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STRESS ANALYSIS OF HYBRID JOINTS USING DIFFERENT MATERIALS VIA 3D-FEM

Aldaş, K., and Sen, F.
Aksaray University, Department of Mechanical Engineering, 68100 Aksaray, Turkey
E-mail: faruk.sen@deu.edu.tr (Corresponding author)

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Abstract

The aim of this work a three dimensional stress analysis of hybrid joints using different materials. Hybrid joint was designed both adhesively bonded and pinned single lap joints. Aluminum, copper, steel and titanium were selected as adherent materials, whereas the epoxy resin was preferred for adhesive. Three dimensional finite element models have been created to obtain stress distributions using ANSYS software. After the modeling and meshing process, both pinned boundary condition with tensile loading and uniform temperature were performed for double loading conditions on the model. It is understand that the positions of stresses were considerably affected from existence of pin hole, so stresses were concentrated around it. Additionally, steel adherents cause higher stresses than other used materials. The titanium adherents provided lower stresses.

Keywords: Stress analysis; hybrid joint; single lap joint; epoxy adhesive.

1. Introduction

An adhesive is a substance used to join together the surfaces of two solid materials to produce a joint with high shear strength. If a good joint is formed, the adherend material may fracture or rupture before the adhesive [1]. Therefore, adhesive bonding method is commonly used these days in approximately all the many industries and this is mainly owing to its high strength-weight ratio, low cost and high efficiency [2]. However, the design of safe and cost effective bonded joints is a foremost challenge. It forces on the engineer to have a excellent understanding of the effect of material and geometric parameters on the joint's strength [3]. In real applications, the adhesive joints knowledge not only mechanical loadings but also thermal loadings. Since the adhesive joints consist of materials with different mechanical and thermal properties, the thermal strains in the joint members might cause serious stresses [4]. Moreover, joints are formed by using mechanical fasteners frequently. Pin or bolt joints are unavoidable in complex structures due to their low cost, simplicity, and facilitation of disassembly for repair [5]. On the other hand, the mechanical joint always requires fastener holes. Cutting the fastener holes creates local failure and stress concentration, and consequently, leads to a loss of structural strength. [6]. In brief, the most challenging problem faced by a design engineer is the likely weakness of the adhesive bond and the poor through-thickness strength of the adherents. One promising approach is to apply through -thickness reinforcement using small diameter metallic or fibrous pins [7].

A transient thermal analysis of an adhesively bonded and laser-spot welded joint was carried out on a thermal model developed for the laser-spot welding of multi-layered metal sheets using a pulsed Nd:YAG laser. In the thermal stress analysis, the material non-linear properties of adhesive and metal sheets were considered by the non-linear finite element method (FEM) [8]. Morais et al. [9] studied on the strength of stainless-steel joints bonded with two epoxy adhesives. The experimental programme included tests on single-lap and butt joints, as well as thick-adherent and napkin ring shear tests. However, FEM increased worries on the true adhesive strengths, because of the complex stress state in joint tests and pressure-dependent adhesive performance. Notwithstanding some suspicions, FEM illustrated that failure could be fairly well predicted by a maximum shear strain criterion. Rastogi et al. [10] obtained thermal stresses in aluminum-to-composite, symmetric, double-lap joints using FEM. The joint configuration considered aluminum adherent in combination with four different unidirectional laminated composite adherents under uniform temperature loading. Silva and Adams [11] investigated a mixed adhesive joint. Experiments were performed for titanium/titanium and titanium/composite double lap joints. It was shown that, for a joint with dissimilar adherents, the combination of two adhesives gave a better performance over the temperature range than a high temperature adhesive alone. Silva and Adams [12] were studied on adhesive joints with dual adhesives to be used over a wide temperature range theoretically, too. A numerical analysis was done using finite element models to calculate the stress distribution in a mixed adhesive joint so as to decide the best possible design of titanium/titanium and titanium/composite double lap joints. According to numerical analysis results, for a joint with dissimilar adherends, the combination of two adhesives gives a better performance over the temperature range considered than the use of a high-temperature adhesive alone, too. Grassi et al. [13] developed a simple and efficient computational approach for analyzing the benefits of through-thickness pins for restricting debonds failure in joints. It is suggested that the resulting model can be used to path the evolution of competing failure mechanisms, including tensile or compressive failure of the adherents, joint debonding and ultimate failure associated with pin rupture or pullout. Sayman et. al. [14] determined bearing strength in fiber reinforced laminated composite bolted-joints under preload. In that study, pinned and bolted joints were compared according to their failure behaviors. Pakdil et. al. [15] observed the failure response of glass-epoxy laminated composite bolted-joints with clearance. The main purpose of that study was deciding the effect clearance on failure occurrence. Briefly, based on the literature, many researchers have studied either adhesively bonded or pinned single lap joint. Nevertheless, the analysis of hybrid joints designed using both adhesively bonded and pinned single lap joints under both thermal loads and tensile loads has not been investigated yet, according to authors' knowledge.

