decrease the computational time as much as possible.

Hexagonally packing array is shown in Figure 1. Yellow and turquoise parts in Figure 1 are fibers and resin respectively. In order to represent the fiber distortion, fiber in the middle of the RVE is translated in y and z directions. The meshed 3D model and translation of the fibers in planar dimensions (y and z directions) are shown in Figure 2. C3D8, 8-noded brick elements with 0.001 µm size are used to mesh the model. In the analysis, fiber distortions are implemented to the model from 0 up to 18% incrementally. In order to present how the fiber is distorted, 6% strain distortions are selected in each directions and presented in Figure 2.

In order to provide symmetry and peroidicity in micromechanical analyses, boundary conditions play very important role. Periodical boundary conditions should be applied for finite elements micromechanical analysis [3]. ABAQUS® has user-friendly Graphical User İnterface (GUI). Peridocical boundary conditions than enable symmetrical deformations are applied by using boundary conditions and equation constraint properties in GUI of ABAQUS. The type of boundary conditions and equation constraints are presented in
Table 3. In these tables, planes are named with respect to the 2D view of the RVE and directions are labelled according to the perpendicular directions in cartesian coordinate system in boundary conditions. Also, C-F-R refer to constraint, free and restricted respectively. Unit strain is applied in regarding directions to deform RVE.

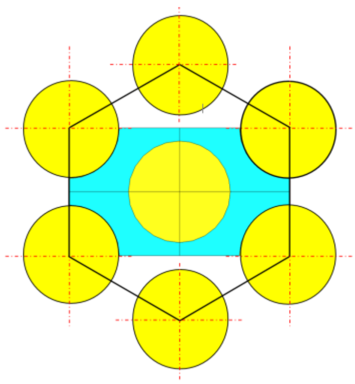


Figure 1. Fiber packing array in hexagonally packed RVE.

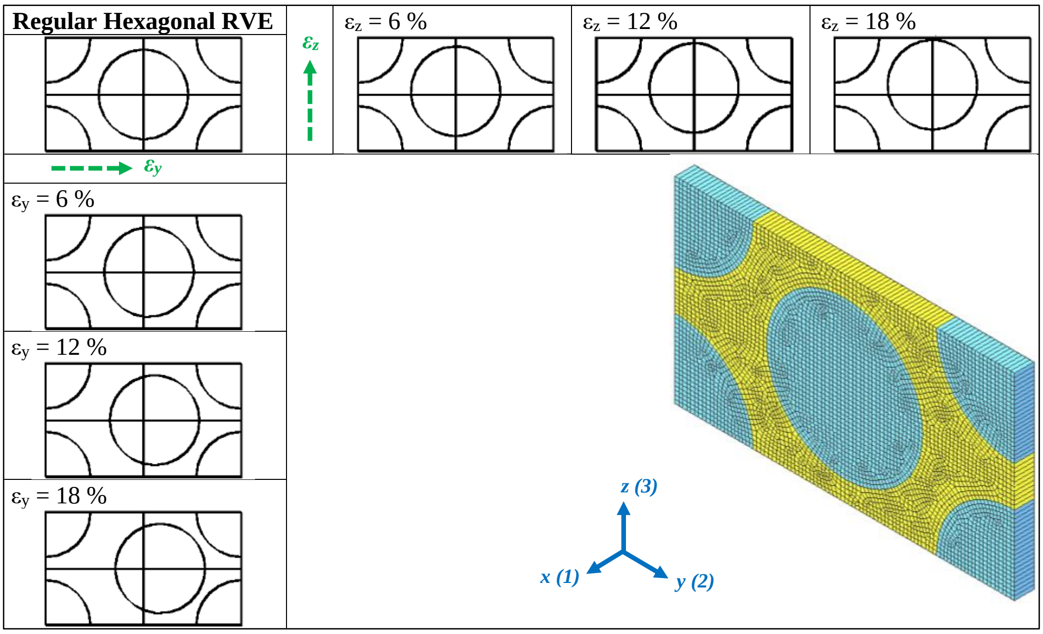


Figure 2. 3D hexagonally packed RVE and sketches of fiber distortions in 2D planar directions.

