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Effects of adhesive thicknesses on the stress distribution in prismatic plug-in joints

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The aim of this study is to research the effects of adhesive thickness, which is one of the factors that affect the stress distribution in the prismatic plug-in joints. The effect of adhesive thickness was theoretically researched in the study. Epoxy-based and acrylic-based adhesives, which are widely used in combining metal joints, were applied. After testing the mechanical characteristics of the adhesives, the models of the prismatic plug-in joints combined with adhesive were designed in the Pro-engineer program. The mechanical analysis of the models was performed in Ansys Workbench and the results are presented as a comparison.

Key words: Adhesive, mechanic properties, bulk specimens, acrylic, epoxy.

INTRODUCTION

Adhesives are generally mixtures composed by chemically mixing materials such as epoxy, phenol, polyamide, polyimide and silicone, which produce the desired design features when at least two different materials are combined by bonding (Morrisey and Johnson, 1985).

Before being compounded, the adhesives may be in various forms such as film, putty, liquid and powder. The adhesives cured by chemical reaction are called structural adhesives. The structural adhesives are load-bearing, flexible, heat-resistant adhesives with high shear strength. The structural adhesives are frequently used in many industries such as aerospace, automotive, shipbuilding and so on. The chemical adhesives cured by chemical reaction and in use today are anaerobics, cyanoacrylates, acrylics, silicones, polyurethanes, epoxies and phenolics (Ciba-Geigy, 1993).

Adhesives that are most widely-used for metal bonding are epoxies. Epoxy adhesives are composed of resin and hardener, and these adhesives provide extremely strong bonding. They are available in three different forms: single component, double component and film. Their deep hardening rate is very good and they can be used for bonding various materials (Solmaz, 2008).

Acrylic adhesives are cured with an activator in an anaerobic environment. Because the adhesive is cured only when it comes in contact with the activator, it is not required to keep open waiting period short or use the mixed materials immediately. The width of the bonding surface must be at least 5 mm in order to break off when in contact with oxygen. Depending on the adhesive type, the adhesive and activator can be applied on the bonding surfaces separately and used for bonding various materials (Loctite, 1998).

When determining the mechanical properties of an adhesive, samples are used in either bulk or joint forms.

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Although, using samples in joint form represents the original loading type in the application area, the adhesion level of the adhesive is tested rather than any mechanical properties. These kinds of disadvantages may be eliminated by using bulk samples (Aydin et al., 2004).

Factors such as overlap distance, adhesive thickness, surface roughness etc. have an effect on the strength of the joints when combined with adhesives. Goland and Reissner (1944) called the shear stress that is parallel to the adhesive layer and normal stress that is vertical to the plane of shear stress as tearing stresses. This study set a reference for many researches relating to adhesive-adherend overlap joints.

The effect of adhesive thickness was firstly examined by Bascom at al. (1977); later, many researchers examined fracture mechanics and traditional stress analysis.

Mall and Ramamurth (1989) double cantilever beam specimens fracture and crack progression by applying cyclic loads of different thicknesses examined and thick adhesive layers for the crack growth rate is expressed at high level.

Turgut and Sancaktar (1991) examined the effects of curing and loading conditions relating to fiber-matrix adhesion on composite materials.

Tamblin et al. (2001) presented the shear results between the adhesive thicknesses of 0.4 to 3 mm via thick adherend shear test (TAST). They explicitly stated that shear strength decreases as the thickness of the adherend pieces increases.

Jarry and Shenoi (2006) 0.1 to 10 mm butt strap adhesive bonding studies used a methacrylate adhesive and increase in the thickness of the adhesive with the significantly reduced load failure.

Grant et al. (2009) accepted that shear strength decreases linearly when the adhesive thickness is increased from 0.1 to 0.3 mm and the reason for this is the flexural stress occurring on the thick adhesive layer.

Davies et al. (2009) carried out research relating to the effect of adhesive thickness and he examined the properties of aluminum joints by using epoxy adhesives via various test techniques. As a result of mechanical analysis, they found that the tensile strength decreases as the adhesive thickness increases as seen in the previous researches and the ideal thickness should be 0.8 mm and below.

Nemeş and Lachaud (2010) researched the effect of the thickness of the adhesive double-lap connection. Adhesive thickness increases, the maximum stress is low, with the exception of shear and peel stresses endpoints expressed uniformly distributed on all the overlap distance.

Fracture mechanics analysis by Daghiyani et al. (1995), Abou-Hamda et al. (1998), and Kawashita et al. (2008) increased the strength of the connections with the increase of the thickness of the adhesive, while, Bascom et al. (1975), and Schmueserand Johnson (1990) stated that the thickness of the adhesive is not important and Chai (1988), Kahramana et al. (2008), and Da Silva et al. (2009) expressed strength reduced (Azari et al., 2011).

Adin (2012) examined the mechanical behavior of the scarf lap joints bonded with adhesive under a tensile loads.

Kimiyoshi et al. (2012) examined the effect of adhesive thickness on tensile and shear strength of a polyimide adhesive. The tensile strength of the butt joints decreased with increasing adhesive thickness. In contrast, adhesive thickness did not seem to affect the shear strength of single lap joints.

In this study, the effects of adhesive thickness and different adhesive types to the stress distribution on prismatic plug-in joints were tried and determined theoretically.

MATERIALS AND METHODS

In this study, the mechanical analysis of prismatic plug-in metal joints combined by using epoxy and acrylic based adhesives were examined. In the study, two adhesives with different properties (1 unit of epoxy-based (Akfix-E300) and 1 unit of acrylic-based (Erde GTR) adhesive were used. Both adhesives include two components and their mixing ratio is 1:1.

Primarily, bulk samples were produced from adhesives in sizes suitable for ISO 527-2 (1993) standards, then tension testing procedures defined on ASTM D1002 (1983) were applied on these samples. The mechanical properties of adhesives and combined pieces obtained as a result of these tests are given in Table 1 and their stress-strain graphics are given in Figure 1.

