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Full Length Research Paper

The effect of overlap length adhesive with bonded in Z type materials

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The usage of adhesives as connecting method is increasing rapidly in today world. Many of research, development and engineering have been made to find the most important parameters of adhesion. In this study, stress analysis of bonded Z type that connected with various adhesives has been investigated. The adhesive thickness and overlap non-angle was constant but overlap length and overlap angle were varied. This paper has deal with the effect of overlap length on predicting of failure load of adhesive. An effective method for numerical solution in finite element method (FEM) has been performed in analysis. The FEM code employed was ANSYS(10.0). Experimental results were compared with numerical results and were found quite reasonable.

Key words: Adhesive, stress analysis, interface, finite element method (FEM).

INTRODUCTION

Adhesive joints have been used in mechanical structures, the automobile and aerospace industries, electric devices, and so on. Due to the many advantages offered by this method of joining, such as stress concentration reduction, the possibility to assemble dissimilar and/or thin materials, and protection against corrosion etc. Some studies have been carried out on the stress distribution of adhesive joints under static loadings such as tensile loads, bending moments and cleavage loads (Sawa et al., 1995).

Adhesive bonding offers many advantages over classical fastening techniques such as welding, riveting and mechanical fastening. The substantial reduction in weight that can be achieved using adhesive bonding is an important advantage, especially for lightweight structures. However, the most common and most important factor influencing the long-term behaviour of unprotected adhesively-bonded metal joints is the presence of high humidity or liquid water (Kinloch, 1983).

When loaded in the tensile mode of adhesively bonded joints, they developed a linear stress pattern along the bonded overlap. Peak stresses, which may be several times the average failure stresses, are produced at the ends of the lap because of two factors: the differential strain induced between the adhesive and the adherends by the load, and the bending of the joint due to an eccentricity that results from the presence of the overlap. As the failure of a simple lap joint is determined by the maximum stresses at the ends of the overlap, joint modifications that produce a more uniform stress distribution yield stronger joints.

Many ideas have been suggested to reduce the high stresses that occur at the ends of the overlap. These ideas can be grouped into two general categories: material modification and geometrical modification. Material modification includes changing the material properties or fracture characteristics of adhesive, for example, by rubber toughening. Geometrical modifications involve altering the shape of the adherend and/or adhesive. Among these methods are preformed adherends, taper, fillets, rounding, adherend shape optimization, etc. (Sancaktar and Nirantar, 2002).

Higuchi et al. (1999) have reported on the stress propagation of adhesive butt joints of T- shaped adherends

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subjected to impact tensile loads. In addition, it has been found that the characteristics of adhesive butt joints under impact loadings are different from those under static loadings. In practice, it is necessary to know the stress propagation and the stress distribution of adhesive joints subjected to impact bending moments from a reliable design standpoint, and to know the difference in the characteristics of adhesive butt joints under impact and static loadings.

A method for making the shear stress uniform along the bond length was presented by Cherry and Harrison (1970). This method was based on simple static equilibrium conditions. The tensile strains on both adherends were set equal to each other at each point by modifying the adherend thickness. It was assumed that the displacements through the thickness of the adhesive were negligible, the adhesive layer was thin enough so that the edge effects could be ignored, the bond length was much greater than the adherend thickness, and that the plane faces remained parallel to each other. Furthermore, peel stresses were not considered in this model. The ideal adherend profile for making the shear stress uniform was found to be a symmetric taper of the adherend along the bondline. It was also found that in addition to being a function of the adherend thickness, the shear stress was also a function of the Young's modulus of the adherends.

Borgmeier and DeVries also studied the effect of the modification of the lap joint geometry by tapering the adherends. A fracture mechanics approach was used for predicting adhesive joint failure to facilitate its application to practical joint configurations. In these studies, two groups of samples were tested: unmodified, and modified with tapered adherends. They reported that tapering of the adherends reduced the rate at which shear stress increased as the bond termini were approached. This, in principle, results in a more uniform distribution of the shear stresses over the overlap region of the joint (Borgmeier and DeVries, 1998).

In their stress analysis of single lap joint using FEM, Baylor and Sancaktar (1995) showed that if the mesh density along the transverse direction of the overlap was greater than 3 elements per mm, then the variation in maximum principal stress and von-Mises stress with mesh density would be effectively removed. It was also shown that for an adhesive thickness of 0.2 mm, 25 elements per mm in the peel direction would result in the uncoupling of these stresses with mesh density. Therefore, the FEM used in this work was designed with these two mesh densities as constraints on design.