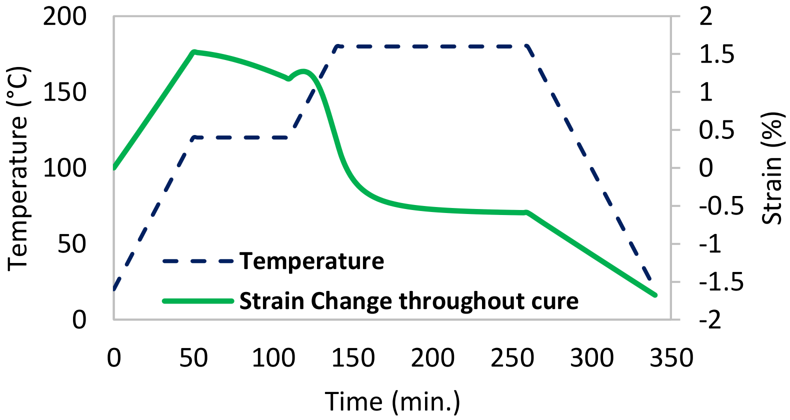
Table 3. Boundary conditions for cure hardening and normal load modes.

PLANE	X	Y	Z
BACK	R	F	F

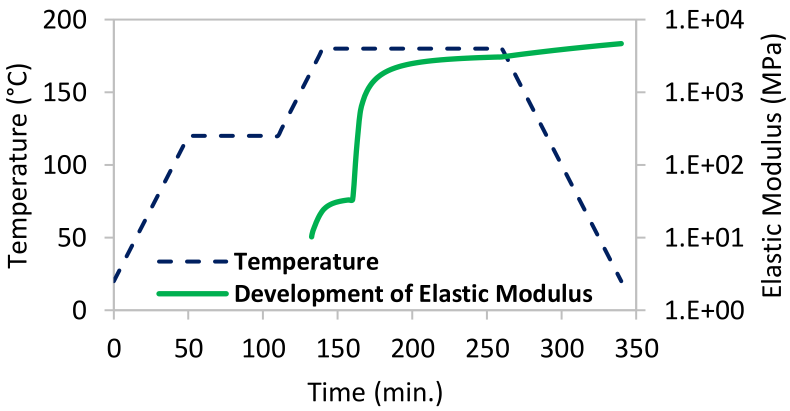
FRONT	C	F	F
LEFT	F	R	F
RIGHT	F	C	F
BOTTOM	F	F	R
TOP	F	F	C

B. THERMOMECHANICAL PROPERTIES

In order to investigate and calculate the thermomechanical properties of composite, instantaneous thermochemical and thermoelastic behavior of only 8552 resin during cure cycle is implemented into the model. It consists of instantanoues thermal and chemical strain and developing elastic moduli of 8552 resin throughout cure cycle. They were measured experimentally by Ersoy et al. [32]. They are presented in Figure 3.a and b. respectively. It is not possible to model it via the graphical user interface, and they are implemented to the model with user-defined subroutine, UMAT. This enables to calculate the process induced residual stresses, coefficients of thermal expansion and elastic properties of the composites. Even the consideration of different calculation methods results with different residual stress distribution inside the RVE. Maximum Principal and Raghava’s modified von-Misses (developed for polymer resin) stress criteria are considered to investigate the residual stress distribution. Equations 1-2 represent these failure criteria.



(a)



(b)

Figure 3. a. Strain change of 8552 resin b. Development of elastic modulus of resin throughout MRCC.

$$\frac{\sigma_{max}}{{\sigma_r}^T} \tag{1}$$

$$\frac{{\sigma_{vm}}^2}{{\sigma_r}^T \cdot {\sigma_r}^C} + \left(\frac{1}{{\sigma_r}^T} - \frac{1}{{\sigma_r}^C}\right) I_1 \quad (2)$$

IV. RESULTS AND DISCUSSION

B. 1. Process Induced Residual Stress in Regular RVEs

Residual stress distribution in the matrix of undistorted RVE with respect to three different calculation criteria are presented in Figure 4. Reason for showing the matrix only is due to the fact that compressive residual stresses induce in the fibers and they do not cause a detrimental effect during subsequent tensile loading but the stresses in the matrix is very important for progressive failure analysis.