As shown in Figure 1, Erde GTR displays a nonlinear material behaviour. Thus, elasto-plastic analysis will be made for this adhesive in ANSYS (Academic Teaching Advanced, Version 12.0) software. The stress-strain data required for elasto-plastic analysis was selected from Figure 1b and these values are given in Table 2.

In the study, 3 different overlap distances, 3 different sample widths and 3 different adhesive thicknesses were used. The analysis parameters used are summarized in Table 3.

Models in the sizes given in Figure 2 (Aydin et al., 2012) were prepared in accordance with these parameters. Elastic and elasto-plastic stress analyses of the models were made by using ANSYS Workbench 12.0, the finite element program. 3-Dimensional solid models of prismatic plug-in joints were prepared in the Pro-Engineering program and these models were transferred to ANSYS Workbench for finite element analysis. The solid models of prismatic joints prepared in 3 different overlap distances are shown in Figure 3.

The mesh structure, boundary conditions and loading condition of the models prepared by ANSYS are given in Figure 4. In the analysis carried out, different elements were used for metal and adhesive materials: Solid 187 for metal materials, Surf154 for adhesive materials, Conta174 and Targe 170 for the contact surfaces of metal and adhesive materials. A more sensitive mesh process was carried out by comparing the area where the binding process that is critical for stress distributions was carried out (Figure 5).

The von-Mises flow criteria given in Equation 1 were used for calculating the equivalent stress values occurring on the adhesive layer and the materials adherend.

$$\sigma_{eqv} = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x.\sigma_y + 3\tau_{xy}^2} \quad (1)$$

Table 1. Mechanical properties of adhesives and combined pieces.

Material	Testing method			
	ISO 527	ISO 527	ISO 527	ISO 178
	Yield strength (MPa)	Tensile strength (MPa)	Poisson ratio	Elasticity module (Mpa)
Akfix E300	-	34.1	0.32	758
Erde GTR	2.01	7.9	0.36	93
St 60	-	600	0.35	210000

Table 2. ERGE GTR stress-strain values.

Node	ε (%)	σ(MPa)
1	0.003	0.732
2	0.007	1.787
3	0.011	2.389
4	0.013	2.942
5	0.017	3.569
6	0.019	3.927
7	0.022	4.459
8	0.025	4.871
9	0.029	5.324
10	0.035	5.891
11	0.041	6.404
12	0.048	6.817
11	0.516	7.010
12	0.059	7.388
13	0.073	7.909
14	0.077	7.759
15	0.082	7.544

Table 3. Parameters used in the study.

Male specimen overlap (plug-in) distance: a (mm)	Female specimen width: b (mm)	Adhesive thickness: t (mm)
10	10.2	0.1
20	10.6	0.3
30	11	0.5

While determining the damage load in the finite elements analysis the tensile strengths given below were taken into consideration and shown as σ^* in the graphics.

σ_{Akfix} = 34.1Mpa σ_{EGTR} = 7.9Mpa

The critical areas on the prismatic plug-in joints combined with an adhesive are the contact surface of the adhesive and interfaces of the material adherend. Thus, the A-C line shown in Figure 6 was taken into consideration for the stress analysis of the adhesive layer. In order to compare the stress distributions occurring on the adhesive layer, the stress distributions obtained from the adhesive layer on the A-C line were normalized by dividing this value with the tensile strength value obtained by tensiling the bulk sample of each adhesive uniaxially (σ_{Akfix}, σ_{EGTR}). In the same way, in order to compare the stress distributions occurring on different overlap distances, the horizontal coordinate value of the point (x), the stress distribution of which was calculated, was normalized by being divided with its own overlap distance (a). As a result of the stress analysis, the stress distribution occurring on the A-C line is given in Figure 7.

The graphics of the stresses occurring were prepared by using

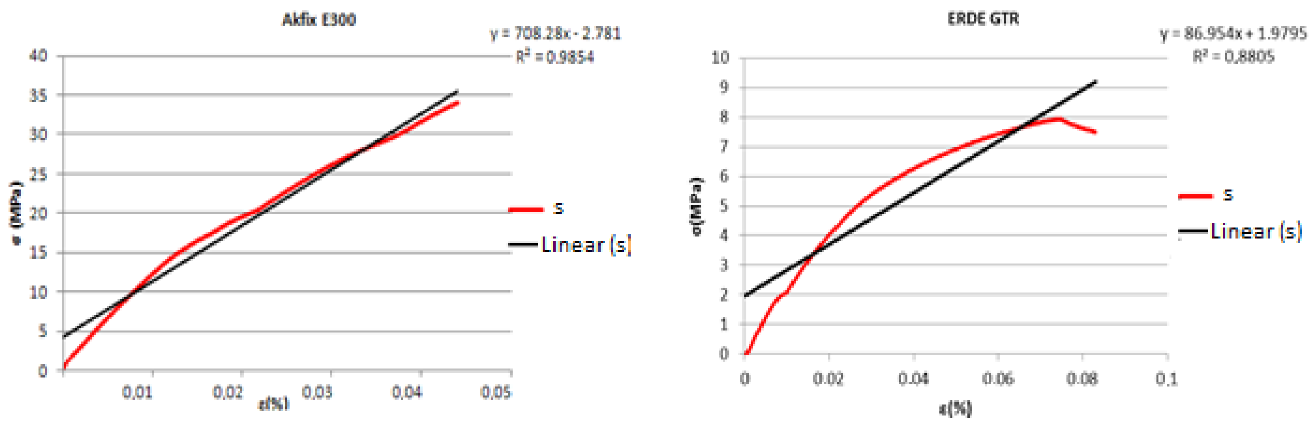


Figure 1. Stress-strain behaviors of adhesives: (a), Akfix E300; (b), Erde GTR.

