

# THERMAL RESIDUAL STRESSES IN THERMOPLASTIC COMPOSITE DISC WITH HOLES USING 3D-FEM

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## ABSTRACT

In this study thermal residual stresses were calculated for a composite disc with many holes using 3D-FEM. Most of previous studies related to thermal stresses and residual stresses of composite disc were performed as two dimensional, but present study was done using three dimensional modelling and FEM, firstly. The composite disc was thermoplastic matrix and steel fibres for reinforcement material as unidirectional for radial direction. Different uniform temperature distributions were subjected to the thermoplastic composite disc as thermal loads. Finite element method (FEM) was used to compute thermal residual stresses. For this purpose, the thermal stress analysis was carried out in two stages as elastic and elastic-plastic solutions. All modelling and solution processes were done using ANSYS finite element software which is known as a general purpose engineering simulation. According to obtained results, thermal residual stresses in thermoplastic composite disc were created by applied thermal loadings owing to the composite disc having different thermal expansions in radial and tangential directions.

**Keywords:** Residual stress; Composite disc; Thermal analysis; Multiple holes; FEM.

## 1. INTRODUCTION

The development of advanced composite materials has constituted to a revolution in material applications in recent years. The high stiffness and strength to weight of fibres, along with other properties such as environmental resistance, make composite materials increasingly popular as potential candidates for materials substitution [1]. Fibre-reinforced composite materials consist of fibres of high strength and modulus embedded in or bonded to a matrix with distinct interfaces between them. In this structure, both fibres 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 [2].

Reinforced thermoplastics have become very frequently used due to the fact that they are easy to use and mould as well as have certain mechanical characteristics and size stability. The tensile strength of reinforced thermoplastics can be enhanced and the deformation that emerges under pressure can be decreased considerably. In addition, as the rigidity of the thermoplastic accelerates, a recognizable drop is observed in the expansively. Among other advantages of attached to reinforced thermoplastics are high-resistance to corrosion, less shrinkage in

mould, less contraction in moist environments, and less modification in dimension. Reinforced thermoplastic plates softened through heating are widely used in not only avionics and space industry but also automotive sector as they are produced in unheated moulds and are appropriate for recyclable material utilization [3].

Sayman et al. [4] performed an elastic-plastic thermal stress analysis on thermoplastic composite disc reinforced curvilinearly with steel fibres underneath uniform temperature distribution. The solution was applied numerically, for non-hardening case. Rossit and Laura [5] investigated unsteady thermal stresses caused by the existence of a hot, central nucleus, in disc or cylinders. The temperature field was calculated in terms of a Fourier-Bessel expansion and then, radial and tangential stresses were evaluated analytically. The considered problem was of basic interest in mechanical and naval engineering systems. Trende et al. [6] examined residual stresses and dimensional changes in the compression moulded glass-mat reinforced thermoplastic parts. A heat transfer and crystallization model with temperature dependent matrix properties was used to compute input to the subsequent thermal stress analysis. Both an isotropic viscoelastic and a transversely isotropic

elastic material model were analysed through finite-element calculations.

Sen [7] performed an elastoplastic thermal stress analysis for a thermoplastic composite disc that is unidirectional reinforced by steel fibres. The finite element method (FEM) was used to compute thermal elastic and elasto-plastic stress distributions in the model of the composite disc. The solution is performed using the ANSYS program. In order to evaluate the effects of uniform temperature, different temperature loadings are applied to the disc model uniformly. Sen et al. [8] carried out an elastic-plastic stress analysis on a steel fibre reinforced thermoplastic composite disc under a parabolic temperature distribution. The elastic, elastic-plastic solutions obtained analytically, at different temperatures. Tsai-Hill theory was used as a yield criterion in the solution. Solution was also performed by FEM using ANSYS software code. It was found these two solutions are in good agreement. Sen [9] investigated the effect on thermal and residual stresses of parabolic temperature loading in a thermoplastic composite disc. FEM was used to estimate the thermal elastic, elasto-plastic, and also the residual stress distributions in the selected model of the composite disc using ANSYS. The values of the tangential stress components both elastic and elasto-plastic solutions were higher than the radial stress components. Besides, the residual stress components were calculated using elastic and elasto-plastic solution results. Sen and Aldas [10] obtained thermal stresses in a thermoplastic composite disc unidirectional reinforced by steel fibres. The temperature loading was chosen so as to vary linearly from inner surface to outer surface along the radial sections of the disc. Linear thermal loads were selected as to differ from each other. In addition, the residual stress components were also calculated using both elastic and elastic-plastic solution results.