Figure 4 shows that highest residual stresses are concentrated at the fiber/matrix interface with respect to both Maximum Principal and Raghava's MvM criteria. However, the planes of the maximum residual stresses are different in each case. Figure 4.a shows that the highest Maximum Principal residual stresses are considered at 30° and 90° planes with respect to y plane. The reason for this stress concentration is beacuse these are the resin rich regions where the fibers have the longest distance between each other. On the controversy, regions between the closest fibers have the lowest Maximum Principal residual stresses. Figure 4.b shows that the position of the maximum Raghava's MvM residual stresses occur at the same planes, at 30° and 90° planes with respect to y plane. The minimum residual stresses occur at the intersection region of the distances between three fibers and this repeats according to the geometry of the RVE as shown in Figure 4.b.

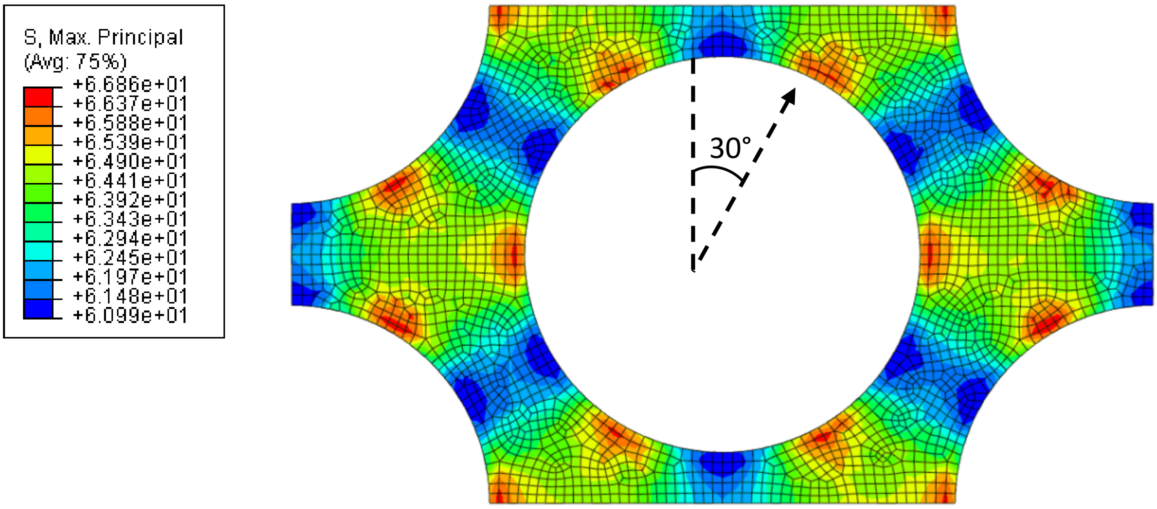
Table 4 shows the maximum residual stress values in the matrix with respect to different criteria. Maximum residual stresses are important because the failure onset starts if the maximum residual stress value reaches to 121 MPa, given in Table 2, or parametrically reaches to 1 during subsequent loading. On the other hand, average residual stresses should be calculated from the stress distributions in Figure 4. The average residual stresses are shown in Table 5. Average residual stress calculations within micromechanical model enables to calculate the macro-level residual stresses in a ply or UD laminate. It can be calculated from Table 5 that, multiplication of fiber volume fraction (57.4%) with the compressive residual in fibers and its summation to multiplication of tensile residual stress in resin with resin volume fraction (42.6%) gives "0" residual stress. That is the case in unidirectional laminates, because stress relief occurs with shape distortions.