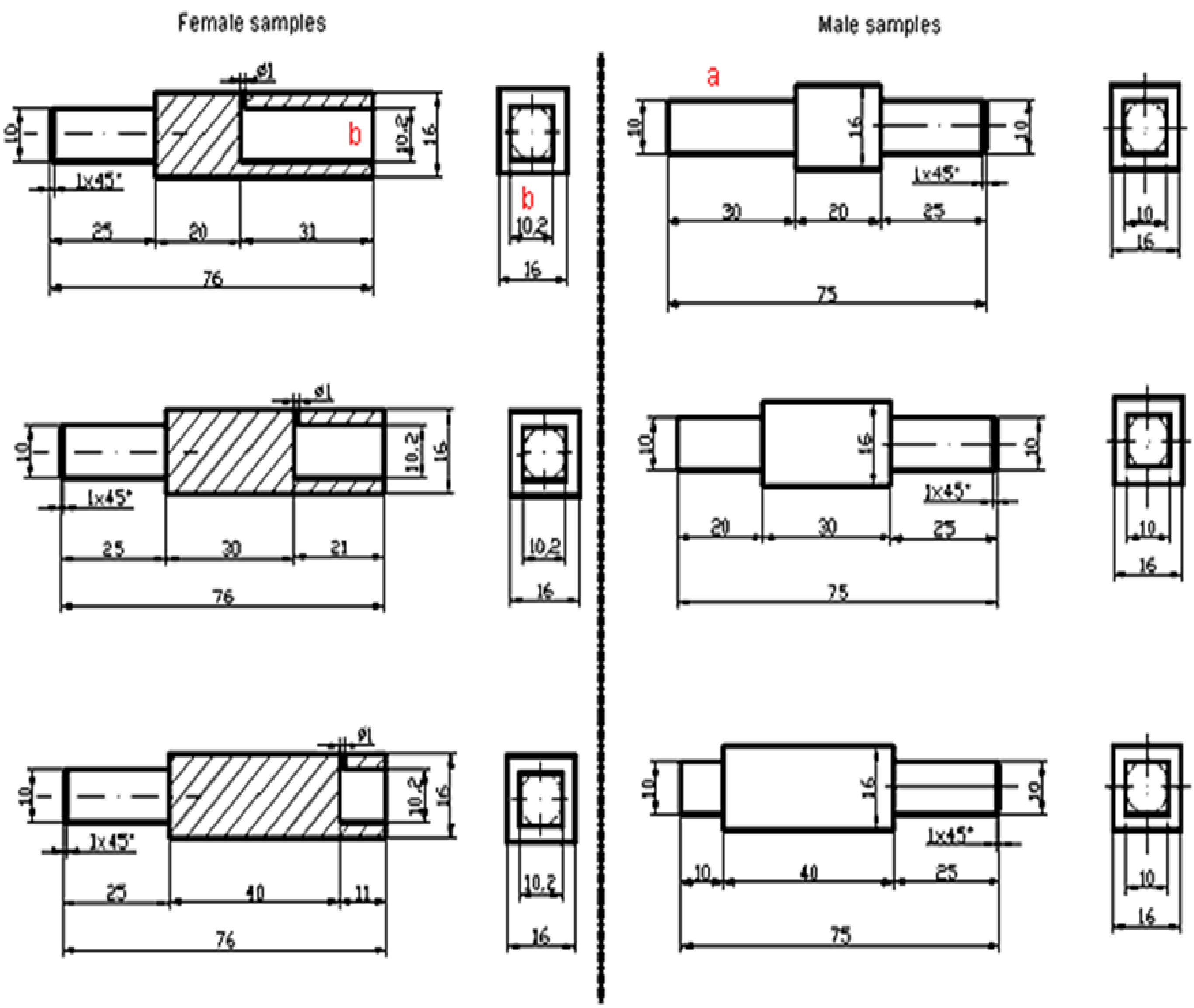


Figure 2. Dimensions of analyses models.

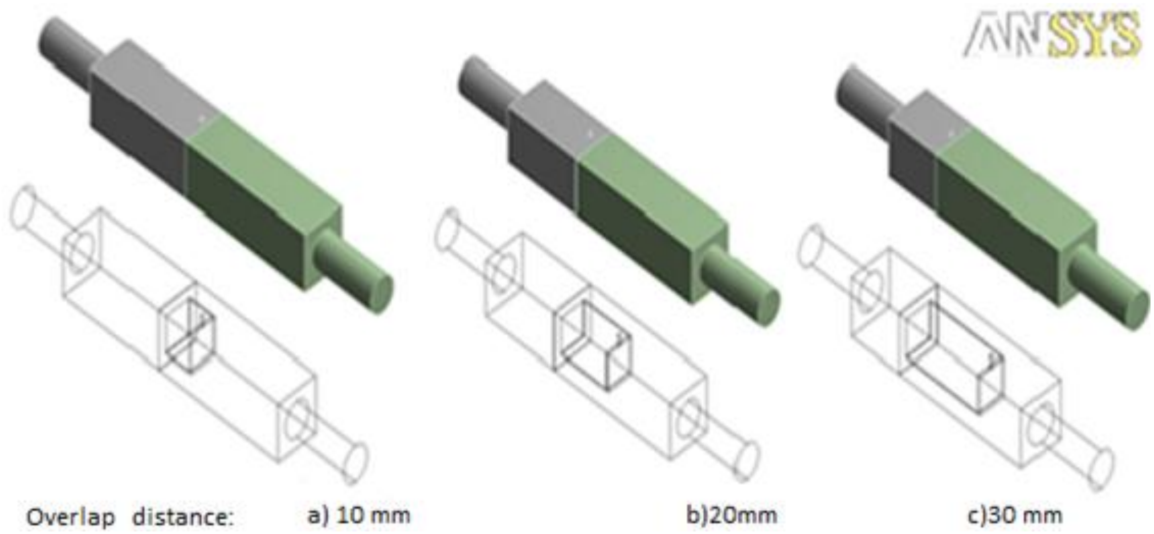


Figure 3. Perspective view of the models.