The effects of loading rate, fiber sizing, test temperature and global strain level on the adhesion strength between carbon fibers and a thermosetting epoxy (Epon 815) are studied using the single fiber fragmentation test procedure. Analytical methodology describing the viscoelastic behavior observed is also presented. The possibility of rate-temperature-interphase thickness superposition for the interfacial strength function is illustrated based on the analytical models discussed. Experimental data are discussed using Weibull statistics and also presented in the form of percent relative frequency histograms for the fiber fragments in a collective fashion. The use of histograms allows for interpretation of the skewness in the data population (Sancaktar et al., 1992).

In this study, the mechanical behaviours of bonded Z ties steel using two adhesives with different properties under a tensile load was analyzed. Experimentally results are compared with numerically results (FEM). In order to assess the performance of the adhesives (E type adhesive and W type adhesive) in this work, tensile experiments on the joints with different angle lap joint were carried out. The FEM calculations were performed in elastic deformation and it was assumed that the strain rate of the adhesive was small. The effects of overlap length adherends and the geometry of Z shaped adherends stresses at the interfaces were examined. Furthermore, the characteristic of adhesive joints of Z shaped joints subjected to tensile loads were examined by FEM.

The stress analysis of the Z shaped joints was performed via non-linear finite element method by considering stress behaviours of adhesives and adherend (steel; $Fe_{49}Cr_{15}Mo_{14}C_{18}B_3Er_1$). Experimental results were compared with the FEM results obtained by Temiz (2006).

FINITE ELEMENT CALCULATIONS AND CONFIGURATION JOİNTS

Figure 1 shows the models for calculations of adhesive joint and FEM. Coordinate system (x,y) of specimens is used as shown in Figure 1. Supports are inserted into edges of the adherends as shown in Figure 1 to attach object to the specimen.

In this study, Ansys finite element package was utilized to evaluate the stresses. The Ansys code version 10.0 and two dimensional volume elements, Plane 82 and plane 2, were employed for the joints. The mesh density can affect the strain predictions in the adhesive layer. The mesh density remained 1 elements/mm. In adhesive geometries the mesh in the adherends was denser than adherends. However, further dimension changes cause only little effect when a specific size of finite element is reached (Işcan et al., 2010). A smaller element size will generally give a higher strain. For this reason, the size of the elements in the mesh was reduced until a stable maximum strain value had been achieved.

Consequently, 5 elements through the adhesive thickness were used in the models, as shown in Figure 1, and the number of elements was varied for each overlap

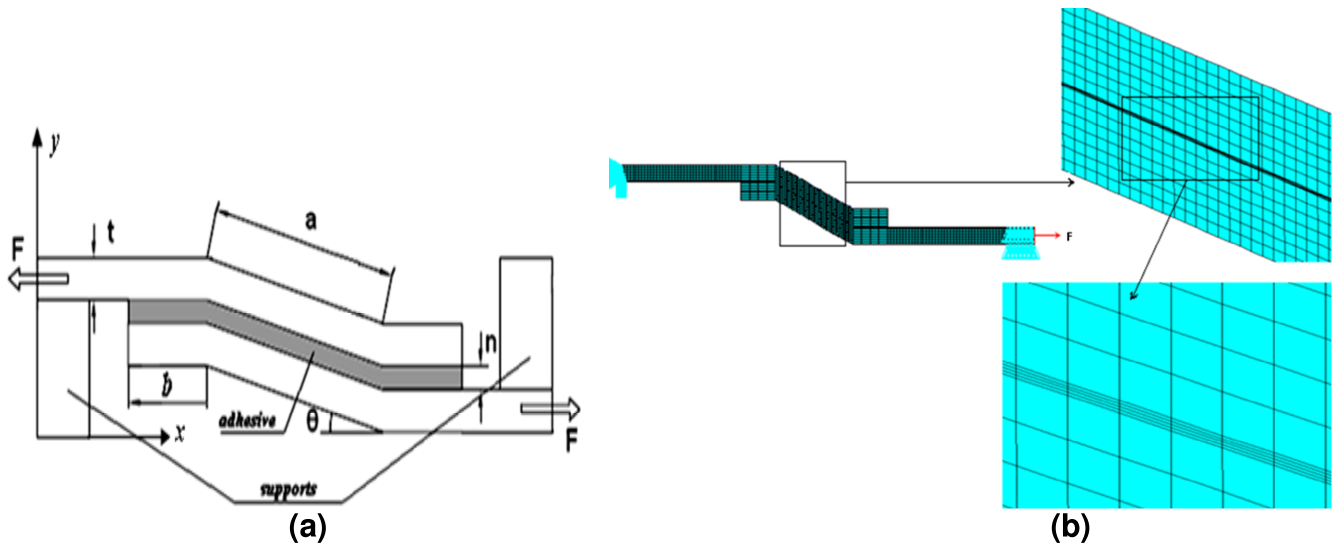

Figure 1. Configuration of specimens: (a) geometry; (b) Mesh details and boundary conditions.

length. In the joints of adherend with adhesives, the nominal bondline thickness considered in all cases was 0.20 mm. The adhesive layer was divided into five meshes of 5 mm thickness in the y (thickness) direction after the effect and accuracy of the mesh divisions on the stress wave propagations and stress distributions were examined. When the minimum thickness of element was chosen (t = 5 mm), it was confirmed that a difference in the calculated results of the interface stress distributions were very small.