Kaynak et al. [11] studied to find out the influences of uniform thermal loads on a composite disc having many pin/bolt holes. Polymer composite disc reinforced short glass fibres were successfully produced by using injection and compression moulding techniques, and microstructural observations were carried out using an electronic microscope. A thermo-elastic stress analysis was performed utilizing FEM and ANSYS. The circular holes were created in the disc because of observing these effects on thermal stresses. The thermal loads were applied to the disc at a uniform distribution. Sen [12] aimed to investigate elastic-plastic thermal stresses in a thermo-

plastic composite hollow disc with multiple holes. Different uniform temperature distributions were subjected to the disc as thermal loadings. FEM was used to calculate both thermal and residual stresses via ANSYS. Sen and Sayer [13] investigated to observe the influence of multiple holes on thermal stresses in a thermoplastic composite hollow disc. For this purpose, a thermoplastic composite disc is reinforced by steel fibres as curvilinear for radial direction, and thermal loads are carried out for uniform distribution at various temperatures. The solution is completed in two parts that are elastic and elastic-plastic analysis. Additionally, residual stresses are calculated using these analysis results.

It is pointed out that the load-carrying capacity of the reinforced discs is much higher than that of the traditional isotropic steel discs of the same geometry; in addition, the weight of the former is several times lower [14-15]. A closed form solution for the stress analysis in curvilinearly orthotropic disc and cylinders under pressure can be found in literature [4]. However for rectilinearly orthotropic discs, the solution can be performed under specific conditions [5]. In addition, some thermal stress problems for beams, cylinders, bars, plates, etc. are explained for easy understanding by Noda et al. [16].

In this study, thermal residual stresses were calculated for a composite disc with many holes using 3D-FEM. Since previous studies related thermal residual stresses with/without holes were performed as two dimensional modelling and solution according to literature survey and knowledge of the authors.

## 2. MATERIALS AND METHODS

### 2.1 Thermoplastic Composite Disc

The material of composite disc was manufactured at Mechanics Laboratory of Dokuz Eylul University by Sen [17] using thermoplastic composite method of Bektas and Sayman [18]. in same laboratory. Anyway, production process of thermoplastic matrix composite was explained in these previous studies [17-18]. Briefly, composite material was produced using high-density polyethylene (HDPE) as a thermoplastic matrix material and stainless steel fibres as unidirectional reinforcement material as seen in Fig. 1 [17-18]. Thus, it is named as steel fibre reinforced thermoplastic composite disc in the literature. For production, firstly, polyethylene granules were put into the moulds and temperature of electrical heater was increased up to 190 °C. Then, thermoplastic material was held under 2,5 MPa for 5 minutes at this temperature value. Later temperature

**Table 1:** Mechanical properties and yield strengths of the composite layer [17]

$E_1$ (MPa)	$E_2$ (MPa)	$G_{12}$ (MPa)	$K$ (MPa)	$\nu_{12}$	$X$ (MPa)	$Y$ (MPa)	$S$ (MPa)	Thickness of each layer (mm)	Thermal expansion coefficients ( $1/^\circ\text{C}$ )	
									$\alpha_1$	$\alpha_2$
41000	1200	420	76	0.25	39	5	14	2	13.1E-06	131E-06

of electrical heater was decreased to 30 °C under 15 MPa pressure value in 3 minutes, hence a polyethylene layer was produced.

Finally, the steel fibres were put into between two thermoplastic layers and processed as previous processes. To complete the process, thermoplastic composite disc was produced as 2 mm thickness. The mechanical properties of thermoplastic composite material were listed in Table 1 [17]. These mechanical properties were determined experimentally using Instron 1114 test machine and using strain gauges. During the 3D-FEM solution, thermoplastic composite material was assumed to be linearly hardening. Moreover, it was assumed that the mechanical properties of it didn't change with applied temperature.

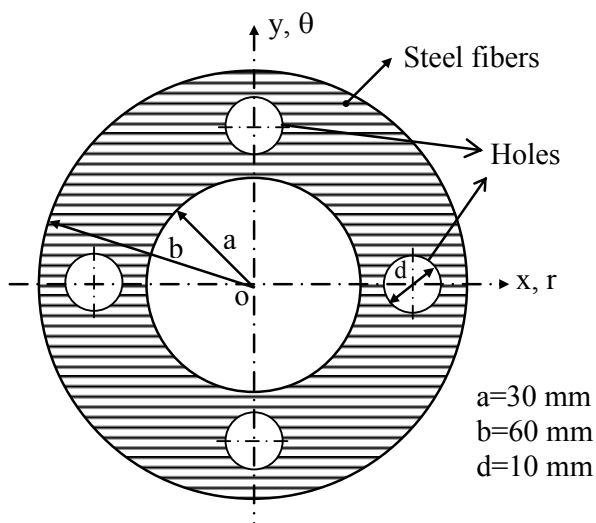
## 2.2 Thermal Stress Problem

Unidirectional steel fibre-reinforced thermoplastic hollowed composite disc is shown in Fig. 1. The inner and outer radius of disc are  $a=30$  mm and  $b=60$  mm, respectively. As seen from this figure, many circular holes are also created on disc. The diameter of each hole is assumed as  $d=10$  mm.