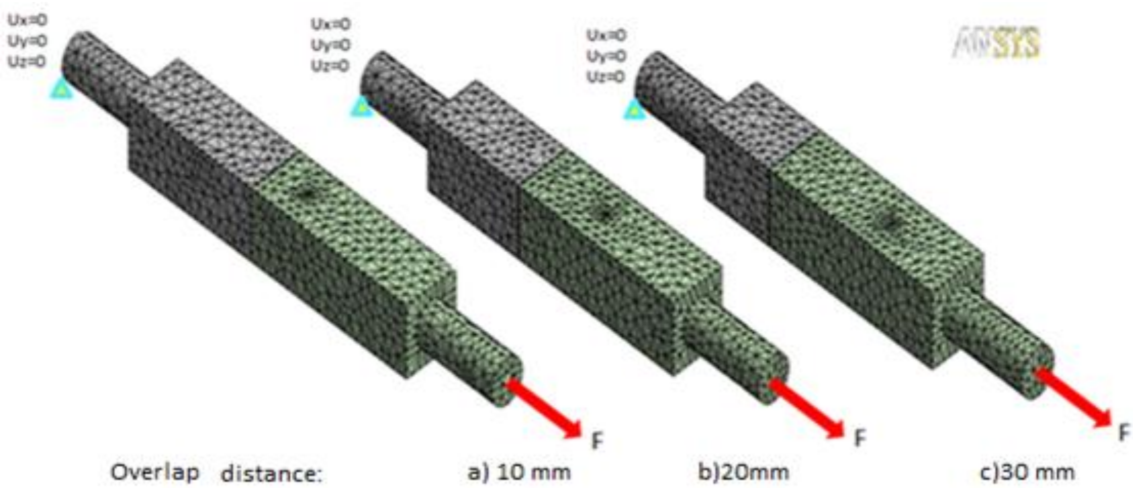


Figure 4. Mesh structure and boundary conditions of the models.

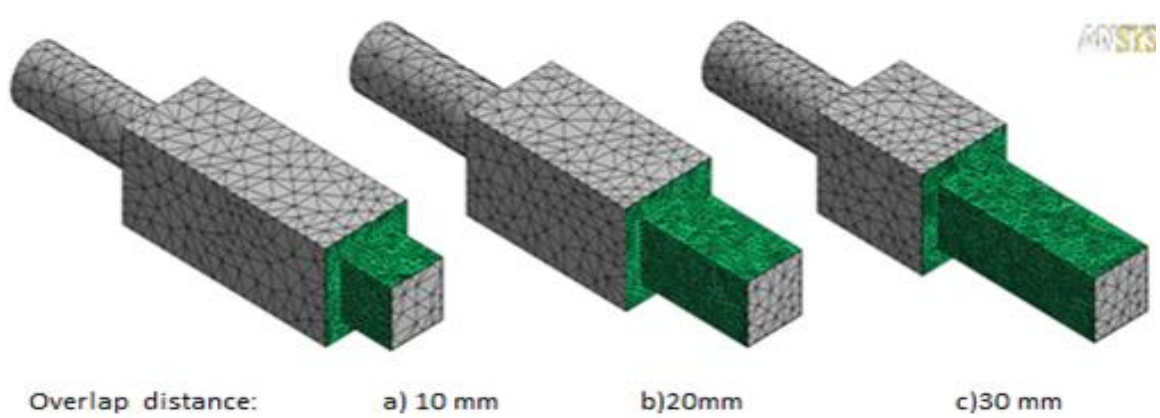


Figure 5. Adhesion areas and meshed male models.

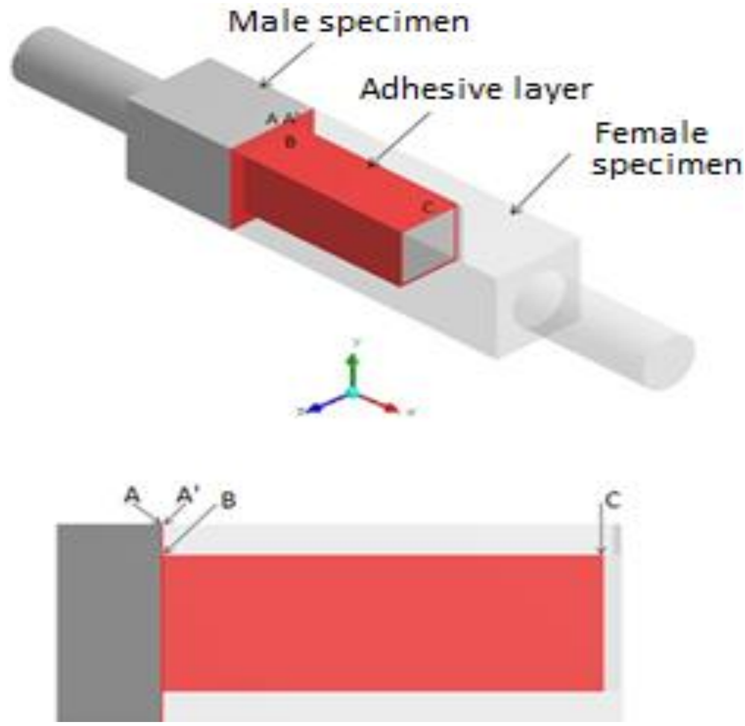


Figure 6. Prismatic plug-in joint critical area (A-C line).