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EXPERIMENTAL METHOD

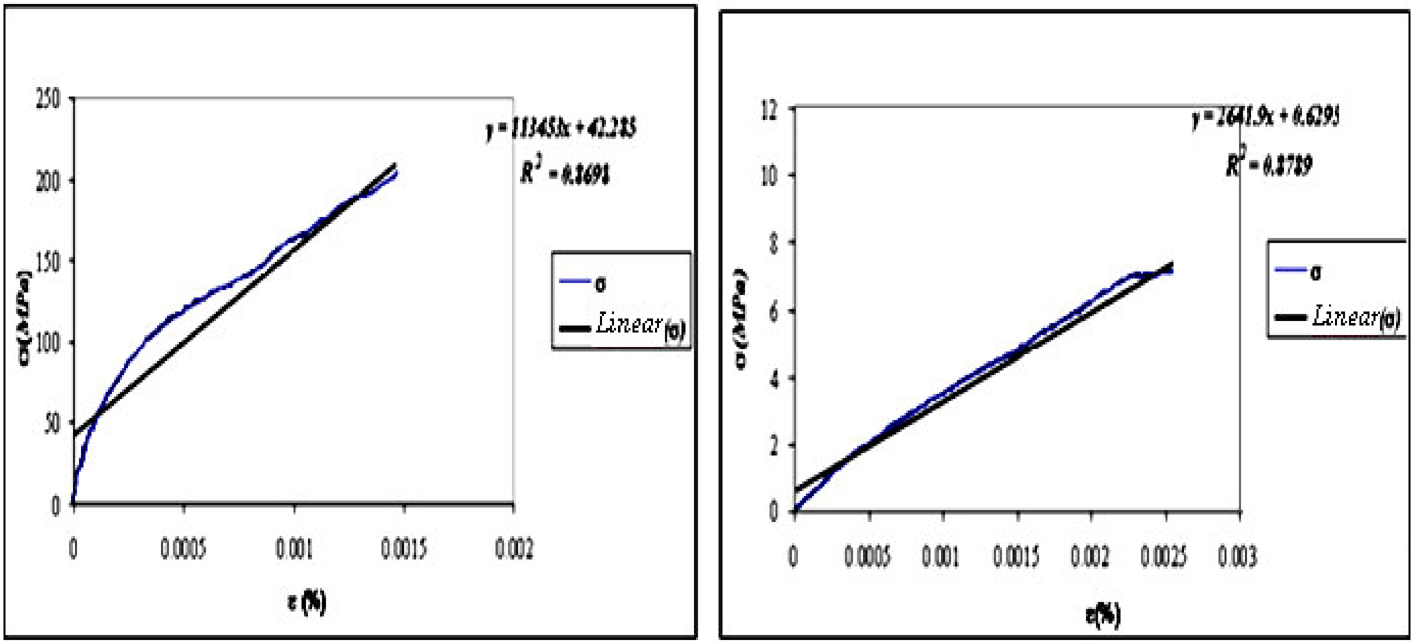
Figure 1 shows the dimensions of the specimens used. The specimens were made of steel ($Fe_{49}Cr_{15}Mo_{14}C_{18}B_3Er_1$) and they were joined by an E and W adhesives of which Young's modulus was 1.68055 and 1.92454 GPa and Poisson's ratio was 0.28 and 0.30, respectively. The surface impurities were removed using aseton, the interfaces of the specimens were joined by the adhesive, and the joint was cured at room temperature for 24 h (Işcan, 2007). The stress–strain (σ –ε) behaviors of the adhesives was determined from bulk dumb-bell (dog bone) specimens tested under the conditions specified. Three specimens were tested to failure at a crosshead speed of 1 mm/min. The other experimental details are described in Adin et al. (2010). Typical tensile stress-strain curves for the two adhesives are shown in Figures 2a and 2b, while the geometrical parameters and materials properties used in the FEM are given in Tables 1 and 2, respectively.

The tests were performed using Instron 1114 machine at room temperature (23°C) and 50% relative humidity. During tensile testing, the crosshead speed was maintained at 1 mm/min, and a 5 kN load was used. Three or four specimens were tested for each experimental condition analyzed. The stress analysis of joint was also carried out and the von-Mises yield criterion was used to calculate the equivalent stress (σ_{eqv}) distributions in the adhesives and adherends.

