Chapter 4 Stress Analysis of Adhesive Bonded Joints

4.1 Introduction

The use of adhesively bonded joint technology has been growing in many structural components to improve the joint performance due to inherent advantages. Adhesively bonding techniques has been widely used due to its ability to distribute a load over a larger area. When the adhesive joints undergo thermal load as well as structural load, stress and deformation fields play an important role in the strength of the adhesive joints. Adhesive bonding technology has also found a good place in joining advanced composite materials. One method of joining composites is through tee-joints. These joints are typical type of connections and are commonly used in many structural applications such as in skin stiffened panel of aerospace structures, ship hulls of marine machineries, etc.

From the discussion in literature review, the obvious fact is that residual thermal stress analysis of adhesively bonded tee joints made of FRP composite materials is not explored till date. In the present chapter focuses on analysis of functionally graded adhesively bonded double supported tee joint made of FRP composite plate under thermo-mechanical loading. Three dimensional FE simulations have been performed to evaluate the stresses and thermal flux with the consideration of three different laminate configurations. The effects of material anisotropy and laminate stacking sequence under coupled field on stress and flux components have been studied. The influence of interaction of thermal and elastic field on the stress behavior of plate has been demonstrated by plotting various graphs of stresses, flux and gradients along the bond length between base plate and support plate with different laminate stacking sequence.

4.2 Finite element modeling

The adhesively bonded tee joint is shown in Figure 4.1, consists of a vertical plate, a base plate and two double supports, in which the vertical plate is bonded to the base plate with the help of two corner supports. Dimensions of the considered tee joint are given in Table 4.1. The vertical plate, support plates and base plate consist of $[0]_8$, $[0/45]_4$ and $[0/90]_4$, graphite/epoxy (Gr/E) FRP composite laminates. The thickness of each ply is taken as 0.25mm. The layer wise orthotropic properties of FRP composite laminate is shown in Table 4.2. The adhesive is used to bond vertical plate with two support plates and base plate. The material properties of adhesive are also given in Table 4.2.

First set of finite element analysis is performed for a purely mechanical loading in the form of applied pressure of 100N/mm at the top edge of vertical plate. For studying the thermoelastic stress behavior, in the second set, the mechanical loading is applied subsequent to the uniform temperature drop from 500^{o} C to the 100^{o}C applied at support plate edge attached to vertical plate on both sides to induce thermal residual stresses in the laminate. In the third set of thermal loading, only temperature drop of 400^{o}C is applied.

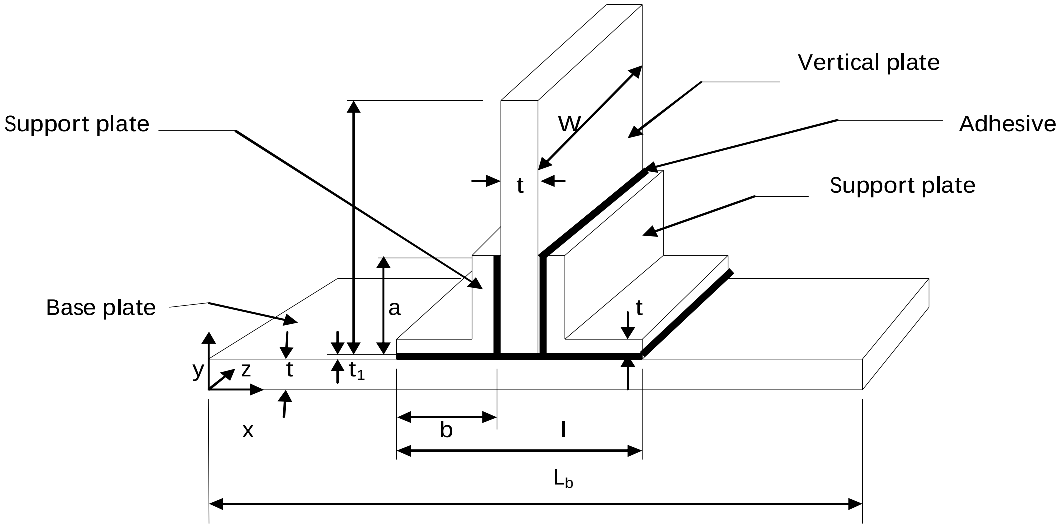

Figure 4.1 Configuration of double supported tee joint

Table 4.1 Dimensions of tee joint model

Parameters	Dimensions (mm)
Vertical support length, a	15
Horizontal support length, b	15
Bond length, l	33
Plate thickness, t	2
Adhesive thickness, t_1	0.5
Vertical plate length, L	40
Base plate length, L_h	100
Joint width, W	10