In this study, a stress analysis was carried out for a mixed joint based on adhesively bonded and pinned single lap joints. Three dimensional finite element model has been created to determine stress distributions. The analysis was applied for four different adherent materials, so the effect of material selection was same hybrid joint.

2. Materials and Methods

A hybrid joint was designed from adhesive bonded and pinned joints with together as seen in Figure 1.

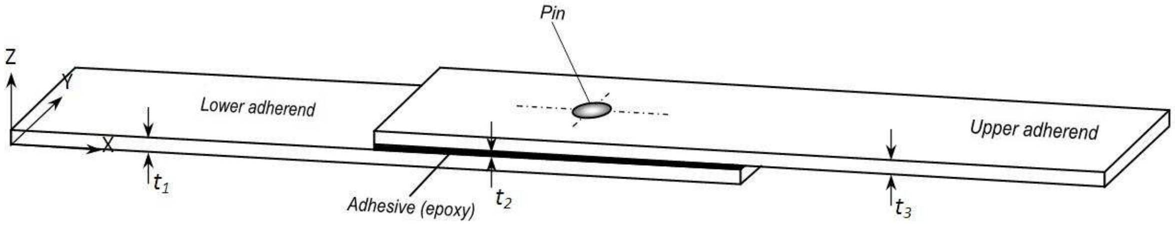


Fig. 1**.** Hybrid single-lap joint

Four different metal materials were selected as adherent materials such as copper, steel, titanium and aluminum, while adhesive was selected as epoxy resin. It is known that epoxy resins are used in many real adhesive applications due to good bonding properties of it. Furthermore, epoxies have exceptional combination of mechanical properties, corrosion resistance, dimensionally stable, good adhesion, relatively inexpensive and good electrical properties [1]. The thickness of each metal adherent was t_1=t_2=2 mm, while the thickness of epoxy adhesive was t_3=0.2 mm. The lengths of each metal adherents and adhesive layer were 100 mm and 50 mm, respectively. In addition, the width of both metal adherents and adhesive layer was 25 mm for the reason that the problem was modeled as three dimensional. Pin diameter selected as 5 mm. On the other hand, both the edge distance-to-hole diameter ratio (E/D) and plate width-to-hole diameter ratio (W/D) were considered as 5. Since some previous studies based experimental tests advised that the best E/D and W/D ratios were 5 for single pinned joints [14-16]. The experiments point out that these ratios supply higher values of failure loads and occurrence of bearing failure mode. This failure mode is desired failure mode get rid of catastrophic failure of pinned joints. Physical properties of adherent metal materials and epoxy adhesive are given in Table 1 [1, 8].

Table 1. Material properties of metal adherents and epoxy adhesive

Property	Copper	Aluminum	Steel	Titanium	Epoxy
Density, ρ (kg/m^3)	8940	2707	7780	4570	1264
Specific heat, c_p (J/kgK)	386	896	460	523	1046
Thermal conductivity, k (W/mK)	398	204	80.3	20.4	0.179
Elasticity modulus, E (GPa)	110	66	207	116	3.3
Poisson's ratio, υ	0.34	0.33	0.29	0.34	0.30
Thermal expansion coefficient, α (μm/m^{o}C)	17.0	23.6	12.6	8.9	43.3

During the numerical study, the finite element method (FEM) was preferred to obtain stresses. Therefore, ANSYS code [17] was used, ever since it is acknowledged as powerful software for both scientific studies and engineering applications. For the period of the mesh creation procedure, SOLID45 element type was used. The geometry, node locations, and the coordinate system for this element are drawn in Figure 2. SOLID45 element is used for the 3-D modeling of solid structures.

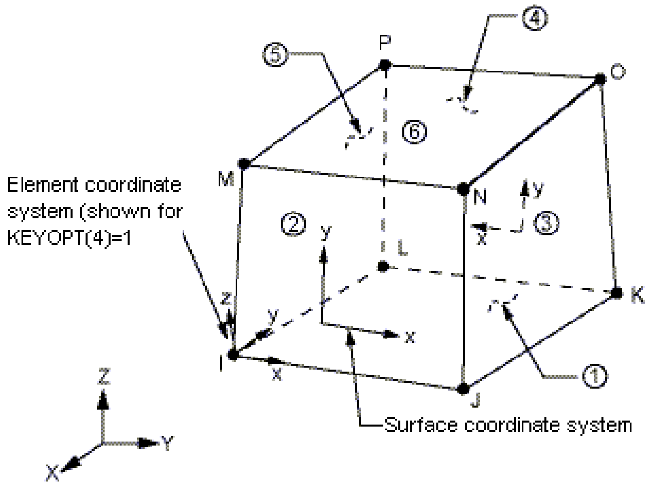


Fig. 2. SOLID45 element type [17]