Table 4. Highest residual stress values in the matrix of regular RVE

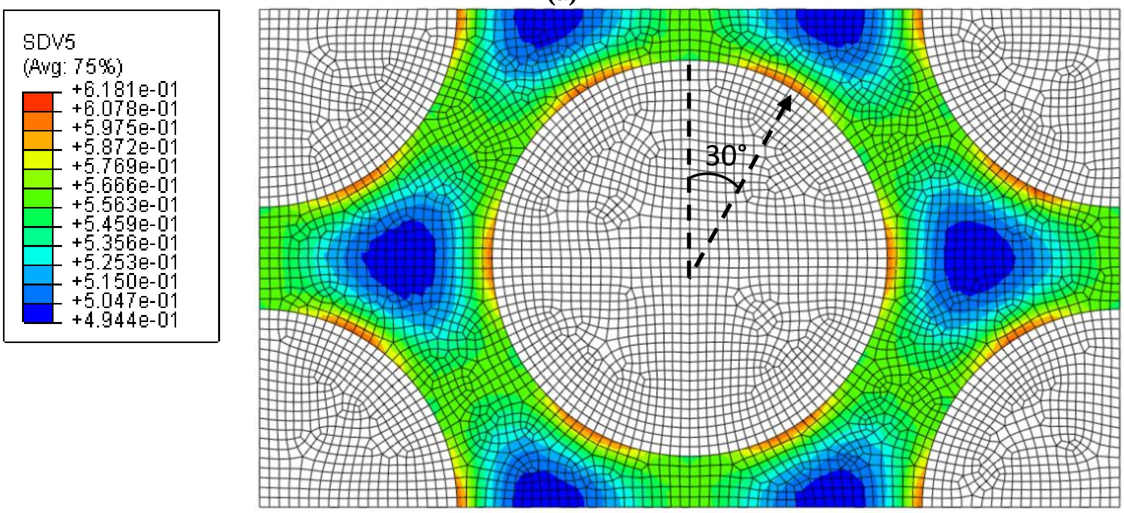
MAX PRINCIPAL		RAGHAVA
67 MPa	0.55	0.62

Table 5. Average residual stress values in regular RVEs

	MAX PRINCIPAL		RAGHAVA
Matrix	64 MPa	0.529	0.558
Fiber	- 86 MPa	- 0.713	- 0.751



(a)



(b)

Figure 4. Process induced residual stress distributions in the matrix of undistorted RVE with respect to a. Maximum Principal, b. Raghava's MvM.

B. 2. Effect of Fiber Distortion to Process Induced Residual Stresses

The values of the maximum residual stress values are not presented here for the sake of brevity. The change in the residual stresses is presented as a trend and the evolution of resiual stresses with fiber distortion are given in this section. Variation of the magnitude of process induced residual stresses with respect to fiber distortion is presented in Figure 5. Increase in the residual stresses are given with normalized values. It is calculated by dividing the resulting residual stress of distorted RVE to the values of regular RVE whose values are given in Table 4. Figure 5 shows that the increase in fiber distortion causes higher process induced residual stresses in the composite at the end of the cure cycle. Variation of residual stresses with respect to the Maximum Principal and Raghava's MvM criteria as a result of fiber distortions in z and y directions respectively fit each other well. An equation to represent the variation of process-induced residual stress values as a result of fiber distortion is a fair determination for researchers to use it in the models. This equation is shown on Figure 5. It represents the variation of maximum residual stress with respect to the fiber distortion strain.

Figure 6 and Figure 7 present the evolution of process induced residual stresses with fiber distortion with respect to different criteria. In each figure, the left columns represent resulting residual stress distribution as a result of fiber distortion in y-direction, whereas right columns represent residual stress evolution as a result of fiber distortion in z-direction. As the fibers get closer due to the increasing distortion, maximum magnitude of process induced residual stresses increase as well. As the distortion rate increases and the fiber approaches to the other, the lowest residual stress concentrates at the closest distance between the fibers which is the 45° plane during distortion in y-direction and 0° plane during the distortion in z-direction as presented in Figure 6 and Figure 7 for both criteria. Besides, as the amount of fiber distortion increases, the magnitude of the maximum residual stresses increases, in other words, higher tensile residual stress concentrate whereas, the magnitude of the minimum residual stresses in the RVE decreases as the fiber distortion increases, which means the concentration of the higher compressive residual stresses. Increase in tensile residual stress concentration cause early failure in the composite when a subsequent tensile load is applied. On the other hand, concentration of higher compressive stress in the RVE brings inital failure when a subsequent compressive load is applied. So, one can predict the failure level of the composite when the effect of unavoidable residual stress and the effect of the fiber distortion are considered during a load mode.