COMPARISON BETWEEN FEM AND EXPERIMENTAL RESULTS

In the FEM calculations, the dimensions and the material constant used are the same as those used in the strain response measurements (Figure 1, Tables 1 and 2). The solution in finite element considering non-linear material behavior is reached by dividing the total load in steps to track the equilibrium paths and iterating to a converged solution at each load increment. In this study, the number of load steps for each joint type changed due to changing predicted damage loads.

The results predicted from FEM and obtained experimentally are shown in Table 3. When the FEM results are compared with the experimental results, the results found are compatible with FEM results. For this reason, in addition to other parameters such as the dependence on strain and the lack of yield criterions of adhesives, it can be said that the residual thermal stresses occurred due to the applied pressure during curing process at elevated temperature need to be taken into consideration so as to simulate accurately the mechanical behaviors of adhesively bonded joints. But, in practice, the magnitude of these stresses is difficult to predict. Therefore, more detailed investigation which comprises the mechanical and thermal properties of adhesives at different temperatures needs to be performed in order to explain the effect of curing pressure on the strength of adhesively bonded joints.



(a) (b)

Figure 2. Tensile stress-strain behaviours of adhesives: a) E type adhesive; b) W type adhesive.

Table 1. Geometrical parameters of the specimens used in experimental and numerical studies (all dimensions in mm) (thickness of all specimens is t = 5 mm).

Overlap length (a)	Overlap length (b)	Adhesive thickness (n)	Overlap angle (θ)
30	25	0.20	15º
45	25	0.20	15º
30	25	0.20	30º
45	25	0.20	30º
30	25	0.20	45º
45	25	0.20	45º

Table 2. The material properties of the adherends and the adhesives.

	Steel ($Fe_{49}Cr_{15}Mo_{14}C_{18}B_3Er_1$)	E adhesive	W adhesive
E_x (GPa)	210	1.68055	1.92454
v	0.32	0.28	0.30

E, Young's modulus; *v*, Poisson's ratio.

In order to predict the damage load, the stress (σ) of adhesives given in Table 2 was used and the adhesives was assumed to fail when the von-Mises equivalent stress (σ_{eqv}) calculated at any point of adhesive layer reaches the stress (σ) of the adhesives. Figure 3 shows FEM calculation and experimental ratios of failure load of joint depending on the non dimensional overlap length. Ratios of failure load was maximum when the overlap length was around a = 30 mm. Furthermore, the experimental rates were higher.

Table 3. Experimental and failure loads for Z type joint.

Overlap angle(θ)	Overlap length (mm)	E type adhesive			W type adhesive		
		F_E (N)	F_{FEM} (N)	F_R	F_E (N)	F_{FEM} (N)	F_R
15^0	30	144.36	152.33	1.05	184.64	186.89	1.01
15^0	45	140.26	150.11	1.07	190.35	195.23	1.03
30^0	30	138.49	149.72	1.08	186.84	191.61	1.03
30^0	45	135.01	147.23	1.09	183.25	189.89	1.03
45^0	30	131.98	145.51	1.10	185.65	191.41	1.03
45^0	45	129.12	142.94	1.11	182.16	189.15	1.04

F_E (N): Experimental damage load of adhesives; F_{FEM} (N): Damage load predicted from FEM adhesives; $F_R = F_{FEM}/F_E$ (Finite Element Analysis load/ Experimental load) (N).

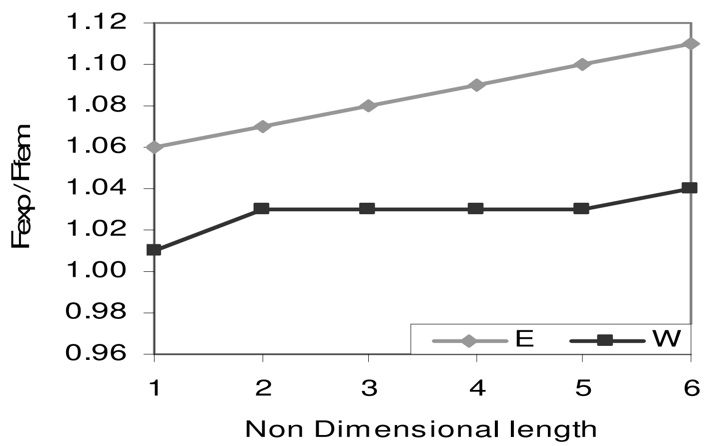


Figure 3. Ratio of failure loads experimental and FEM calculation.