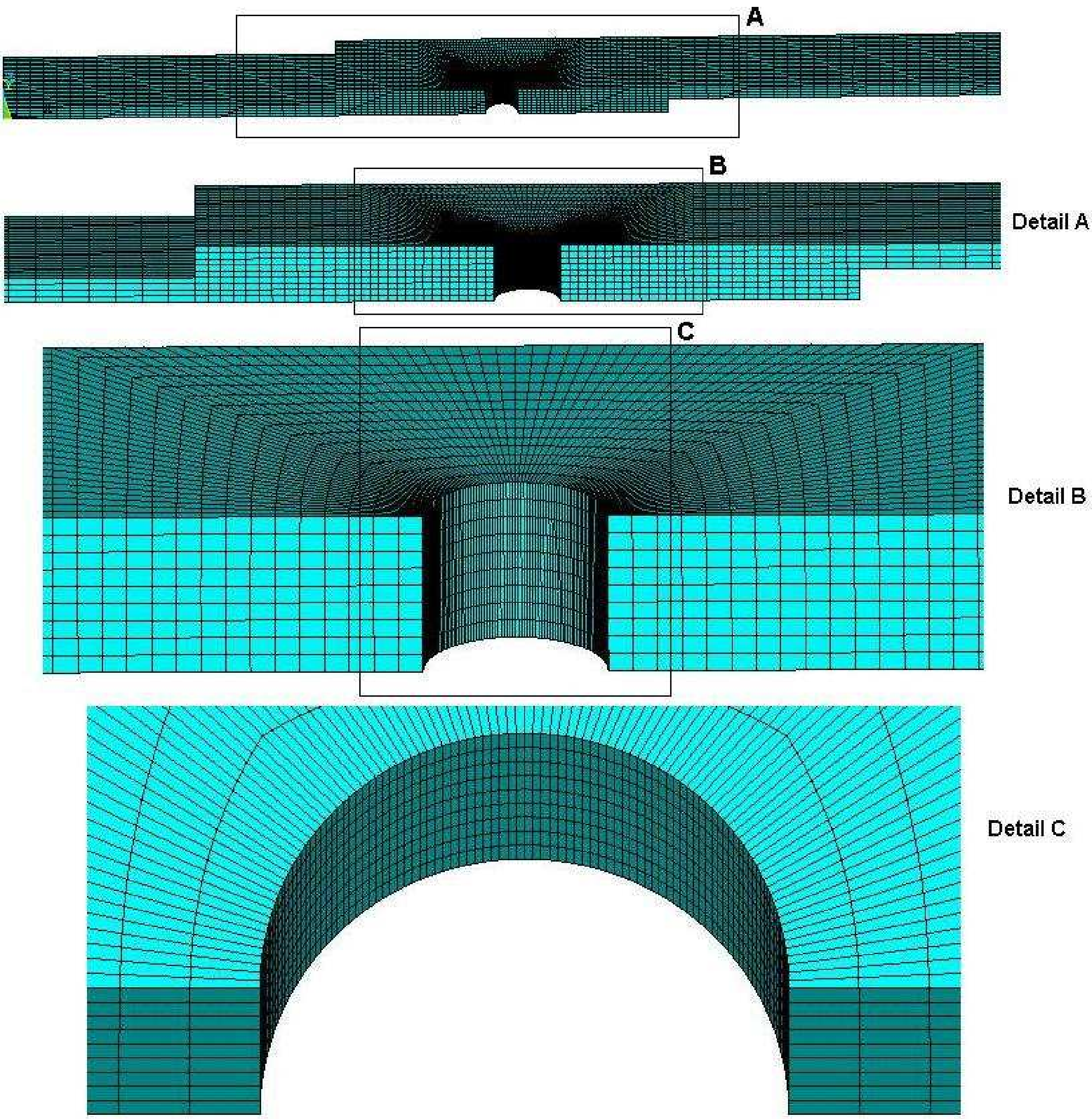
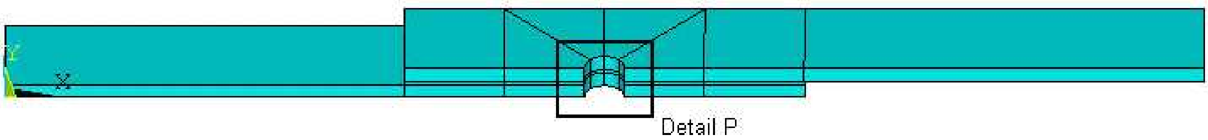
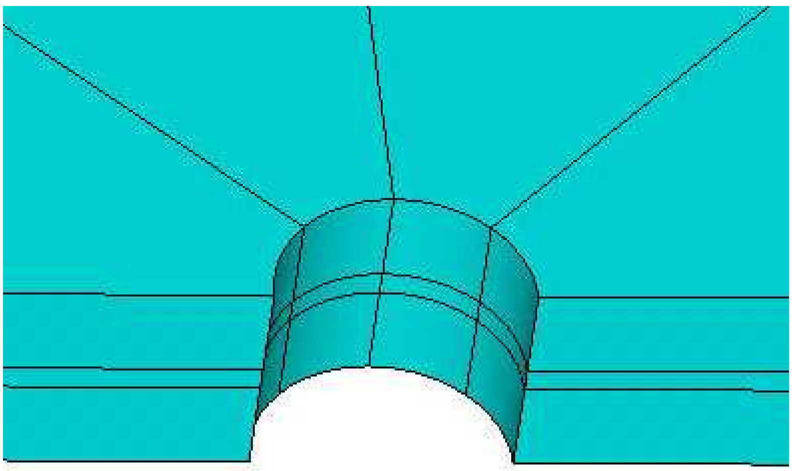