Table 4.2 Thermoelastic material properties [127]

	Graphite/Epoxy	**Epoxy Adhesive**
Elastic Properties		
E_x (GPa)	127.50	E = 2.8 (GPa)
E_y (GPa)	9.00	
E_z (GPa)	4.80	

$G_{xy} = G_{xz}$ (GPa)	4.80	G = 1.42 (GPa)
G_{yz} (GPa)	2.55	
$\nu_{xy} = \nu_{xz}$	0.28	ν = 0.40
ν_{yz}	0.41	

Thermal Properties		
α_x ($/^oC$)	4.3 X 10^{-6}	α = 62 X 10^{-6} ($/^oC$)
α_y ($/^oC$)	1.2 X 10^{-6}	
α_z ($/^oC$)	0.9 X 10^{-6}	
Temperature state:		
$\Delta T = 400\ ^oC$		

Boundary Conditions:

The displacement boundary conditions imposed are

For all nodes along z axis,

at $y = 0, x = 0, u = v = w = 0$

and at $y = 0, x = L_b, u = v = w = 0$

where, u, v and w are the displacements along the X, Y and Z directions respectively.

4.3 Finite element meshing of the analysis domain

The analysis is done throughout the composite laminate using finite element analysis software ANSYS 14.5. Eight-noded layered solid thermal element (solid 278) with coupled field properties has been used to model the analysis domain. Referring to Table 4.2, orthotropic thermo-elastic material properties, typical of a graphite/epoxy fiber-reinforced composite laminate have been input for each layer. Adhesive properties are that of an isotropic resin material. Figure 4.2 shows the three-dimensional meshing pattern of tee joint. Very fine and sweep volume mesh has been done to obtain the accurate results. Relevant error analyses and mesh refinements have been carried out for convergence.