The present FEM analysis results have shown that the most critical points are along the adherend-adhesive interfaces and the maximum peel (σ_y) and shear (τ_{xy}) stresses are located between the centerline and the adherend-adhesive interfaces and at the opposite corner ends of overlap. For this reason, the bondline on the adhesive side was taken into consideration for the stress analysis and all of the stress (σ_x , σ_y τ_{xy}, and σ_{eqv}) distributions were normalized (Figures 4, 5 and 6).

RESULTS AND DISCUSSION

The maximum stress is described in this article. The stress components and the results of FEM calculations for the Z shaped joint are described in Figure 4, 5 and 6. Figures 4 - 6 shows the stress propagations at the positions of the interfaces adhesives. In this case, the stresses were examined up to increase and decrease. In this study, a stress means the stress of an element. In addition, the interface stress shows at the interface of the adhesive. It is observed that stress become maximum at the interfaces. From the results, it can be concluded that the stress of Z shaped joints becomes maximum at the position interfaces. In Figures 4, 5 and 6 normal (σ_x, σ_y), shear (τ_{xy}) and equivalent (σ_{eq}) stresses distributions obtained from the adhesive layers throughout breadth at middle non dimensional overlap have been given. A general examination of this figure disclosed that maximum values of all stress located at middle non dimensional overlap.

From Figures 4a, 5a and 5b it was observed that the maximum values of normal stress σ_x occurred in both adhesive, at middle non dimensional overlap. As overlap length were increased, the stress values decreased also. In addition, the stress (σ_x) is minimum at the overlap a non-dimension in the boundary.

Minimum values of normalized peeling stresses (σ_y) determined at middle non dimensional overlap by means of Figures 4b, 5b and 6b. Maximum values of the peeling stress are determined in both adhesives at edges of non dimensional overlap. As also, overlap length were increased, the stress values decreased.