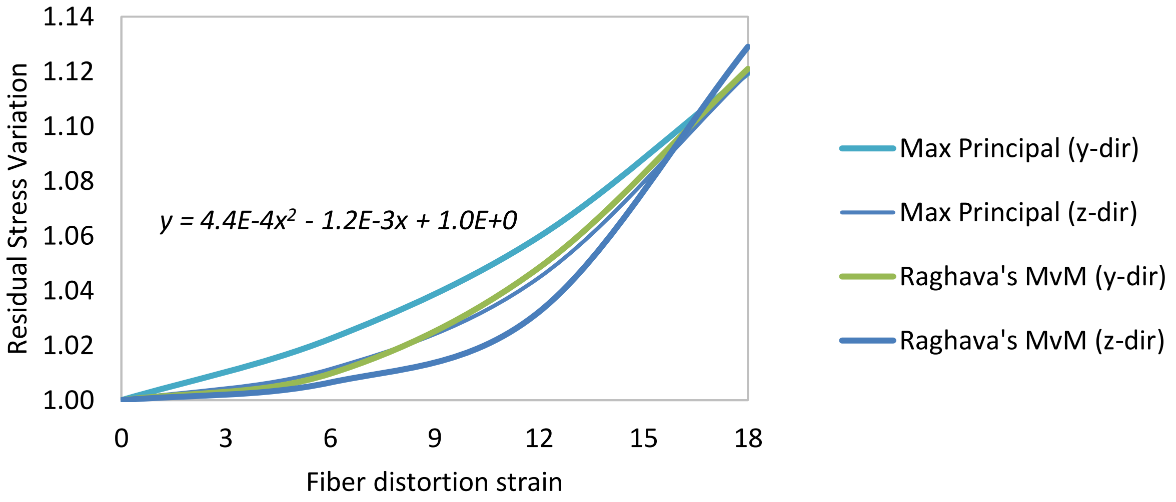


Figure 5. Variation of residual stress as a result of fiber distortion in each direction.