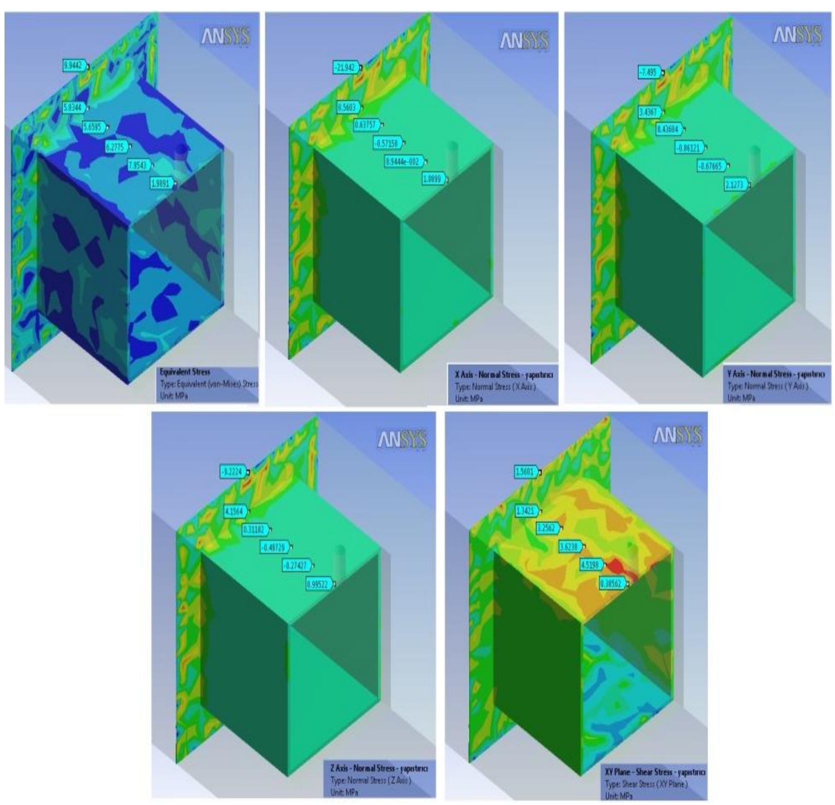
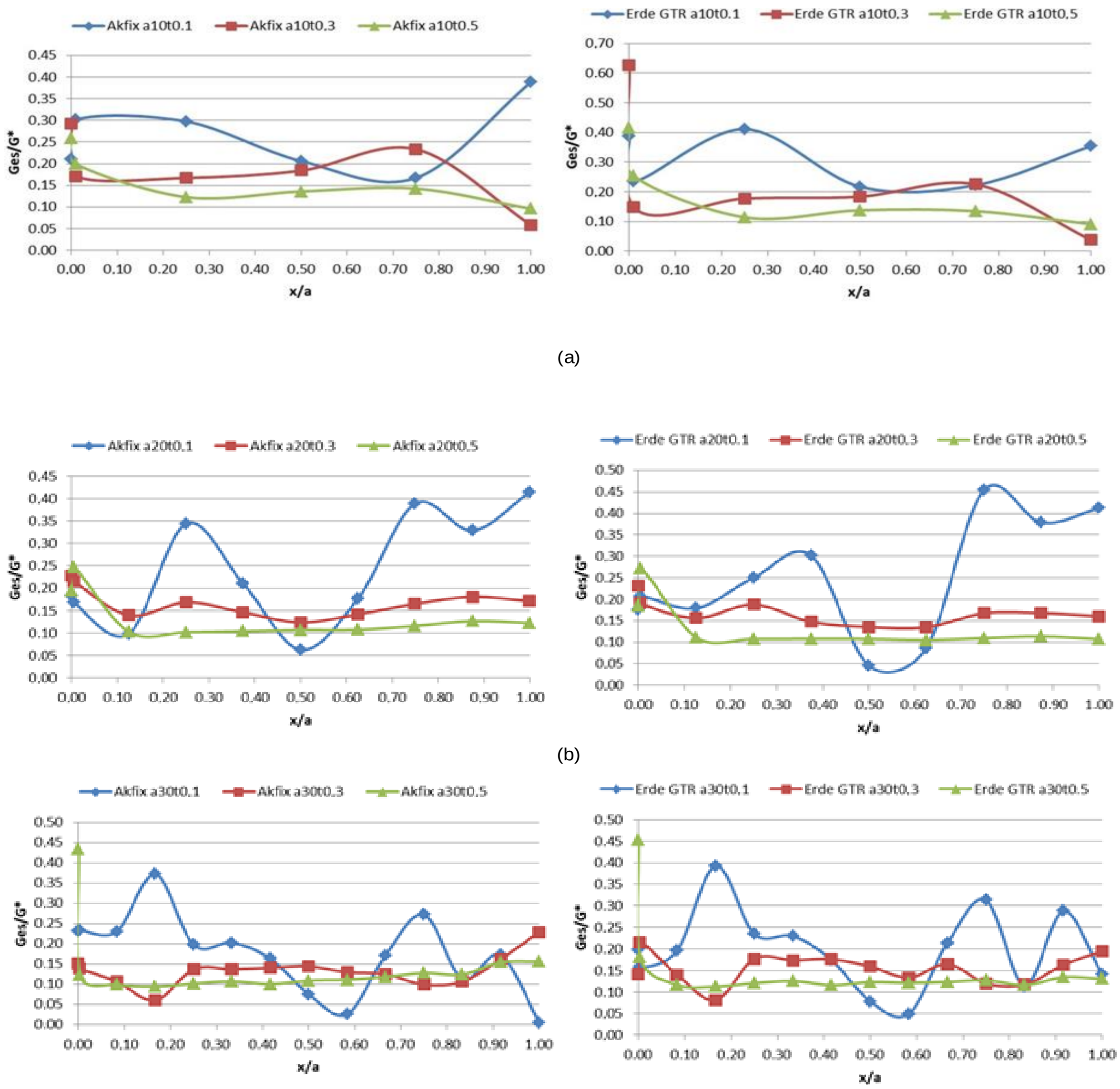


Figure 7. The stress values occurring on adhesive layers as a result of ANSYS analysis (σ_{eqv}, σ_x, σ_y, σ_z, τ_{xy}).



(c)

Figure 8. Equivalent stress distribution occurring throughout the A-C line depending on the overlap distance and adhesive type. a) 10 mm overlap distance, b) 20 mm overlap distance, c) 30 mm overlap distance.

the stress values occurring on the A-C line.

RESULTS AND DISCUSSION

Akfix E300 was combined with Erde GTR, the equivalent stress distribution ratios occurring on the adhesive surface throughout the A-C line for the prismatic plug-in joints with a = 10, 20, 30 overlap distance and t = 0.1, 0.3, 0.5 mm adhesive thickness, normal stress distribution ratios, peeling-stress distribution ratios and shear stress distribution ratios are given in Figures 8, 9, 10, and 11.