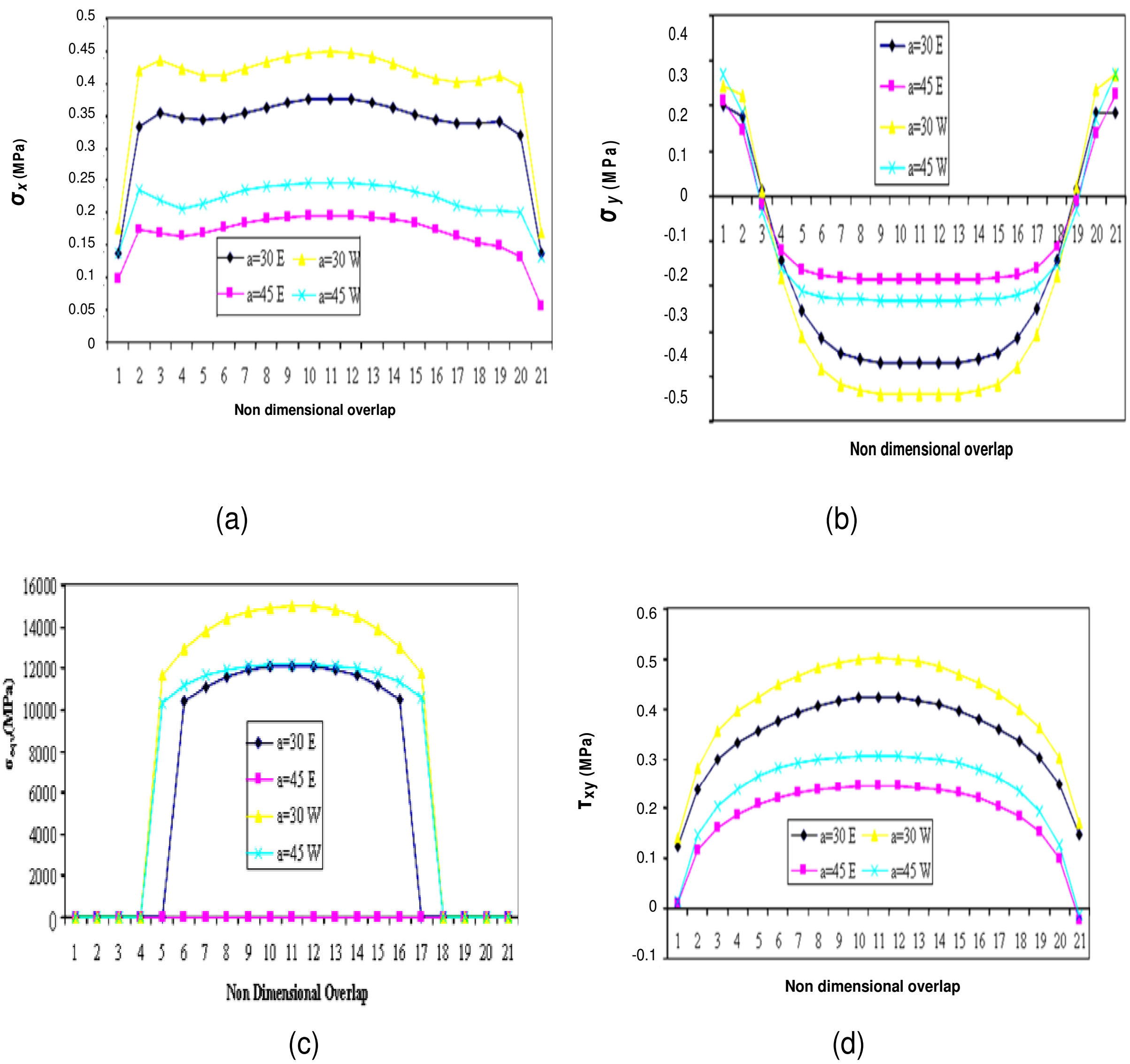


Figure 4. Stress distributions 15^0 for overlap length: (a) normalized σ_x stress distributions; (b) σ_y stress distributions; (c) σ_{eqv} von-Misses distributions; (d) τ_{xy} shear stress distributions.
E: E type adhesive; W: W type adhesive.

Figures 4c, 5c and 6c exhibited that in similar way that of normal stress components, the maximum and minimum values of equivalent stresses (σ_{eqv}) distributions were at sections of edges for both adhesive. The stress distribution characteristic in all overlap angles is almost identical for both adhesive. Taking into consideration Figures 4d, 5d and 6d, it was determined that shear (τ_{xy}) stress distribution was almost the same characteristics in overlap angles $\theta=15^0$ and $\theta=30^0$. The stress values obtained higher values in middle of non dimensional overlap and minimum values occurred at edges. Furthermore, as when overlap length is increased, the values of shear stress are decreased. From the results, the maximum stresses in the special case shown in Figures 4, 5 and 6 become highest at the overlap a length of the specimens. Some figures (Figures 4b, 5d, 5a, 5b, 5c, 6a and 6b shows the distribution of stresses at the interfaces when the elapsed. It is found that the stresses are substantial in these special cases. Theoretically, the stress must be zero at the boundary. However, as has been described before, the stress occurs at point of the specimens along the edge. Thus, the stresses are not zero at overlap length boundaries. In addition, it is also emphasized that the stress distribution in this special case (Figure 5) is different from that shown in Figure 6. The effect of the overlap angle on the stress distribution at