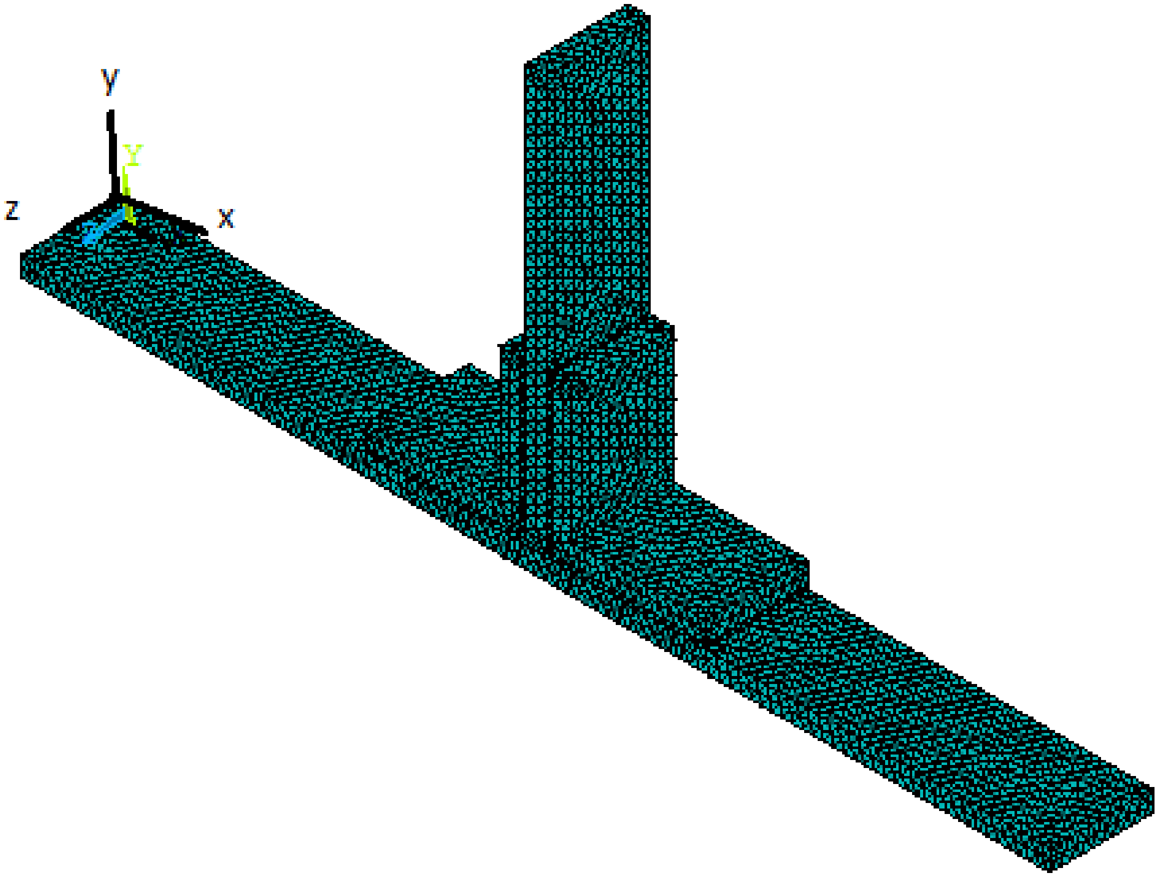

Figure 4.2 Finite element model for double supported tee joint

4.4 Results and discussion

In the preceding analysis, depending upon the loading conditions on double supported tee joint, three types of laminates are considered. Full 3D thermo-elastic finite element analyses have been conducted to account the stresses due to the thermo-mechanical loading on each laminate specimen. Stresses are calculated along the bond length for mechanical and thermo-mechanical loadings for all three laminates. Similarly, thermal flux and thermal gradients are estimated in case of thermo-mechanical and thermal loading. Also, the variation of degree of freedom in both the cases is evaluated and then compared. Distribution of stresses, flux and gradients along the bond length for various locations of double supported tee joint are discussed below.

Laminate A: [0]$_8$

The stress distribution on the mid surface of adhesive layer of tee joint with Gr/E FRP material and fiber orientation angle $[0]_8$ are shown in Figure 4.3. The comparison of von-Mises stress between mechanical and thermo-mechanical along bond length is shown in figure. The value of stress is more for thermo-mechanical than that of mechanical. Figs. 4.4 and 4.5 show the thermal gradient and thermal flux acting on tee joint with thermal and thermo-mechanical loading, respectively. The rate of variation of gradient with bond length is approximately same in both thermal and thermo-mechanical loading. It is seen that as the value of bond length increases, the gradient value also increases linearly. In vector sum of thermal flux, values of flux are almost similar for thermal and thermo-mechanical.

The various values of Degree of Freedom (DOF) along bond length are shown through graphs (Figure 4.6). This graph is drawn for all three types of loading and then their values are compared. It is found that there is vast difference in the values of DOF for mechanical and thermo-mechanical but for thermal and thermo-mechanical, it is almost same.

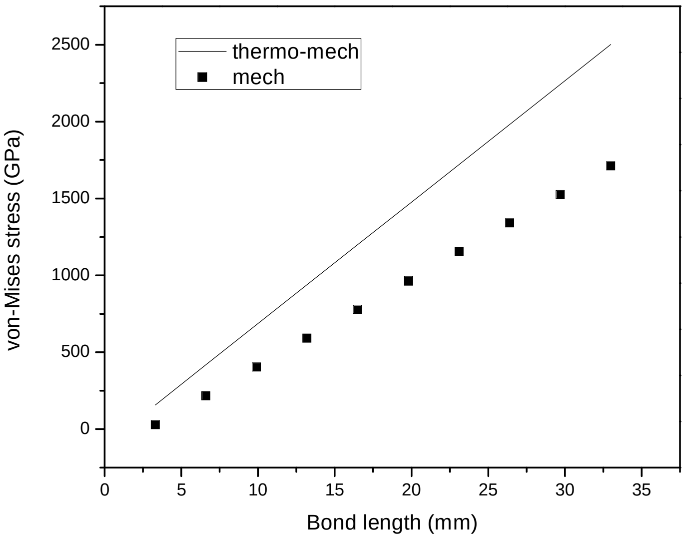

Figure 4.3 Variation of von-Mises stress at different bond length of laminate A $[0]_8$