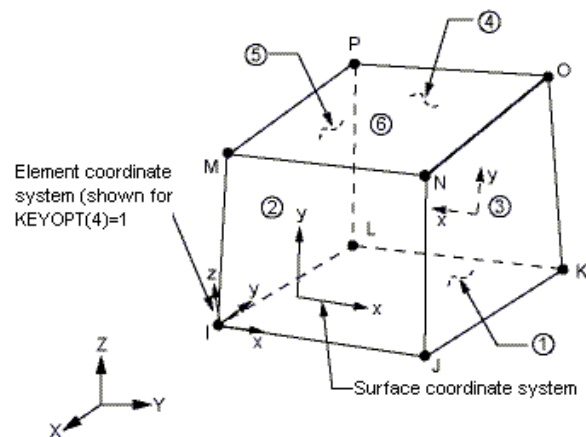
The finite element method (FEM) was preferred to obtain thermal elastic, elastic-plastic and residual

stress components. But three dimensional finite element model (3D-FEM) was used for a composite disc problem in this work as a start. Therefore it was modelled as a three dimensional with a thickness through z-direction as  $t=4$  mm. Because of using FEM and ANSYS program was used for both modelling and solution of thermal stress problem for disc. Since, ANSYS is known as a general-purpose finite element code for various engineering problems.

Element type was chosen as SOLID 45 for mesh structure. The geometry, node locations, and the coordinate system for this element are shown in Fig. 2 [18]. This element type is used for the 3-D modeling of solid structures. The element is defined by eight nodes with three degrees of freedom at each node; translations in the nodal x, y, and z directions. The element has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. A reduced integration option with hourglass control is available. The element is defined by eight nodes and the orthotropic material properties. Orthotropic material directions correspond to the element coordinate directions. The element coordinate system orientation is as described in Coordinate Systems [18]. The selection of this element type was very important for this problem. Since disc model created as three dimensional and it is intended to compute residual stresses on it. It is known that residual stresses can be obtained with elastic-plastic analysis. Anyway, this element is suitable both three



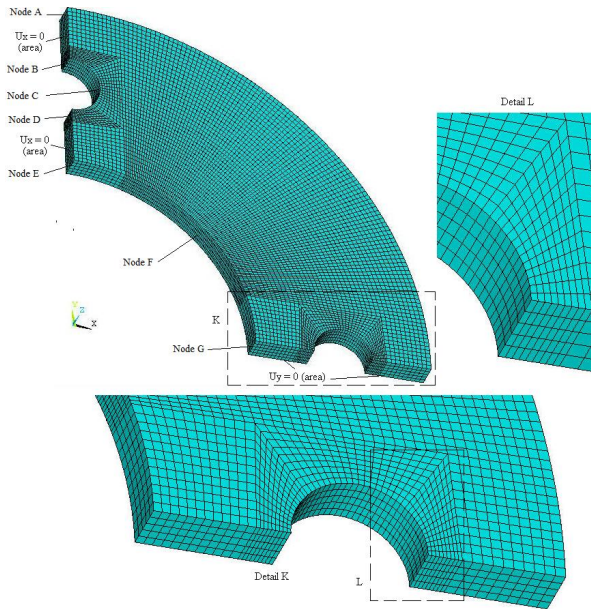
**Fig. 1:** Schematic view of unidirectional steel fibre reinforced thermoplastic composite disc with many holes



**Fig. 2:** SOLID45 element type in ANSYS [19]

dimensional problems and plasticity.

Boundary conditions and 3D-FEM model of the hollow composite disc with multiple holes, which was modelled in ANSYS, is illustrated in Fig. 3. The mesh details where surroundings of multiple holes are also illustrated in this figure as Details K and L. Achievement of good mesh structure is very important for FEM solutions, if the model has multiple holes, particularly. Since, holes are not plotted via straight lines. Meanwhile, it is seen from Fig. 3, mapped mesh is created on composite disc model. Mapped mesh structure is more suitable than free mesh. It is also known that mapped mesh is limited in terms of the element shape and it contains the pattern of the mesh [19-20]. After generation of mesh structure on 3D-disc, 26190 elements and 32652 nodes were produced. Additionally, it should be said at this point that a quarter part of the whole disc model was created owing to the symmetry of disc.