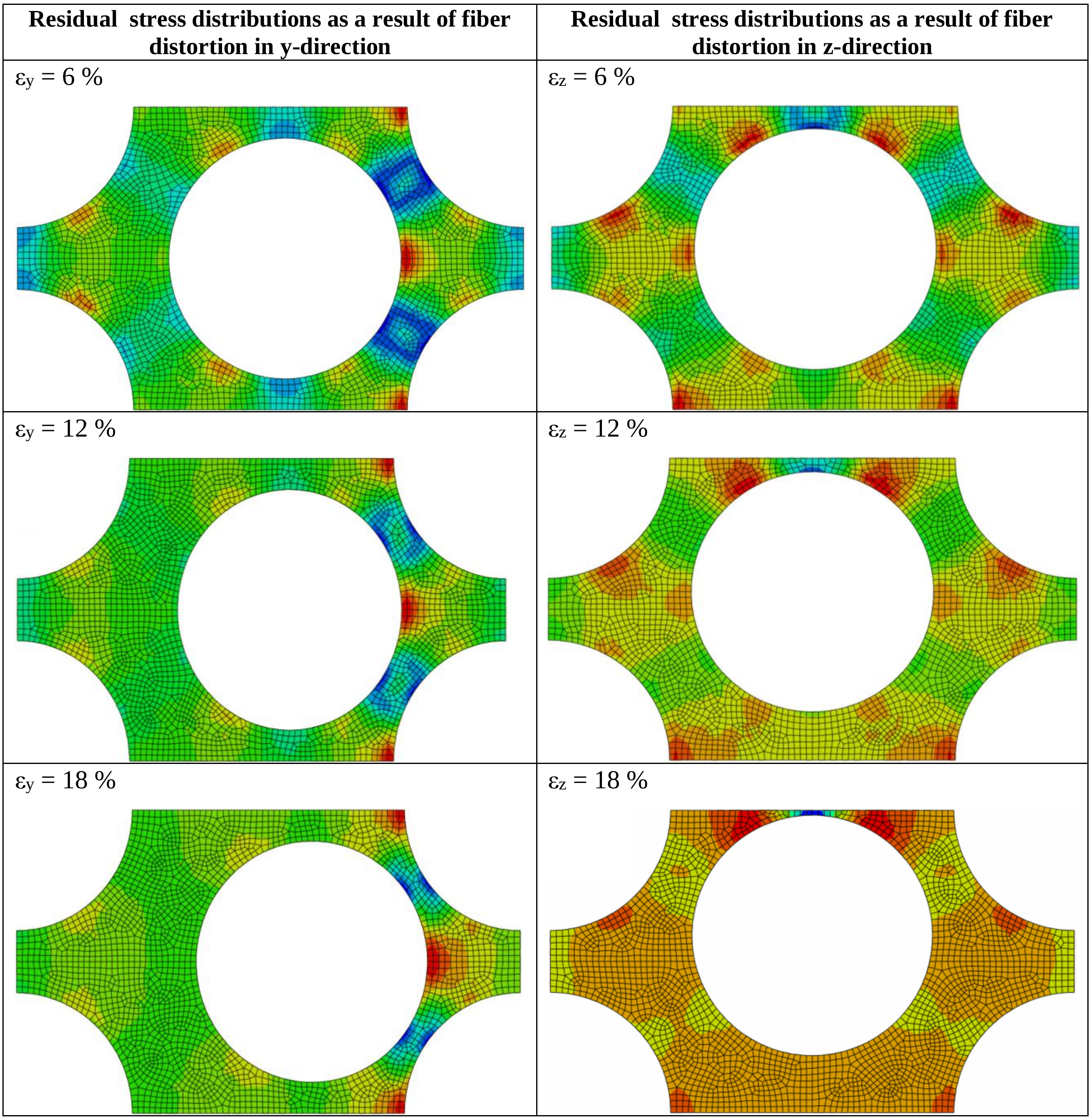


Figure 6. Variation of Maximum Residual Stress distribution with fiber distortion