As shown in Figure 8, for the 10 mm overlap distance, while the equivalent stress ratio gets the maximum value in both adhesives for x/a = 0 and minimum value for x/a = 1 when the adhesive thickness is t = 0.3 mm or t = 0.5 mm, it gets the minimum value for x/a = 0 and the maximum value for x/a = 1 when t = 0.1 mm. The equivalent stress ratio decreases as the adhesive thickness increases throughout the A-C line.

For 20 mm overlap distance, while both adhesives are in a corrugated form throughout the A-C line for the adhesive thickness of t = 0.1, it is seen that the equivalent stress is distributed regularly for the adhesive thicknesses of t = 0.3 and t = 0.5. The equivalent stress

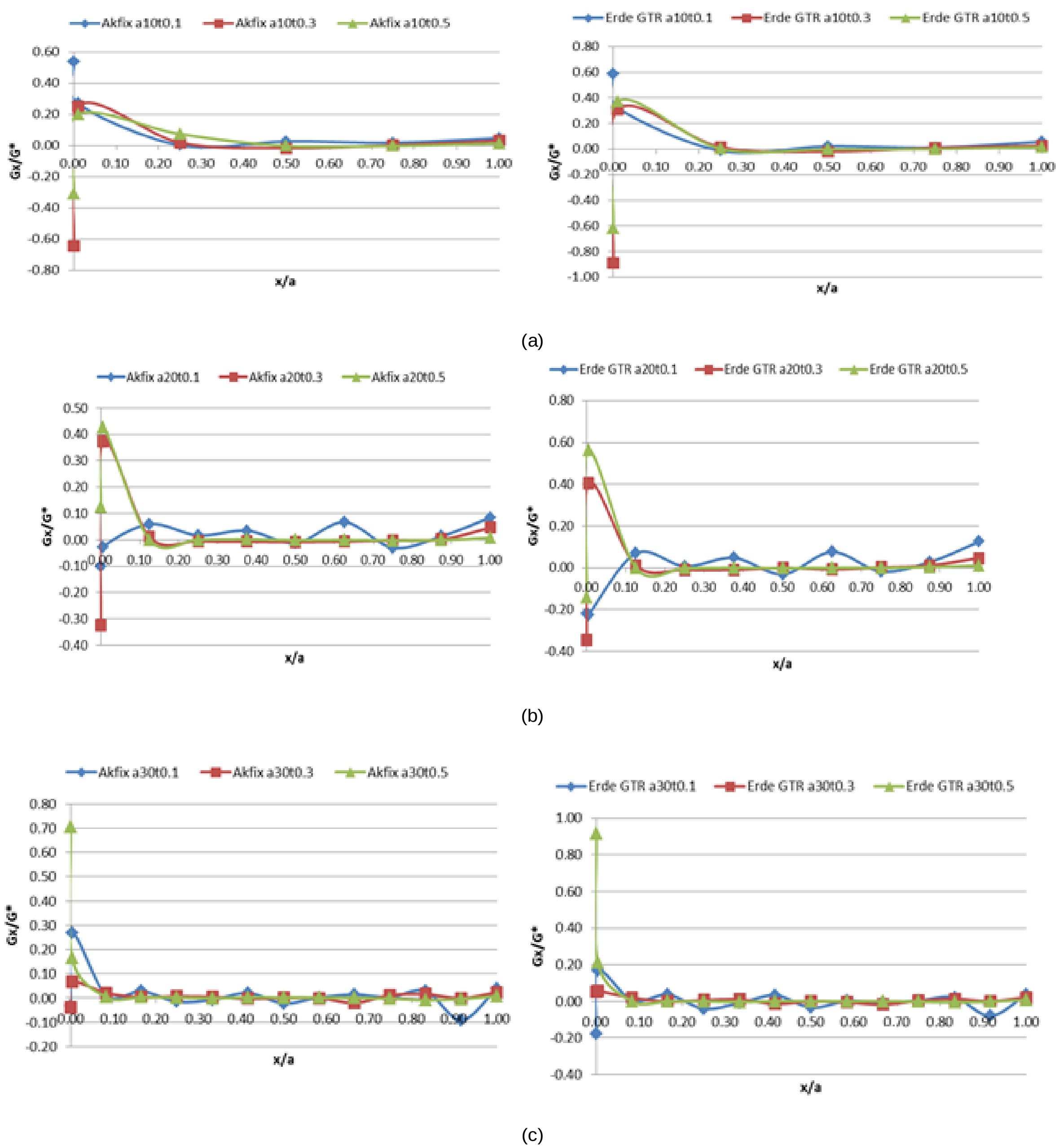


Figure 9. Normal stress distribution occurring throughout the A-C line depending on the overlap distance and adhesive type. a) 10 mm overlap distance, b) 20 mm overlap distance, c) 30 mm overlap distance.

ratio decreases as the adhesive thickness increases.

For 30 mm overlap distance, while both adhesives are in a corrugated form throughout the A-C line for the adhesive thickness of t = 0.1, it is seen that the equivalent stress is distributed more regularly for the adhesive thicknesses of t = 0.3 and t = 0.5.

In Figure 9, for the 10 mm overlap distance, normal stress ratio gets the maximum values for all thickness values in both adhesives for the ratio of x/a = 0. In the ratio of x/a = 0, while normal stress becomes effective as much as tensile stress for t = 0.1, the effect is as much as for the compressive stress for t = 0.3 and t = 0.5. It was seen that the normal stress ratio decreases as the adhesive thickness increases.

For the 20 mm overlap distance, normal stress ratio gets the maximum value in both adhesives in the ratio of x/a = 0 for t = 0.1 and the small corrugated distribution continues until the end of the joint. It was seen that the normal stress ratio decreases as the adhesive thickness increases.