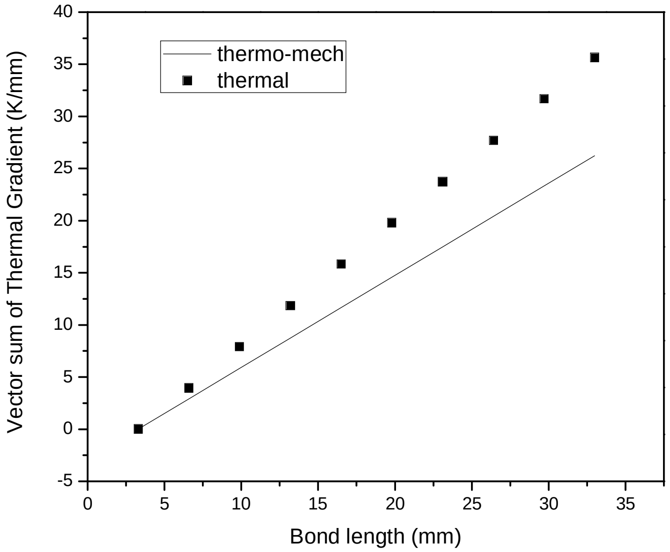

Figure 4.4 Variation of thermal gradient at different bond length of laminate A $[0]_8$

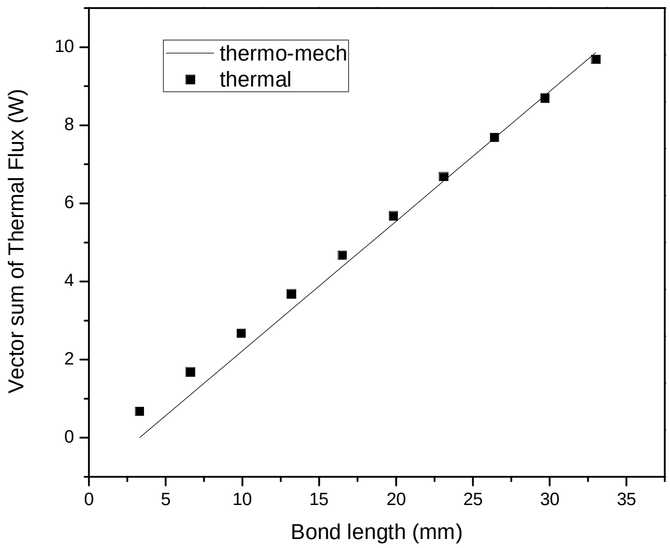

Figure 4.5 Variation of thermal flux at different bond length of laminate A $[0]_8$

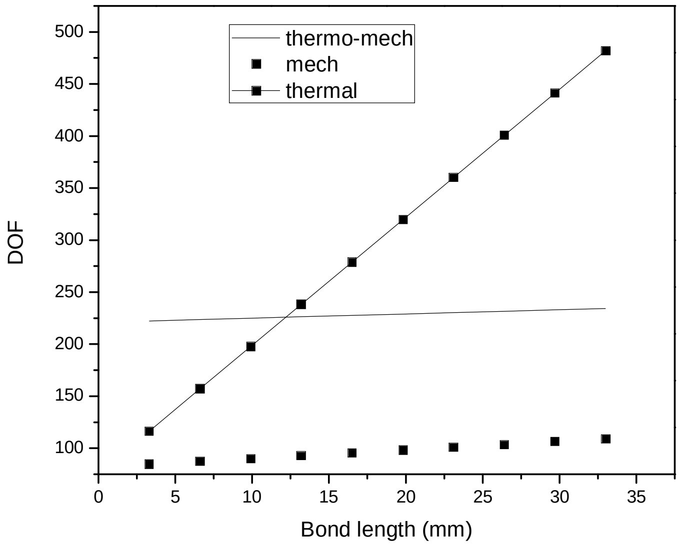

Figure 4.6 Variation of DOF at different bond length of laminate A $[0]_8$

Laminate B: $[0/45]_4$

The stresses, gradient and flux along the bond length are displayed in Figs. 4.7-4.9 considering the mechanical, thermal and thermo-mechanical loading. Figure 4.7 represents the variation of von-Mises stress along bond length. It is noted that initially the stress value is same for thermo-mechanical and mechanical but later stress is large for mechanical loading than thermo-mechanical.

Figs. 4.8 and 4.9 show the thermal gradient and thermal flux along bond length for thermal and thermo-mechanical loading for angle ply laminate $[0/45]_4$, respectively. Similar to the above graphs, there is a linear increment in the values of gradients and flux with the increase in bond length. In Figure 4.10, DOF value along bond length is represented. Similar to the symmetric laminate $[0]_8$, here also there is large difference in values of DOF for thermo-mechanical and mechanical and DOF values are almost same for thermal and thermo-mechanical.