Fig. 3. FEM model of hybrid single-lap joint

The element is defined by eight nodes having 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 [17-18]. The created FEM structure of the hybrid single-lap joint is illustrated in Figure 3. The details of the mesh structure where around pin hole are shown in this figure too. As seen from this figure a good mapped mesh structure was built on the model including around pin hole area. It is accepted that mapped mesh structure is better than other types of mesh structures for a good FEM solution. Besides, a mapped mesh is limited in terms of the element shape it contains and the pattern of the mesh [17-18]. As mentioned before, any hole in structure is needed if the pin, bolt, rivet etc. are used for mechanical joint. Consequently, mesh generation process is very important around the hole zone especially due to occurrence stress concentrations at this zone. On the other hand, the creating of mapped mesh is very difficult if the model has any hole. In this study, the mapped mesh was provided successfully by the author. Moreover, the mesh concentration was made around the pin hole area and near areas as seen from in Detail C in Figure 3. 34350 elements and 42290 nodes were created in the 3D-mode later than that the meshing process. A half part of the whole hybrid joint structure was modeled owing to the symmetry of it as seen from Figure 4. This modeling advantage provided to decrease both element and node numbers and the solution time. The pinned condition was applied on the half model. For this purpose, one side of the model fixed for all directions and a pressure was