**Fig. 3:** Boundary conditions and 3D-FEM model with details and many holes of disc

Thermal stress problem was solved in three steps. Firstly, elastic analysis was done. Secondly, elastic-plastic analysis was studied for plasticity. Finally, thermal residual stresses were calculated using both elastic and elastic-plastic analyses results. For this reason, superposition method was used. The superposition of the elastic stresses and plastic stresses gives the residual stress values as,

$$\begin{aligned}(\sigma_r)_r &= (\sigma_r)_p - (\sigma_r)_e \\(\sigma_\theta)_r &= (\sigma_\theta)_p - (\sigma_\theta)_e \\(\sigma_z)_r &= (\sigma_z)_p - (\sigma_z)_e\end{aligned}\quad (1)$$

Concisely, the magnitudes of thermal residual stress-

es are calculated using Equation (1). Thermal stresses occurred because of uniform temperature loading on 3D-disc. Applied uniform temperature values were selected as 70, 75, 80, 85, 90, 95, 100, 105 and 110 °C. Since it was intended to see changing of both elastic and plastic thermal stresses related to increasing uniform temperature loading. Besides, it was aimed to find the beginning and changing of thermal residual stresses. For that reason, elastic solution and elastic-plastic solution were carried out step by step and these created disc models for each uniform temperature loading.

### 3. RESULTS AND DISCUSSION

Calculated maximum values of thermal elastic, plastic and residual stress components on three dimensional thermoplastic disc are listed in Table 2. According to this table, thermal stresses are determined for both tensile and compressive form. The tensile and compressive stress form explanations are valid for elastic and plastic stresses in this table. Maximum values of tensile stresses are calculated higher than maximum values of compressive stresses for both radial and tangential directions. But absolute values of compressive stresses are higher than tensile stresses of z-direction for elastic solution. In the meantime, this result cannot be valid for z-direction of plastic solution. Table 2 also points out that thermal residual stresses are obtained for both tensile and compressive forms.

It is understood that thermal stresses are increased by increasing applied uniform temperature loadings. Increase in thermal stresses is seen as linearly for elastic stresses, whereas nonlinear increasing is seen for plastic stresses. This result is very important and appropriate for real problems. Since, it is known that increasing of thermal stresses is not occurred as linearly. Briefly the highest values of elastic, plastic and residual stresses are calculated for 110 °C thermal loading, while the lower values of there are computed for 70 °C. The maximum values of elastic tensile and compressive stresses are obtained as 16,572 MPa and -5,481 MPa for radial and tangential directions, respectively. Meanwhile, the maximum values of plastic tensile and compressive stresses are calculated as 16,341 MPa and -5,231 MPa for radial and tangential directions, respectively.

Owing to three dimensional FEM analyses, both thermal stresses and thermal residual stresses are determined in composite disc. Nevertheless Table 2 points out that calculated thermal and residual stresses for both radial and tangential directions are