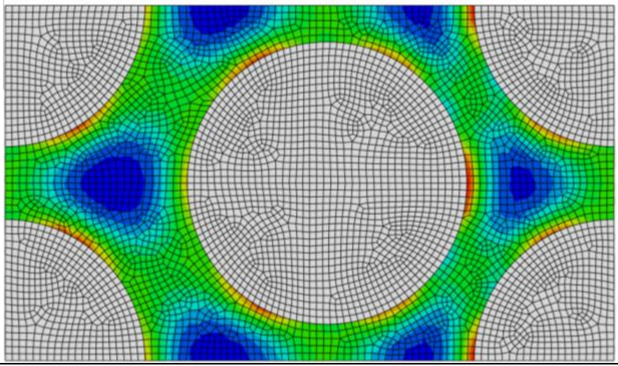
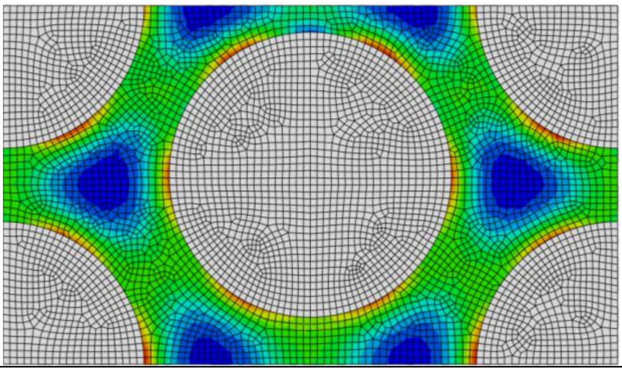
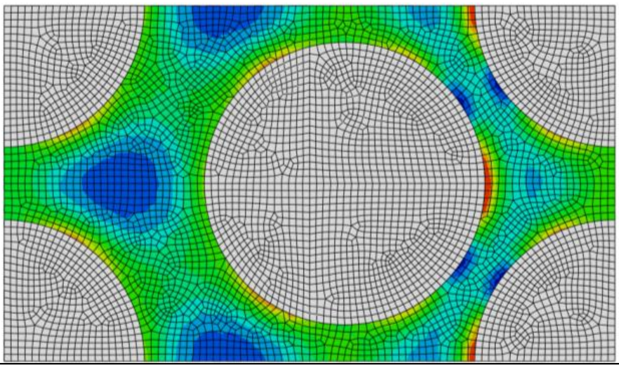
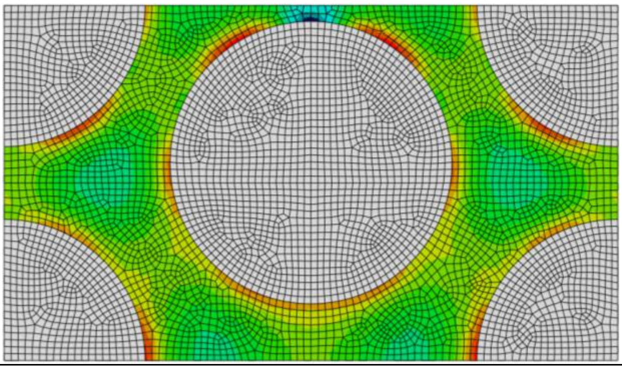
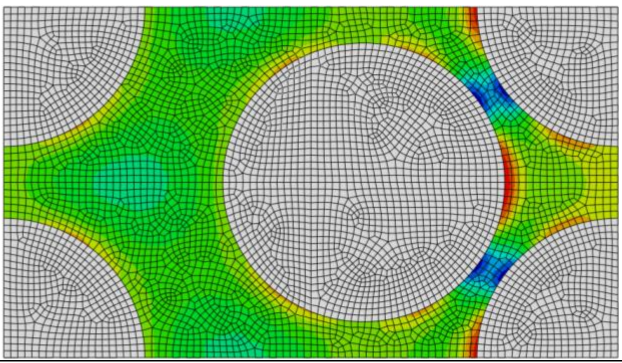
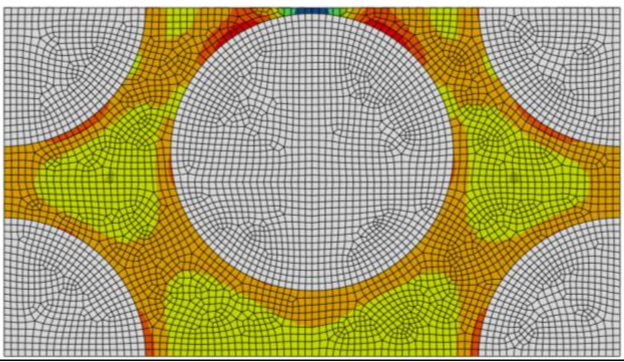
Residual stress distributions as a result of fiber distortion in y-direction	**Residual stress distributions as a result of fiber distortion in z-direction**
ε_y = 6 % 	ε_z = 6 % 
ε_y = 12 % 	ε_z = 12 % 
ε_y = 18 % 	ε_z = 18 % 

Figure 7. Variation of Raghava's MvM residual stress distribution with fiber distortion.

B. 3. Effect of Fiber Distortion to the Coefficients of Thermal Expansion

CTE value calculations with regular RVE is found to be 0.23 με/°C in fiber direction, whereas it is 35.6 με/°C in transverse directions. Such difference in each direction is due to the fact that the stiffness of the fiber is excessive in longitudinal direction and prevents the motion of the composite material in this direction, while low stiffness in transverse directions provides easy deformation with temperature and results with high CTE value. The trend of the variation of CTE values with fiber distortions is very similar to each other as shown in Figure 8. However, because of the different characteristics in each directions, a single equation cannot be obtained if the CTE values normalized. Because of this, two equations are presented on Figure 8 to represent the variation of CTEs with fiber distortion. They are best represented with 3rd order equations and they can distinguished according to the colors and the magnitudes of the coefficients.