a) Half model



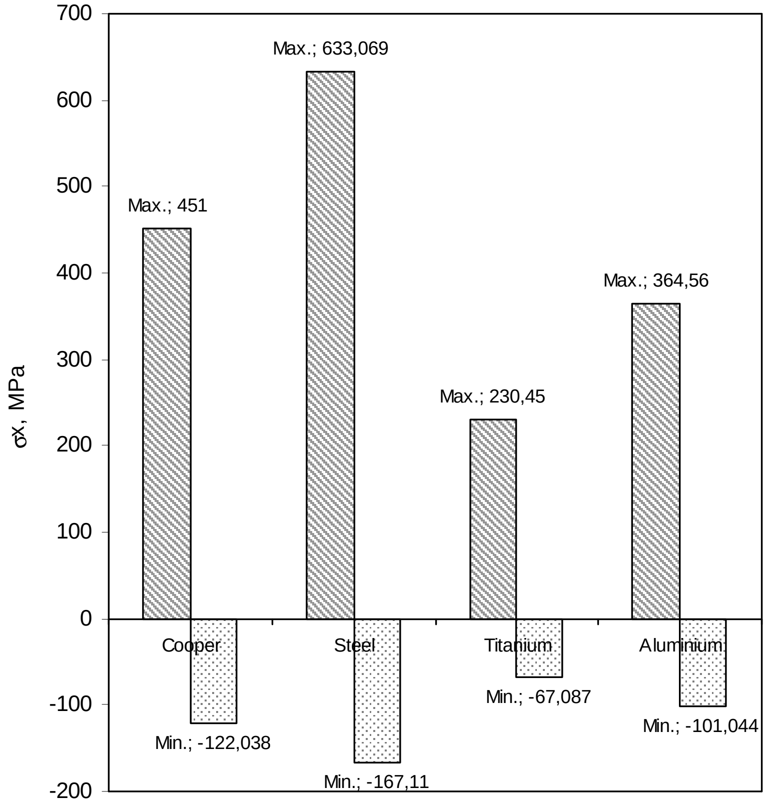
b) The view of Detail P

Fig. 4. The viewing of half model

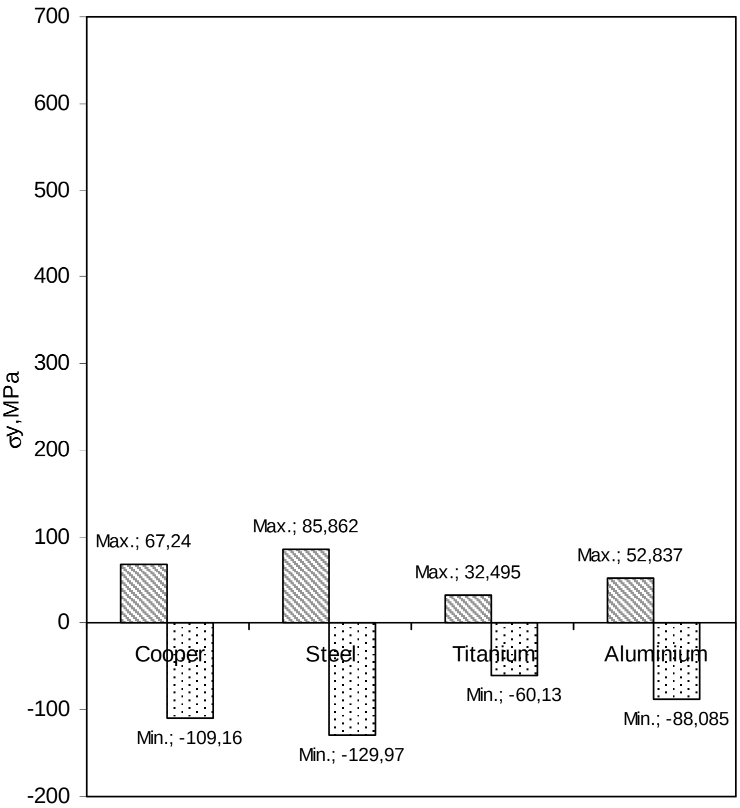
applied on other side as 10 MPa. Following, a uniform temperature load as 45 ^{o}C was performed on the half model. As a result the solution for hybrid joint was done under both thermal and tensile loads.

3. Results and Discussion

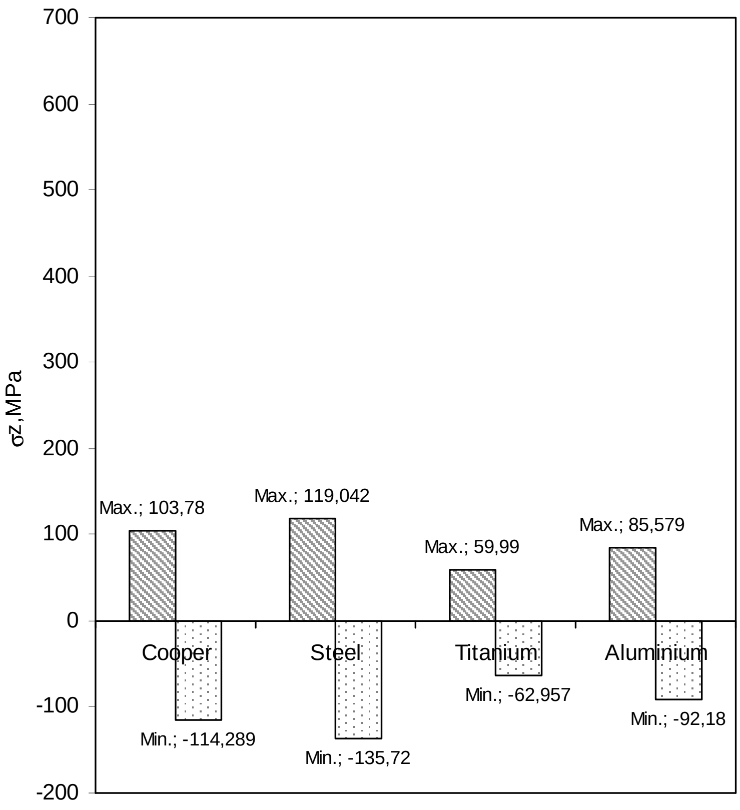
Comparison of maximum stresses for different directions is shown in Figure 5. This figure pointed out that stresses for x-direction are higher than both y and z-directions. Since the tensile load was applied through x-direction. The lowest stresses were calculated for y-direction. Moreover, tensile stresses are higher than compressive stresses for x-direction only. The differences between tensile stresses and compressive stresses for x-direction are very high for each adherent material. However, the absolute values of compressive stresses are higher than tensile stresses both y and z-directions. According to Figure 5, the lowest stresses were calculated for titanium adherents, whereas the highest values of it were computed for steel adherents. This result is also true for all directions. In other words, titanium adherent is suitable hybrid joint under same tensile loading and temperature loading because of the occurrence lowest stresses. Additionally, the highest value of tensile stress is calculated as 633.069 MPa for x-direction and steel adherents, while the uppermost value of compressive stresses is computed as 167.110 MPa for x-direction and steel adherents