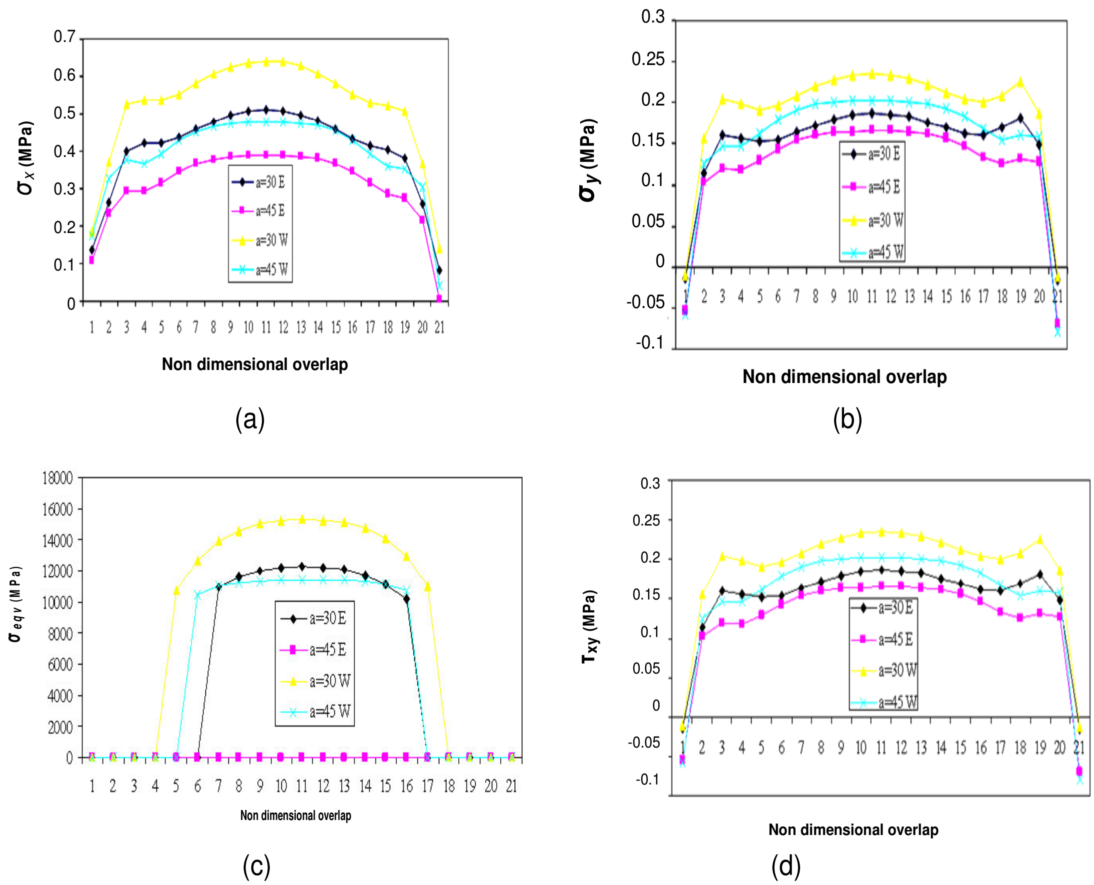


Figure 5. Stress distributions 30^0 for overlap length: (a) normalized σ_x stress distributions; (b) σ_y stress distributions; (c) σ_{eqv} von-Misses distributions; (d) τ_{xy} shear stress distributions.

the interfaces is examined. It was found that the position where the highest value in centre of overlap length increased. It is found that the highest value of stresses σ_x increases along non dimensional overlap of the adhesive as the value of overlap length increases. Furthermore, the effect of overlap angle on stresses propagation is examined. In the FEM calculations, the overlap angles are changed and the calculations were done under the same conditions. In addition, it is also observed that stress distribution in the adhesive joint.

In order to predict the ultimate strength given in Table 2, the adhesive was used. Therefore, the equivalent stress, normal stresses and shear stresses were calculated using the von-Mises yield stress. A solution in FEM considering material behavior is reached by dividing the total load in steps to track the equilibrium paths and iterating to a converged solution at each load increment. Hence, each load step was applied for all joint types. Consequently, exposes the adhesives both shear (τ_{xy}) and peel stress σ_x. The peel stress (σ_y) at the free ends of the overlap is very important in this region. It is an important point to be considered that the increase in overlap length causes an increase in the failure load occurred, when Table 3 is examined. Also, the failure occurs within the adhesives and is partly cohesive and adhesive, but very close to the steel adhesive interface. Finally, it can be concluded that interfacial bond damage occurs in the joints.

Figures 4d, 5d and 6d indicates that more shear stress are transferred from the end to the centre of the overlap with increasing the overlap length (θ), due to the reduced the elastic deformations on the adhesives. Therefore, the effect of shear stresses on the failure and strength of the adhesively bonded joints increases. Similarly, it is evident that more equivalent stress is transferred from the end to the centre of the overlap with increasing the overlap length, as seen from Figure 4c, 5c and 6c.

As observed for the normal and shear stresses along the overlap length on adherends (Figures 4, 5 and 6) σ_x, σ_y, and τ_{xy} shear stress distribution are higher for the joints with both type adhesive. Similarly, when the von-Mises equivalent stresses are examined together it can clearly be stated undertakes elastic deformations on the adhesives. This situation provides the important increase