**Table 2:** Maximum values of thermal elastic, plastic and residual stress components on disc

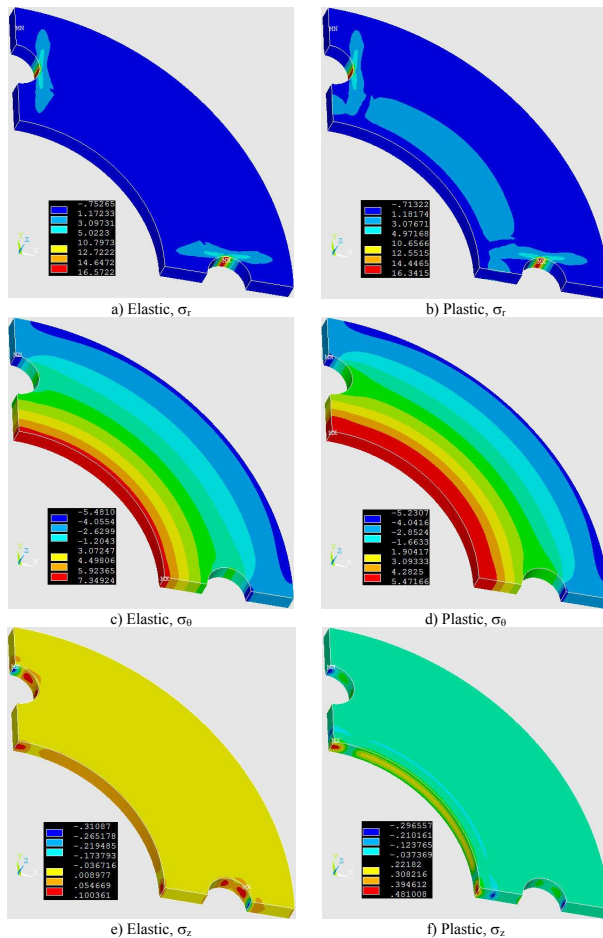
T (°C)	Stress Form for elastic and plastic stresses	Elastic Stresses (MPa)			Plastic Stresses (MPa)			Residual Stresses (MPa)		
		$(\sigma_r)_e$	$(\sigma_\theta)_e$	$(\sigma_z)_e$	$(\sigma_r)_p$	$(\sigma_\theta)_p$	$(\sigma_z)_p$	$(\sigma_r)_r$	$(\sigma_\theta)_r$	$(\sigma_z)_r$
70	Tensile	10,546	4,677	0,063	10,546	4,677	0,063	0	0	0
	Compressive	-0,478	-3,488	-0,197	-0,478	-3,488	-0,197	0	0	0
75	Tensile	11,299	5,011	0,068	11,299	5,011	0,068	0	0	0
	Compressive	-0,513	-3,737	-0,211	-0,513	-3,737	-0,211	0	0	0
80	Tensile	12,053	5,346	0,118	12,551	5,152	0,160	0,498	-0,194	0,042
	Compressive	-0,547	-3,993	-0,242	-0,827	-3,992	-0,242	-0,280	0,001	0
85	Tensile	12,806	5,679	0,077	12,854	5,290	0,300	0,048	-0,389	0,223
	Compressive	-0,581	-4,235	-0,240	-0,581	-4,231	-0,239	0	0,004	0,001
90	Tensile	13,559	6,013	0,082	13,641	5,374	0,384	0,082	-0,639	0,302
	Compressive	-0,615	-4,485	-0,254	-0,612	-4,464	-0,253	0,003	0,021	0,001
95	Tensile	14,312	6,347	0,086	14,383	5,419	0,430	0,071	-0,928	0,344
	Compressive	-0,650	-4,734	-0,268	-0,641	-4,679	-0,265	0,009	0,055	0,003
100	Tensile	15,066	6,681	0,091	15,078	5,445	0,455	0,012	-1,236	0,364
	Compressive	-0,684	-4,983	-0,282	-0,667	-4,878	-0,276	0,017	0,105	0,006
105	Tensile	15,819	7,015	0,095	15,078	5,445	0,455	-0,741	-1,570	0,360
	Compressive	-0,718	-5,232	-0,296	-0,667	-4,878	-0,276	0,051	0,354	0,020
110	Tensile	16,572	7,349	0,100	16,341	5,472	0,481	-0,231	-1,877	0,381
	Compressive	-0,752	-5,481	-0,310	-0,713	-5,231	-0,296	0,039	0,250	0,014

higher than z-direction. The reason of this, composite disc is not restricted through z-direction with a boundary condition as seen in Fig. 3. But composite material properties of it cause to produce stresses for z-direction. In engineering construction, composite disc may be affected by pressure through z-direction for example reduces speed or stopping etc. Therefore higher values of stresses can be produced in applications. In other words stresses should not be ignored for z-direction.

Table 2 is also indicate that thermal residual stresses did not occur for 70 and 75 °C uniform thermal loading, they are obtained for higher and equal than 80 oC. After this temperature loading thermal residual stresses are increased by increasing temperature. In other words plastic behaviour in composite disc is started with 80 oC loading. Residual stresses for

tangential direction are higher than both radial and z-directions. It is very interesting that magnitudes of residual stresses for z-direction are close to radial direction results. As mentioned previously thermal residual stresses are very important for z-direction, since they cause to produce important residual stresses. The highest value of it is -1,877 MPa for tangential direction.

Table 2 is created by using maximum and minimum values of thermal stresses on disc, but this table cannot give information about distribution of stresses on disc. Therefore elastic and plastic thermal stress distributions for all directions for 110 °C thermal loading are plotted in Fig. 4 as an example of all analyses. It can be said that maximum and minimum values of stresses are shown in the same region for other thermal loadings. According to Fig. 4 distribu-