a) For x-direction



b) For y-direction



c) For z-direction

Fig. 5. Comparison of maximum stresses for different directions

It is known that von Mises stresses are very important for isotropic materials. Therefore, comparison of maximum von Mises stresses for each adherent material is illustrated in Figure 6. According to this figure the highest value of von Mises stress was obtained as 575.46 MPa for steel adherent, while the lowest value was calculated as 205.96 MPa for titanium adherents. Additionally the uppermost values for other analyzed adherents are 326.29 MPa and 401.74 MPa for aluminum and copper, respectively.
Stress distribution on adhesive layer should be evaluated for adhesively bonded joints. For that reason von Mises stress distributions on adhesive layer are drawn in Figure 7. According to this figure, stresses are concentrated around the pin hole. The highest von mises is calculated as 12.74 MPa for aluminum joint, while the lowest value is computed as 6.69 MPa for titanium joint. Moreover, it is calculated as 7.00 MPa for steel joint. This means that the difference of von mises stress on the adhesive between titanium joint and steel joint is very small. This difference can be neglected. Consequently, the lowest von mises stresses are observed both titanium and steel joints. The highest value of it for copper joint is 9.48 MPa.

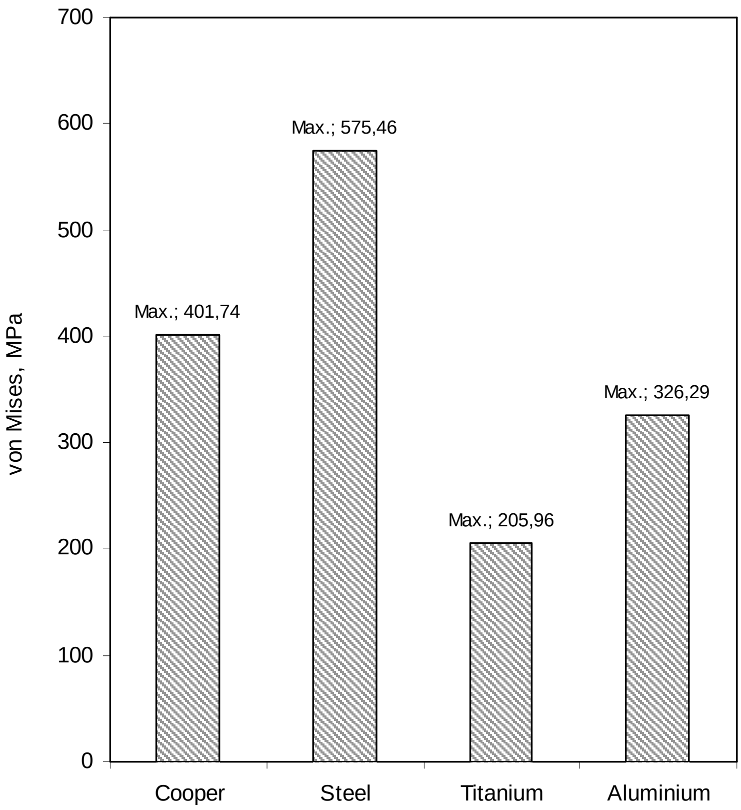


Fig. 6. Comparison of maximum von Mises stresses

As mentioned previously the higher stresses were observed for x-direction because of the applied tensile load through this direction. Stress distributions on adhesive layer for x-direction are plotted in Figure 8. It can be seen from this figure, the highest values of stresses were occurred both compressive and tensile forms around the pin hole. According to previous experimental studies [14-16], the compressive stresses can cause bearing failure and tensile stresses can create net tension failure. The occurrence of stress concentrations and form are very suitable associated with previous experimental studies on single pinned lap joints. The lowest and highest values of stresses on adhesive layer for x-direction were calculated 15.79 MPa and 4.60 MPa for aluminum and titanium joints, respectively.