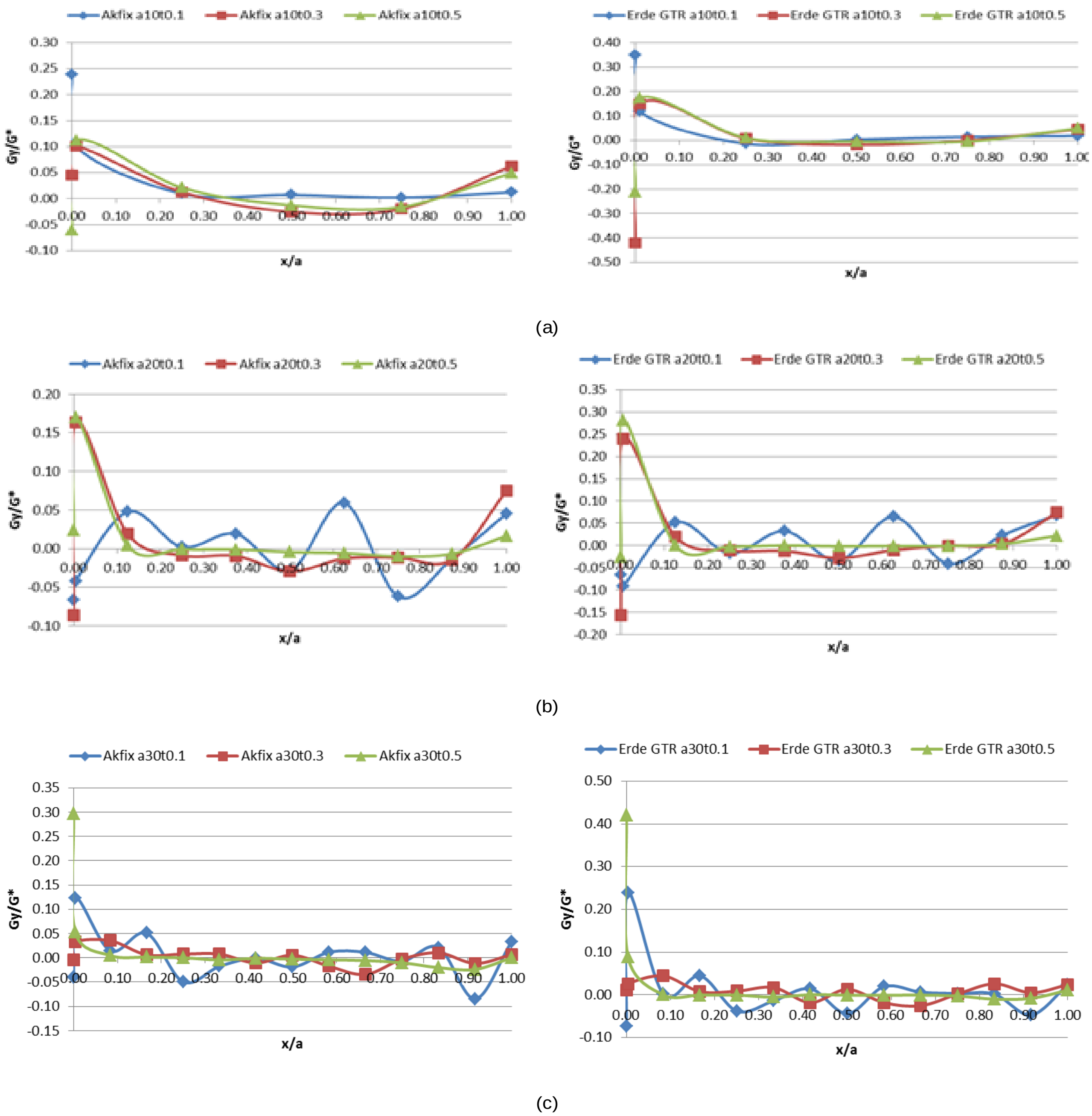


Figure 10. Peeling stress distribution occurring throughout the A-C line depending on the overlap distance and adhesive type. a) 10 mm overlap distance, b) 20 mm overlap distance, c) 30 mm overlap distance.

For the 30 mm overlap distance, the highest stress ratio for both adhesives was obtained for the adhesive thickness of t = 0.1. It was seen that the normal stress ratio decreases as the adhesive thickness increases.

In Figure 10, for the 10 mm overlap distance, peeling stress ratio gets the maximum values for all thickness values in both adhesives for the ratio of x/a = 0, while the peeling stress effects as tensile stress or t = 0.1 and t = 0.3, it effects as compressive stress for t = 0.5.

For the 20 mm overlap distance, the situation of both adhesives is similar to Figure 9b in terms of tensile stress.

For the 30 mm overlap distance, the situation of both adhesives is similar to Figure 9c in terms of tensile stress.

In Figure 11, for the 10 mm overlap distance, while the stress values obtained in the ratio of x/a = 0 for all adhesive thickness values are close to each other,