Increase in the CTE values cause easier shape distortions with temperature change at the end of the cure cycle of composites. As seen in Figure 8, increasing amount of fiber distortion can make this shape distortions much easier at the end of the cure cycle. This study proves the detrimental effect of fiber distortions in terms of CTE values. It means that even a small amount of fiber distortion causes changes in its material properties. The values and the equations in Figure 8 can be used for further FEM analysis to investigate the effect of consequence of fiber distortion on the subsequent mechanical properties of composites to analyze the shape distortions.

Measuring the process induced residual stresses or CTE values in composites requires large experimental study. Besides, repeating it for composites with different fiber distortion amounts is an extensive work. Thus, it is not easy to corralete the findings of this study with real experimental results. However, the findings of this study can be easily used for further numerical studies for shape distortion analyses and micromechanical loading analyses. Since the scope of this study is to investigate the effect of the fiber distortion on the thermomechanical behavior, the results are limited to variation of process induced residual stresses and the CTE values.

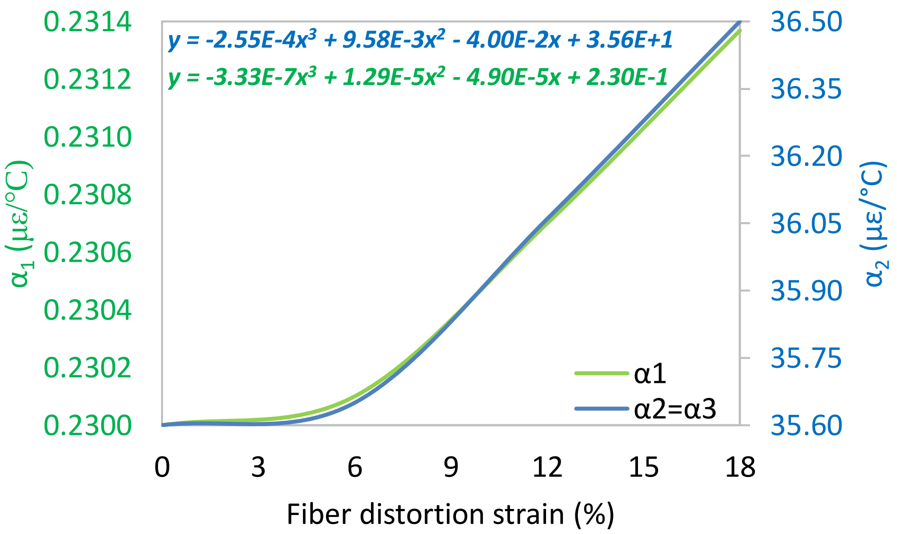


Figure 8. Variation of CTEs with fiber distortion.

V. CONCLUSION

This study presents the effect of fiber distortions, a composite manufacturing defect, on the resulting thermomechanical characteristics of composites. Specifically, it shows the detrimental effect of fiber distortions on process-induced residual stresses and CTEs by using finite elements micromechanical models. It is found that the calculation of residual stresses with respect to different criteria gives similar results and 18% fiber distortion in transverse directions causes 12% increase in the process-induced residual stress magnitues, aligned with 2nd order equation trend. In addition to this, distribution of the residual stresses in the RVEs with different distortions show similar behavior with respect to both Maximum Principal and Raghava's MvM criteria. On the other hand, CTE values in each directions are seen to change similarly with fiber distortion. Third order equations can be drawn for the CTE values to represent their variation with fiber distortion strain. This study clearly shows the importance of consideration of manufacturing defects, that is fiber distortion specifically in this study, on the thermomechanical properties of composites. The findings of this study can be used for shape distortion and micromechanical loading analyses to investigate the effect of resulting properties due to fiber distortion.

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