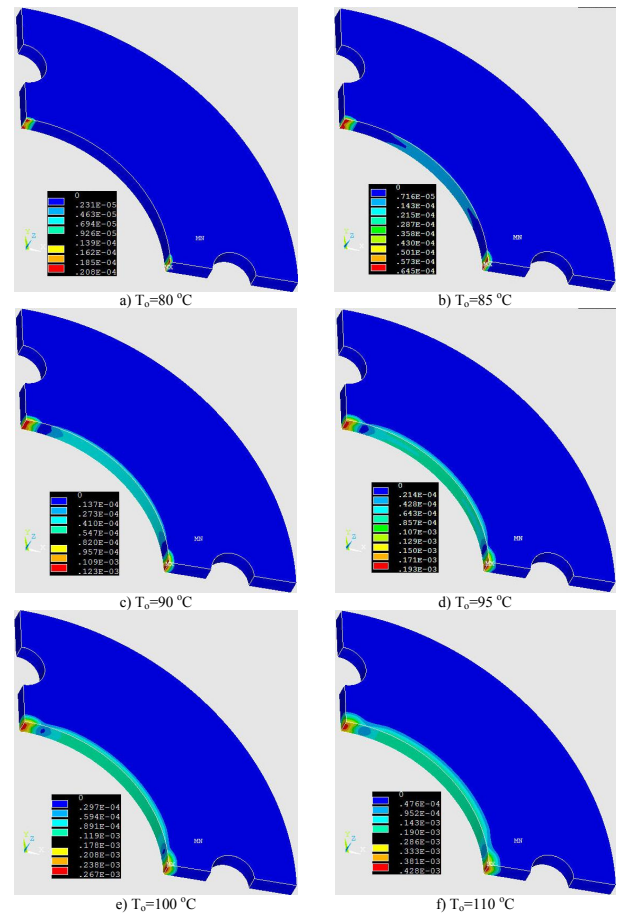


**Fig. 4:** The distributions of elastic and plastic stresses on disc at 110 °C (MPa)

tions of elastic and plastic stresses are different from each other. Additionally, their values are dissimilar. Thermal residual stresses are also calculated using dissimilarity results between elastic and plastic results.

Fig. 4 points out that stresses are higher than both tangential and z-direction. Additionally stresses for z-direction are seen in negligible level to compare stresses of radial and tangential directions. Higher stresses for tangential direction are shown in inner surface of the disc, whereas the highest stresses are determined on surroundings multi holes for radial direction. Therefore failure, fatigue etc. of composite disc may be started on multi hole regions. It can be said multi holes cause uppermost stresses on composite disc, but holes must be created in many real applications for pins, bolts, rivets etc. Thus, the use of holes is a necessity for the most of engineering applications.

The distributions of equivalent plastic strains for different six thermal loadings are illustrated in Fig. 5. Plastic strain starts on corners of inner surface of



**Fig. 5:** The distributions of equivalent plastic strains for different thermal loadings

composite disc, firstly. The distribution of plastic strain is expanded through whole of inner surface. It is clearly seen from Fig. 5 that magnitudes of equivalent plastic strains increases by increasing uniform temperature loading. Consequently, the highest plastic strain is determined at 110 °C. Furthermore, distribution on disc reaches at its maximum expand zone from inner surface at this temperature.

According to Fig. 4, stresses are concentrated around holes and inner surface of disc. Furthermore Fig. 5 points out that plastic strains starts and expands to the inner surface of the disc. In other words, some zones which are around holes and inner surface of disc are critical. Therefore some nodes are selected from these areas as seen in Fig. 3. They are labelled as Nodes A, B, C, D, E, F and G. They are also selected on midpoint of disc according to z-direction. Figs. 6, 7 and 8 are plotted using data derived from these nodes. Firstly, changing of elastic and plastic stresses related applied temperatures on selected nodes are plotted in Figs. 6 and 7, respectively. Then residual stresses calculated using elastic and plastic results are drawn in Fig. 8. All of this figures point

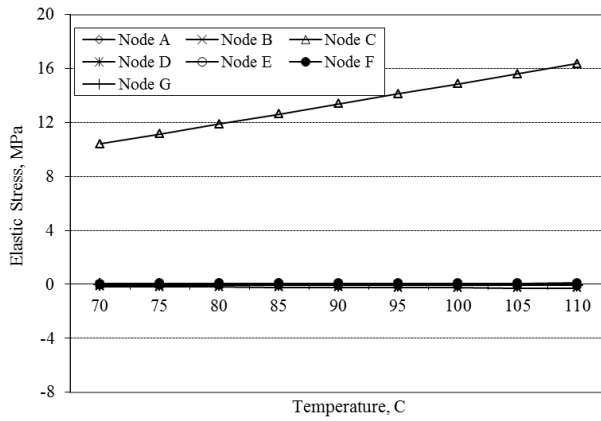
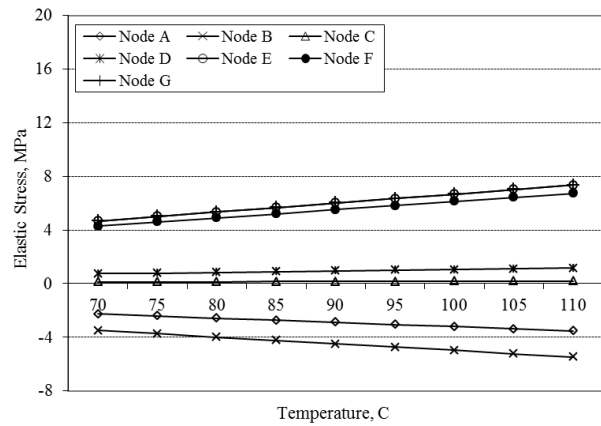
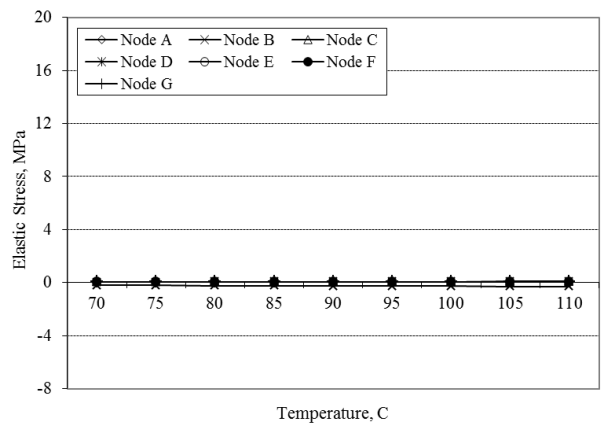