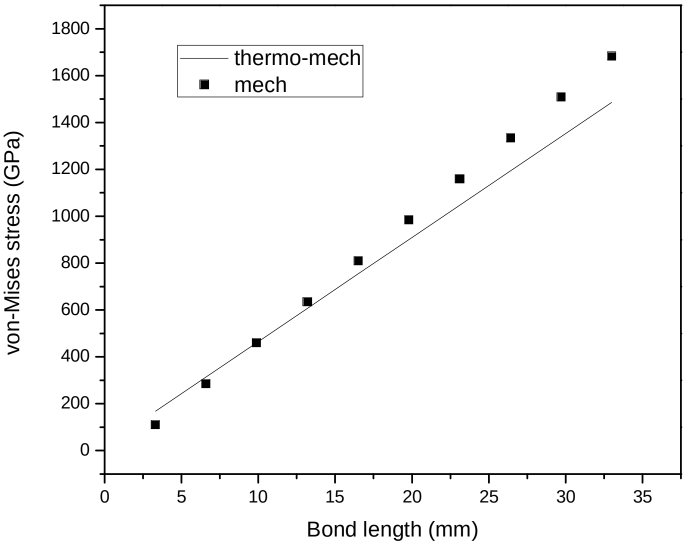

Figure 4.7 Variation of von-Mises stress at different bond length of laminate B $[0/45]_4$

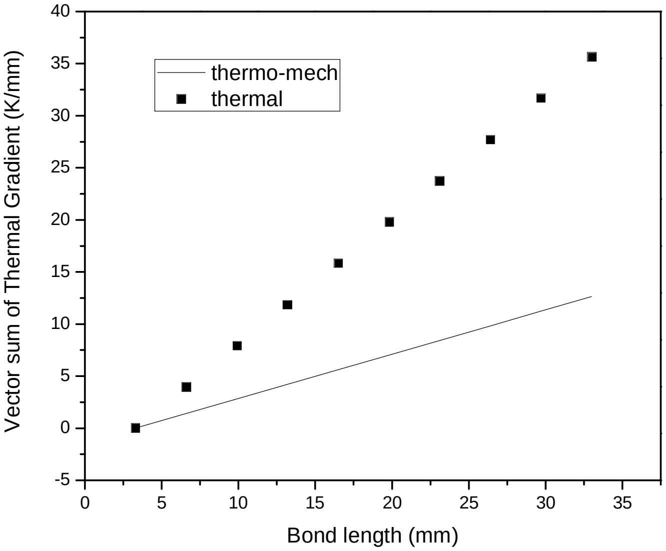

Figure 4.8 Variation of thermal gradient at different bond length of laminate B $[0/45]_4$

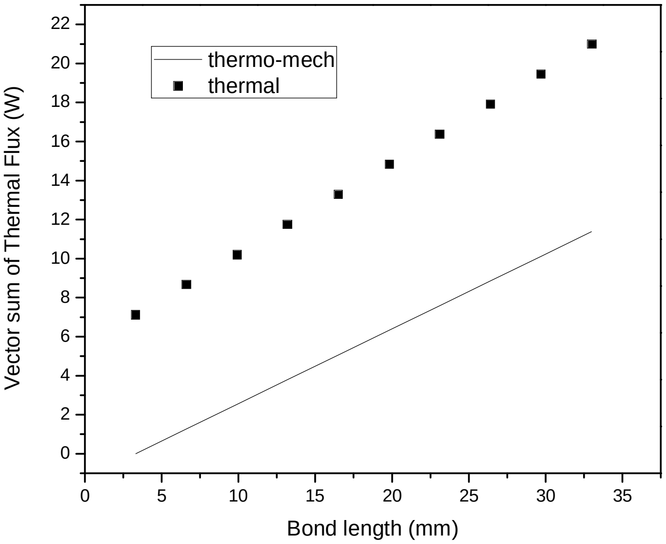

Figure 4.9 Variation of thermal flux at different bond length of laminate B $[0/45]_4$