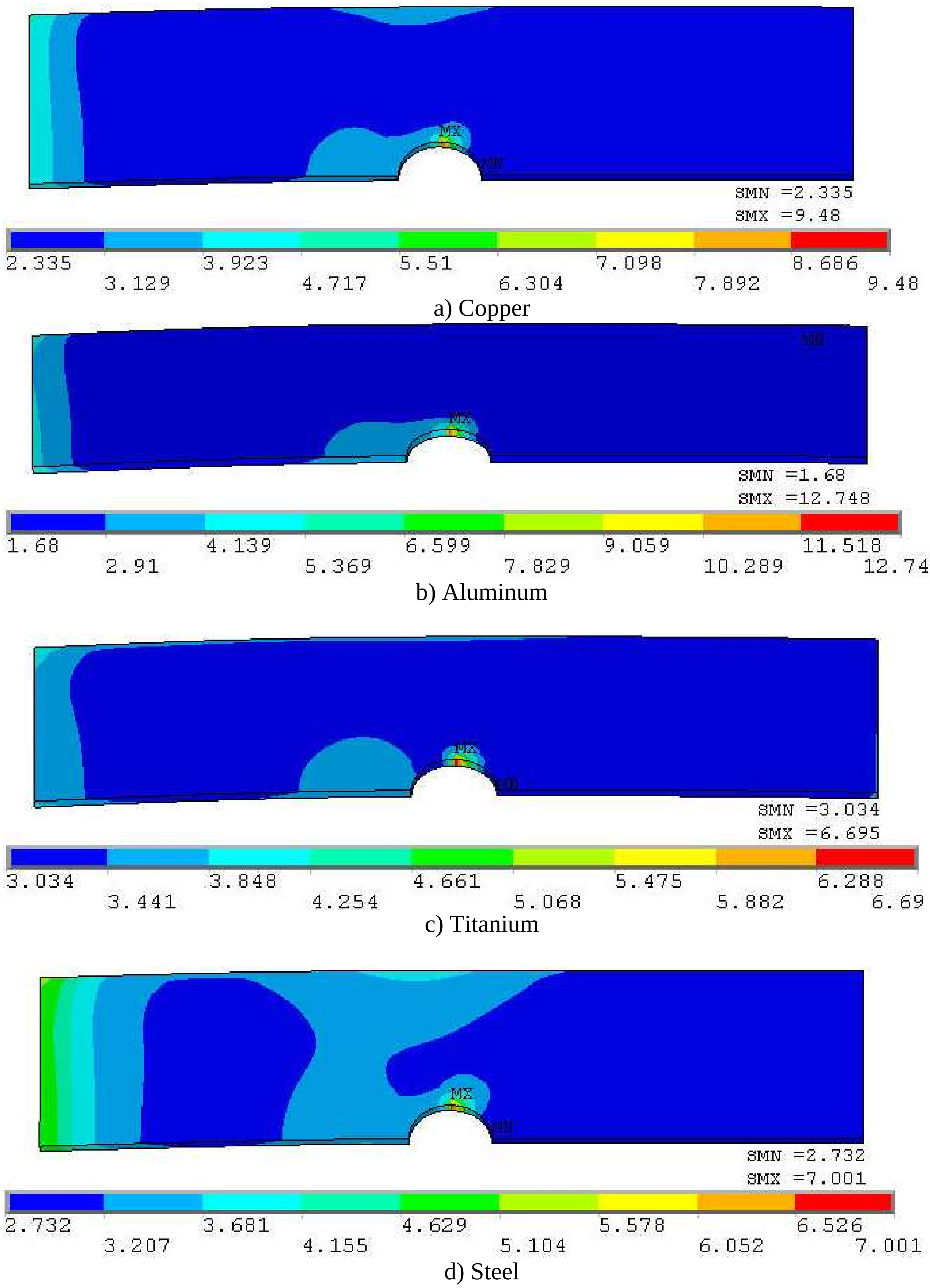
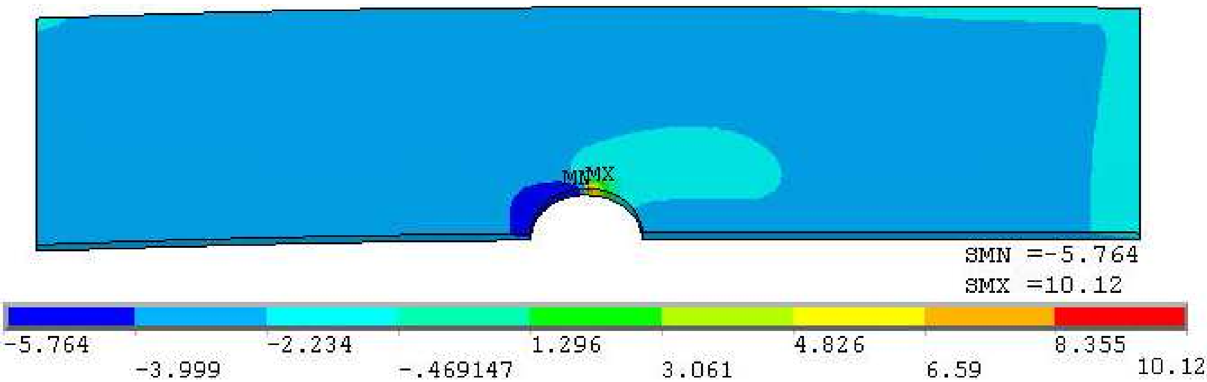
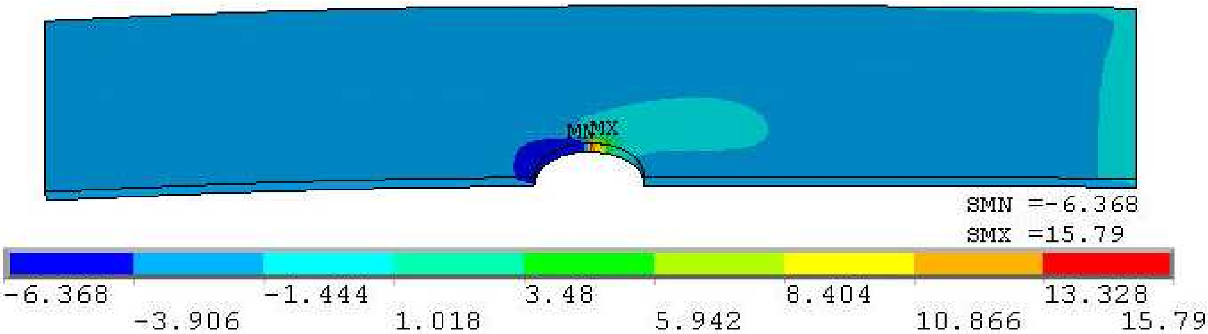