 a)  $(\sigma_r)_e$ , radial direction

 b)  $(\sigma_\theta)_e$ , tangential direction

 c)  $(\sigma_z)_e$ , z-direction

Fig. 6: Changing of elastic stresses related applied temperatures on selected nodes

out that thermal and residual stresses are increasing by increased uniform temperatures for all nodes and directions.

For radial direction, both thermal elastic and plastic stresses reaches higher values at Node C compare with other nodes as seen Figs. 6-a and 7-a. It is important that Node C is selected around hole. For tangential direction, higher values of tensile thermal stresses are calculated for Nodes E, F and G which are selected inner surface of disc. Nevertheless, the

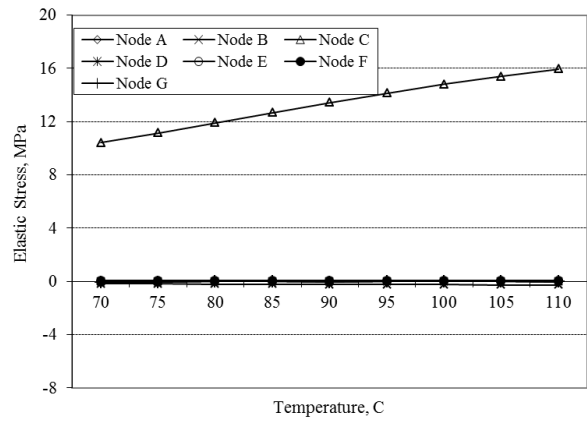
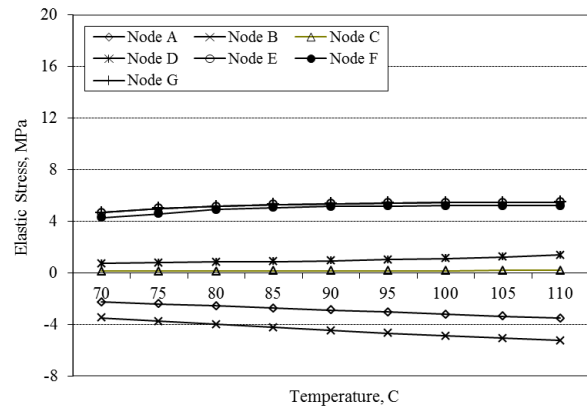
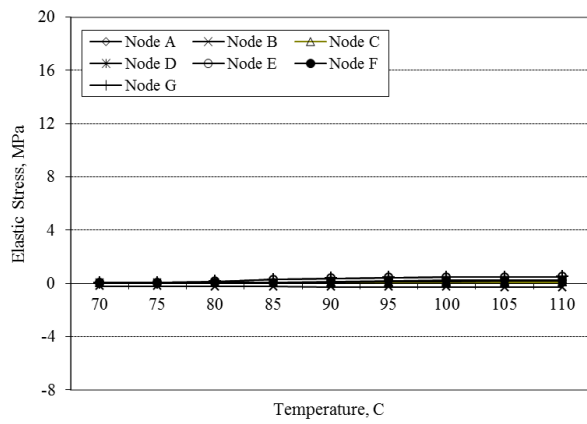
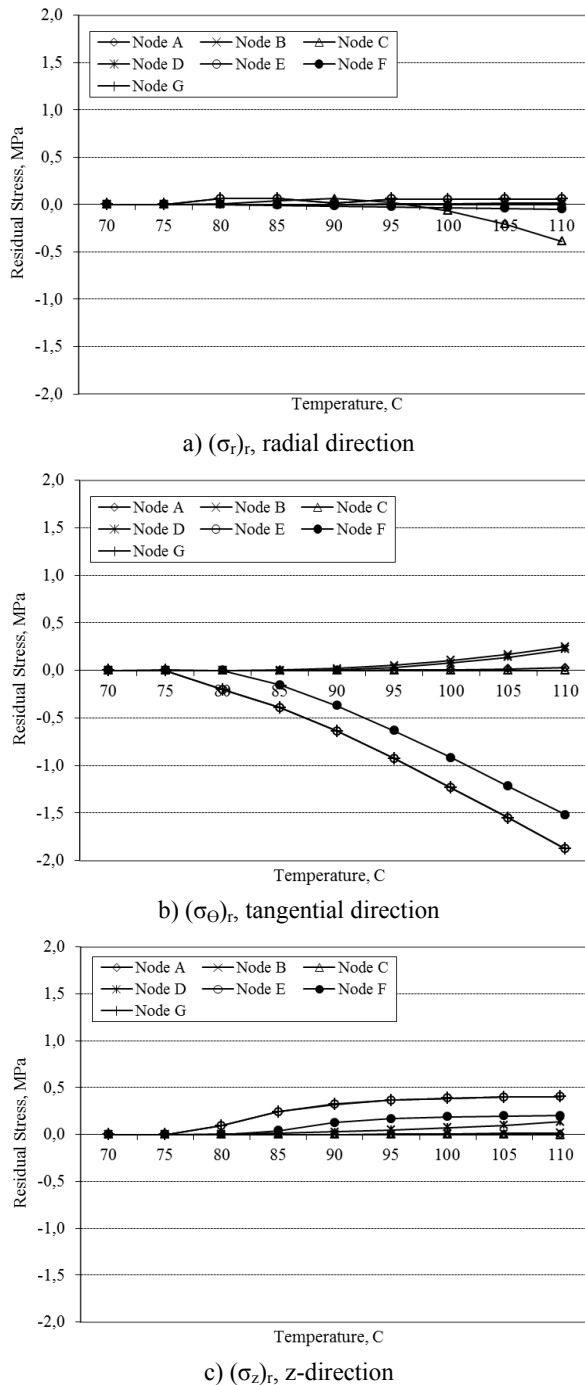