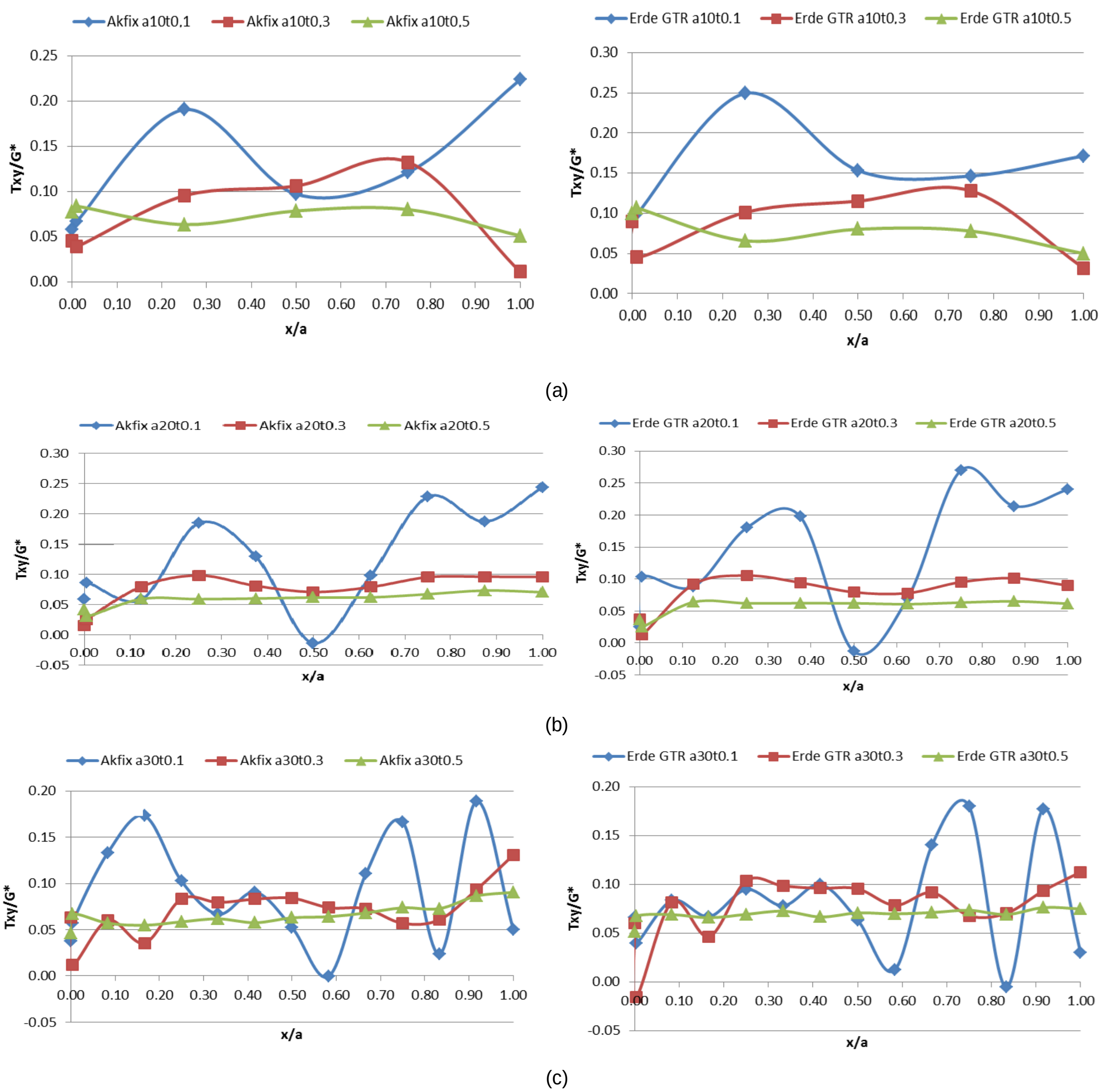


Figure 11. Shear stress distribution occurring throughout the A-C line depending on the overlap distance and adhesive type. a) 10 mm overlap distance, b) 20 mm overlap distance, c) 30 mm overlap distance.

different values are obtained at the end of the joint.

For the 20 mm overlap distance, shear stress spreads throughout the A-C line by being distributed regularly in both adhesives. This situation becomes more apparent as the adhesive thickness increases. The thickness values of t = 0.3 and t = 0.5 provide a more regular formation in terms of shear stress.

In the 30 mm overlap distance, it is seen that shear stress is disrupted in both adhesives and the stress distribution becomes more regular as the adhesive thickness increases. For the adhesive thickness of t = 0.1, the stress is not distributed regularly on the adhesive layer and gets the value of 0 at the centre of the joint by spreading in a corrugated form. It is seen that shear stress distribution is more regular for the adhesive thickness of t = 0.5.

Conclusions

When the distribution of equivalent stress (σ_{eqv}) over the adherend materials are examined according to the results of the ANSYS finite element analysis, it was seen that adhesive thickness is highly effective on the distribution of the stress as a result of the analysis made for the different adhesive thickness values with the same overlap distance. Although, all stress values occurring on the adherend materials and interfaces of the adhesive materials decrease as the adhesive thickness increases, stress distribution forms a regular structure throughout the adhesion line. While the equivalent stress distribution is in a corrugated form and has the maximum value for the adhesive thickness of t = 0.1, the stress distribution is highly regular and has the minimum value for the adhesive thickness of t = 0.5. The maximum equivalent stress values get the maximum values in Erde GTR and minimum values in Akfix E300. Even in the joints on which Erde GTR shows its lowest performance, equal stress values are obtained with Akfix E300. And this means that Erde GTR which is more flexible and shows nonlinear characteristics can carry more loads.

When normal stresses (σ_x) are considered, it is seen that normal stress values increase as the adhesive thickness increases in the same overlap distance. In different overlap distances, the normal stress value also increases as overlap distance increases. Maximum values for normal stress are mostly obtained with Erde GTR.

The structure seen in the distribution of peeling stress (σ_y) is similar to normal stress (σ_x). When compared with normal stress, the difference of peeling stress is the fact that it shows a small decrease with all adhesives ($\sigma_x/\sigma^* > \sigma_y/\sigma^*$). When peeling stress values are examined, it is seen that Erde GTR gets the maximum values. This situation is due to the fact that even though the tensile strength of the other adhesive is higher than Erde GTR, Erde GTR, which is a more flexible adhesive, takes extensive deformations over by distributing more evenly the peeling strengths occurring at the edge of joints.

When shear stress values (τ_{xy}) are examined, it is seen that the adhesive thickness is highly effective on the values and distribution of shear stress. The shear stress values also decrease as the adhesive thickness increases. Increasing overlap distance has an effect on the distribution and change of the maximum and minimum points of the shear stress rather than its intensity. It is seen that the adhesive thickness of t = 0.5 mm is suitable in terms of the distribution of shear stress. When shear stress values are examined, it is seen that Erde GTR gets maximum values. Although shear stress values show small differences depending on the overlap distances and adhesive thickness, these values are obtained as Erde GTR > Akfix E300.

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