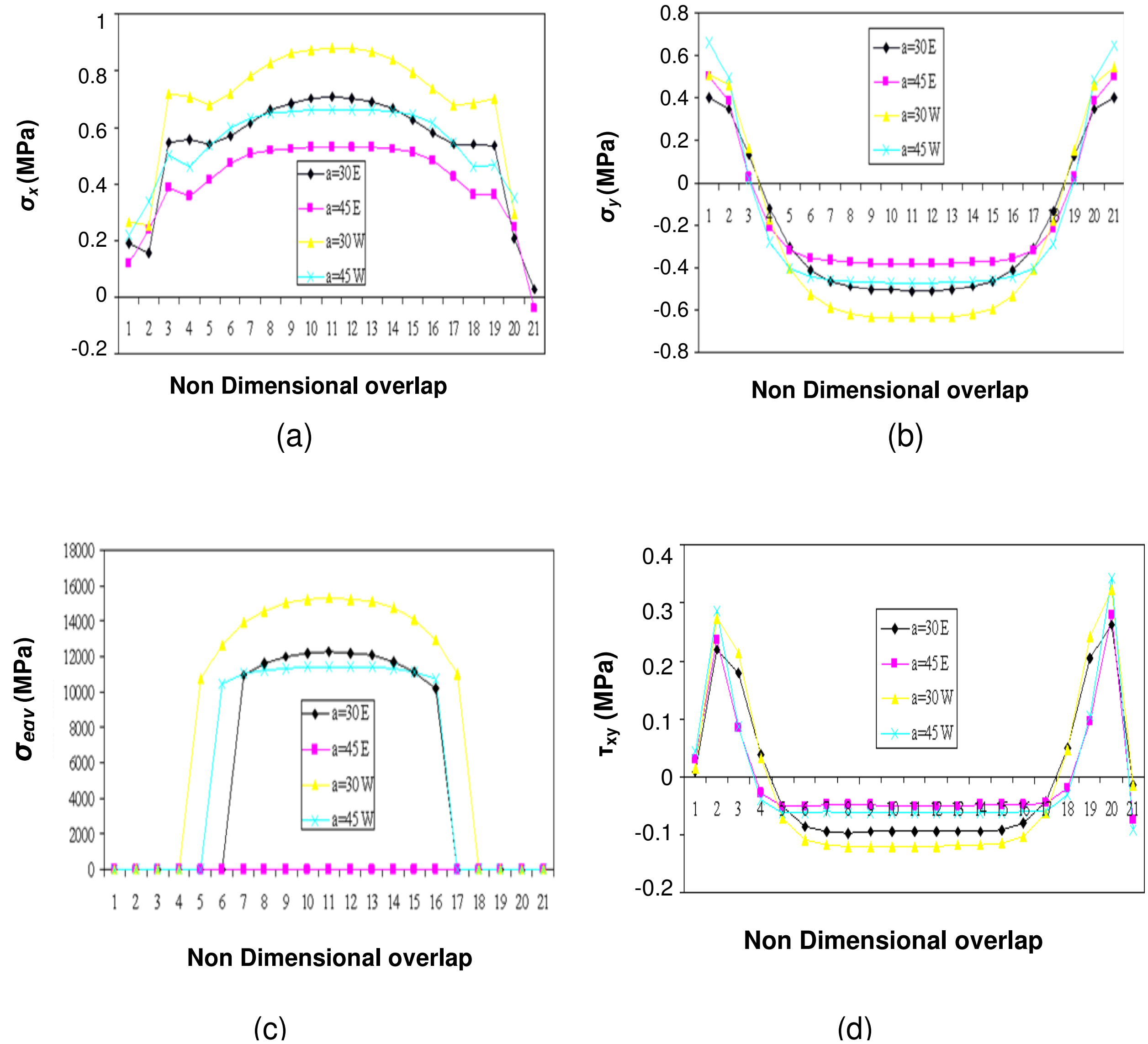


Figure 6. Stress distributions 45^0 for overlap length: (a) normalized σ_x stress distributions; (b) σ_y stress distributions; (c) σ_{eqv} von-Misses distributions; (d) τ_{xy} shear stress distributions.

in the performance of the joint with both adhesive.

Consequently, a fairly good agreement is observed between the FEM results and experimental results (Table 3). In addition to, ratio values are found to be very close to 1. Failure initiation is probably occurred at edges of overlap length within interface of the adhesives. Then, the failure at both free ends promote to the centre of overlap before joining each other.

Conclusions

In this paper, adherends with same thickness and breadth were joined using adhesive. By subjecting to tensile test obtained specimens, failure loads of joints were examined. As a result of the tensile test, following findings were obtained:

It is clear from figures between 4, 5 and 6 that σ_x, σ_y and σ_{eqv} stresses were reduced at “a” overlap point. The σ_y stresses were decreased for the same conditions. With the use of both adhesives, for θ=15°, θ=30° and θ=45°, the σ_y stresses were decreased at “a” overlap point. When angle was increased from 15° to 30° the σ_y stresses were increased and when angle was increased from 30° to 45° the σ_y stresses were decreased.

With the use of both adhesives, for θ=15°, θ=30° and θ=45°, the τ_{xy} stresses were decreased at an overlap lengths.

For both adhesives, the σ_{eqv} stresses were decreased at “a” overlap point as can be in figures.

As can be seen in figures above σ_x, σ_y and τ_{xy} stresses of the W type adhesive were higher than those of E type adhesive. It is because of that, the elasticity module of the W type adhesive is higher than those of E type adhesive. The σ_{eqv} stresses of W type were lower than those of E type. It has been found that there is a close agreement between 3-D FEM and experimental results.

For both adhesives, geometrical exchange has considerable effects on maximum stresses, dependent upon the load.

FEM and experimental results conducted to observe only the effect of overlap length showed that the values maximum of stress occurred at the middle section of the joints, whereas the values minimum of stress at edges. FEM and experimental results showed that overlap length and angle should be the central focus of attention at the adhesively joint designs.

The results of FEM depicted that maximum σ_{eqv} stresses occurring at adhesively bonded joints subjected to tensile load took place at the interface between adhesive and adherend.

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