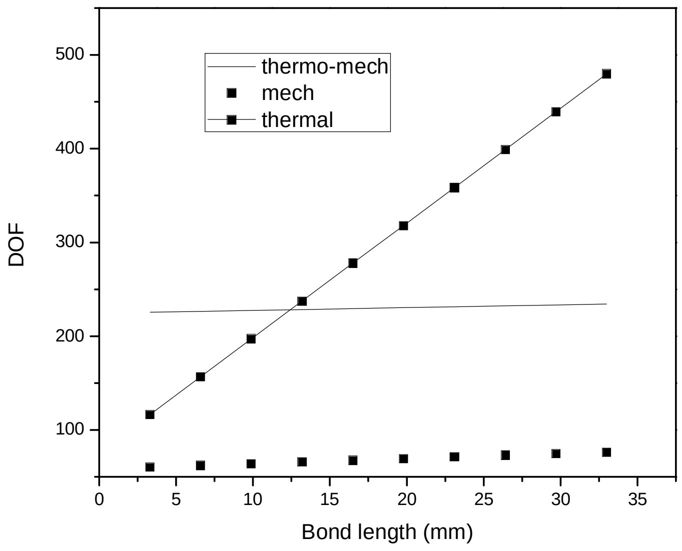

Figure 4.10 Variation of DOF at different bond length of laminate B $[0/45]_4$

Laminate C: $[0/90]_4$

The stress analysis has been done on double supported tee joint with cross ply laminate $[0/90]_4$, shown in Figure 4.11. It shows that the stress values along bond length are nearly same for both thermo-mechanical and mechanical loading. It is noted that initially, stress is little bit lower for mechanical loading but latter on stress become almost equal for both loading conditions.

Figure 4.12 exhibits the thermal gradient along bond length under thermal and thermo-mechanical loading. It is observed that the gradient value increases with increase in bond length. Also, gradient value is higher for thermal loading in comparison of thermo-mechanical loading. In case of thermal flux (Figure 4.13), its value is more for thermal loading similar to case of thermal gradient. For considering the variation of DOF in laminate $[0/90]_4$, Figure 4.14 shows the graph between DOF and bond length for various types of loading. Similar to the above laminates, values of DOF is almost constant for mechanical and thermo-mechanical loading and there is increasing trend in thermal loading condition along bond length.

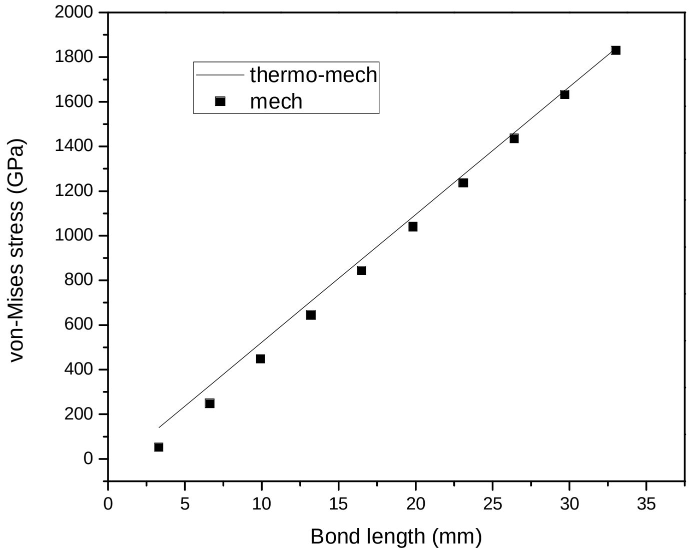

Figure 4.11 Variation of von-Mises stress at different bond length of laminate C $[0/90]_4$

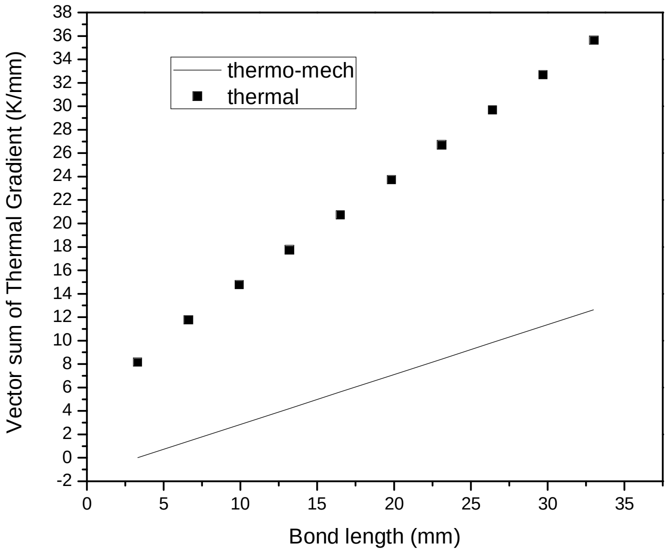

Figure 4.12 Variation of thermal gradient at different bond length of laminate C $[0/90]_4$