 a)  $(\sigma_r)_p$ , radial direction

 b)  $(\sigma_\theta)_p$ , tangential direction

 c)  $(\sigma_z)_p$ , z-direction

Fig. 7: Changing of plastic stresses related applied temperatures on selected nodes

highest values of tensile compressive stresses are computed for Node B selected on symmetry surface. But absolute values of compressive stresses are lower than tensile stresses. For z-direction, thermal stresses are calculated lower than both radial and tangential directions for all nodes.

According to Fig. 8, thermal residual stresses are firstly calculated at 80 °C uniform temperature loading. On the other hand any thermal residual stresses are not calculated both 70 and 75 °C uniform tem-



**Fig. 8:** Changing of residual stresses related applied temperatures on selected nodes

perature loading for all selected nodes. Thermal residual stresses for tangential directions are higher than other directions. Furthermore higher values of residual stresses are calculated for Nodes E, F and G with compressive form. It can be said that the higher values of thermal residual stresses are computed on inner surface of disc and compressive form. As mentioned previously, thermal stresses for z-direction are lower than other directions. Nonetheless thermal residual stresses for z-direction are higher than radial direction for many nodes. It is understood that

any restriction is applied through z-direction in real applications, highest thermal residual stresses can occur on disc. Briefly, many previous studies were performed as two dimensional, but this result indicates z-direction is also important in order to reach accurate results and it shouldn't be neglected. Thus, this study is reached to scope. It may be asked why three dimensional FEM analyses were performed.

#### 4. CONCLUSIONS

According to present thermal and thermal residual stress analysis results of the unidirectional steel fibre-reinforced thermoplastic composite disc with multiple holes via 3D-FEM, the important remarks can be concluded:

1. Owing to 3D-FEM thermal stresses and thermal residual stresses are calculated for radial, tangential and z-directions on three dimensional disc model.
2. Related to boundary conditions thermal stresses for z-direction are negligible level to compare with radial and tangential directions. But residual stress results point out that residual stresses are also important for z-direction.
3. It is understood that, if the disc is restricted through z-direction like real problems, stresses may be higher than present condition. Since thermal stresses for z-direction are only created because of composite anisotropy.
4. In general, high thermal stresses occur in 3D-composite disc under uniform temperature loadings due to different thermal expansion coefficients in principal material directions,
2. Plastic behaviour starts inner surface of disc at 80 oC, initially.
3. Plastic yielding expands when uniform temperature load is upper than ever.
4. The absolute value of radial stress components are higher than tangential stress components.
5. The maximum values of thermal stresses are computed edges of holes for radial direction.
6. Thermal residual stresses are also calculated on 3D-composite disc due to the uniform temperature loadings.
7. Obtained results indicate that residual stresses for z-direction can't be neglected.

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