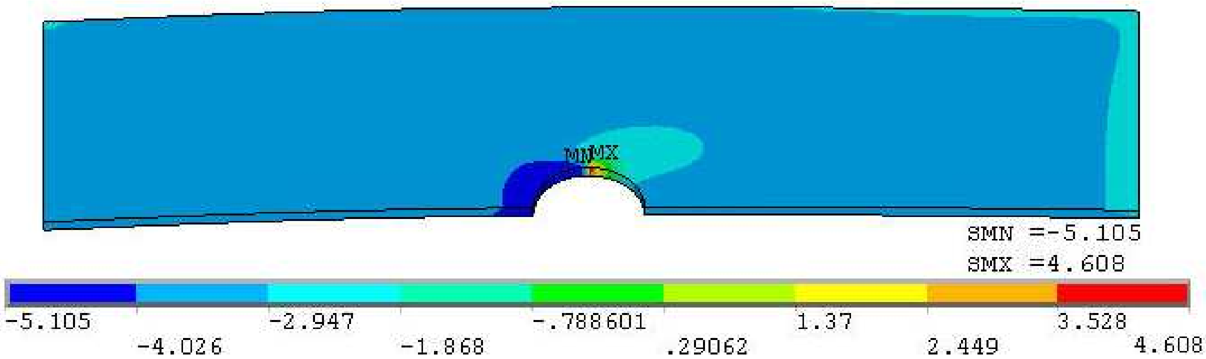
Fig. 7. von Mises stress distributions on adhesive layer (all stresses in MPa)



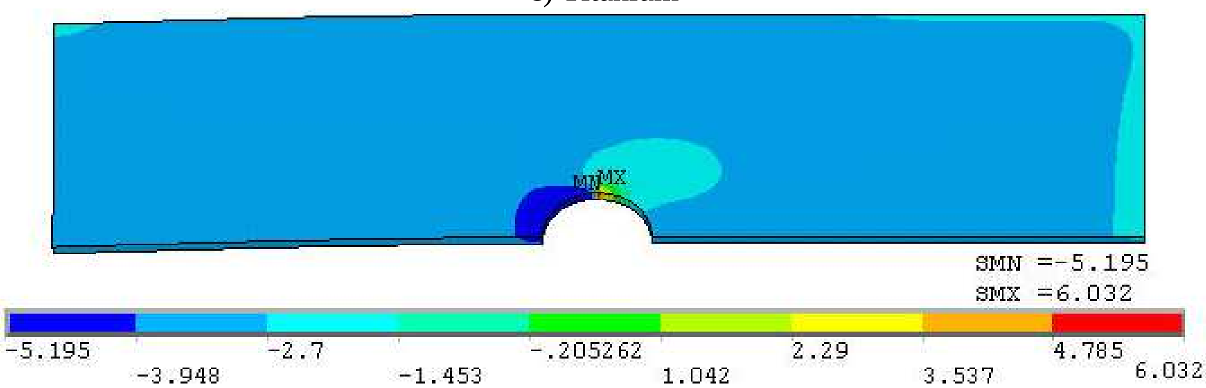
a) Copper



b) Aluminum



c) Titanium



d) Steel

Fig. 8. Stress distributions on adhesive layer for x-direction (all stresses in MPa)

4. Conclusions

In this study, a stress analysis was performed for a hybrid joint based on adhesively bonded and pinned single lap joint using 3D-FEM under both tensile load and uniform temperature load. The four different materials were also investigated and compared with each other. According to analyses results some important remarks can be concluded as; thermal and mechanical mismatches of the metal adherents and epoxy adhesive caused high stress concentrations. Stresses were concentrated around pin hole area both adherents and adhesive, due to the existence of the pin hole. The highest stresses were calculated for x-direction which was tensile load direction. The stresses on steel adherents are higher that other metal adherents, although the highest stress on adhesive layer were observed when aluminum adherents were used. It is known that tensile and compressive stresses may cause net-tension bearing failures, respectively. As a result occurred stress distribution on hybrid joint is suitable with previous experimental studies.

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