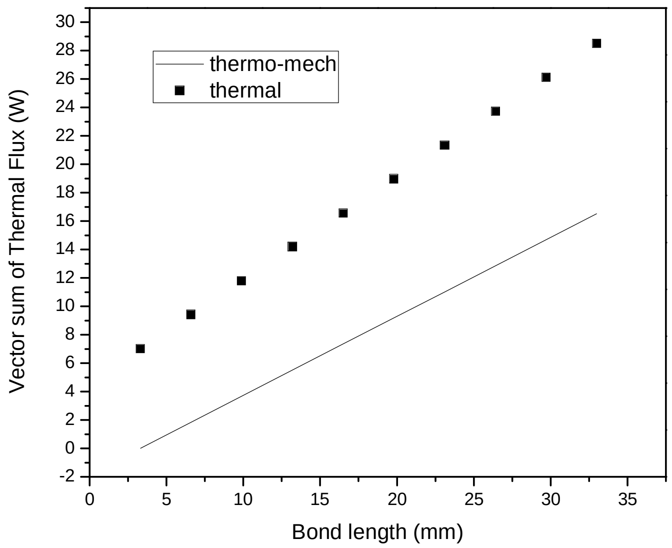

Figure 4.13 Variation of thermal flux at different bond length of laminate C $[0/90]_4$

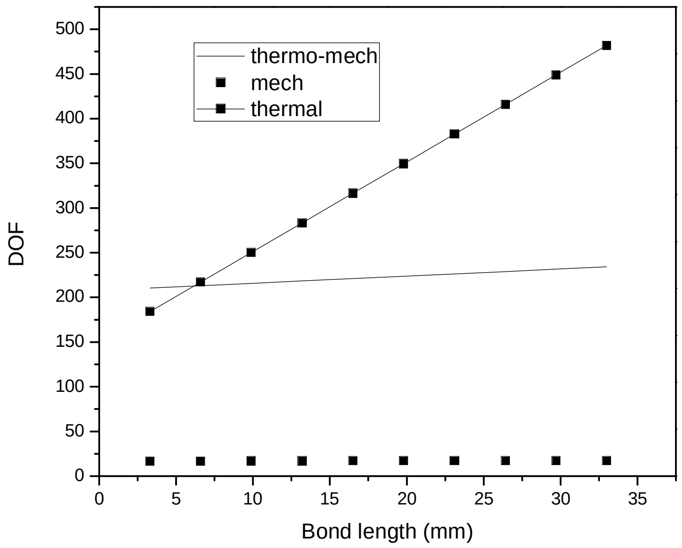

Figure 4.14 Variation of DOF at different bond length of laminate C $[0/90]_4$

From the analysis of above three configurations, i.e., Laminate A, Laminate B and Laminate C, it is noted from plots that stresses, flux and gradients are increases with increase in bond length. In some cases, variation of stress under thermo-mechanical loading dominates over mechanical loading while in other cases; mechanical loading has higher value of stress. Thermal flux and gradients also follow the same trend as stress.

4.5 Conclusion

3D FEA has been conducted for three different laminates for the stress, gradient and flux evaluation of double supported tee joint. Based on the analysis of structurally loaded adhesively bonded functionally graded double supported tee joint subjected to uniform temperature drop, it can be concluded that a multi-lay-up laminate, the varying orientation and stacking sequences along with the heterogeneity of thermo-physical properties affect the stress produced on plate. It is noted that as the asymmetry in angle ply orientation decreases the von-Mises stress on tee joint. The graph between DOF and bond length shows the same trend for different stacking sequence under different loading conditions. In all orientations, there is vast difference in values of DOF under mechanical and thermal loading while for thermal and thermo-mechanical load, its value is approximately same.

This work signifies the relative influence of residual thermal stresses and lamina orientation on the stress behavior in FRP laminates and therefore should be taken into account. Further, effect of bimodularity on strain energy release rate should be analyzed for better understanding and it is incorporated in next chapter.