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Effects of Using Different Metal Materials on Stresses in Metal-Composite Hybrid Joints

Faruk Sen[1,*] and Kemal Aldaş[1]

[1] *Aksaray Üniversitesi, Makine Mühendisliği Bölümü, 68200 Aksaray, Türkiye*
[*] *Corresponding author: faruk.sen@deu.edu.tr*

Özet. Bu çalışmanın amacı, metal-kompozit bağlantılarda farklı malzemelerden yapılmış metal plaka kullanımının gerilmeler üzerine etkisinin incelenmesidir. Kompozit bir plakanın farklı metal plakalara yapıştırıldığı ve pim bağlantısı yapıldığı varsayılmıştır. Metal plakalar alüminyum, çelik, bakır ve titanyumdur. Gerçek bir problem oluşturmak için üç boyutlu modeller oluşturulmuştur. Karma bağlantı üzerine hem çekme yükü hem de uniform sıcaklık yükü birlikte uygulanmıştır. Gerilme probleminin çözümü için sonlu elemanlar metodu (FEM) seçilmiştir, çünkü bu yöntem son zamanlarda birçok mühendislik probleminin çözümü için çok uygun olmaktadır. Elde edilen sonuçlara göre, kompozit plakanın, metal plakanın ve epoksi yapıştırıcının farklı malzeme özelliklerinden dolayı çok yüksek değerlerde gerilmeler meydana gelmiştir. Gerilmeler özellikle pim deliği çevresinde yoğunlaşmıştır. En büyük gerilmeler çelik-kompozit bağlantılarda oluştuğu gözlemlenirken, en düşük gerilmeler titanyum-kompozit bağlantılar için elde edilmiştir.

Anahtar Kelimeler. Gerilme analizi, kompozit bağlantı, karma bağlantı, FEM, ANSYS.

Abstract. The aim of this study is to investigate effects on stresses of using different adherent material in metal-composite hybrid joints. It was assumed that a composite plate was adhesively bonded and pinned to different metal plates. The metal plates were aluminum, steel, copper and titanium. For providing a real problem, three-dimensional finite element models were created. Tensile loads at uniform temperature were tested on the modeled hybrid joints. In order to analyze the stresses of the problem, the finite element method (FEM) was chosen, since this method has proved suitable for solving many engineering problems recently. According to the results, high stresses occurred because of the different material properties of the composite adherent, metal adherent and epoxy adhesive. Stresses were concentrated around the pin hole zone especially. The higher stresses were observed for the steel-composite joint, whereas the lower stresses were obtained in the titanium-composite joint.

Keywords. Stress analysis, composite joint, hybrid joint, FEM, ANSYS.

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1. Introduction

The structural materials most frequently used in design can be categorized in four primary groups: metals, polymers, composites, and ceramics. Composite materials have been in existence for many centuries. No record exists as to when people first started using composites. In the most general of terms, a composite is a material that consists of two or more constituent materials or phases [1]. There has been a dramatic increase in the use of composite materials in all types of engineering structures, for example aerospace, automotive, and underwater structures, as well as in medical prosthetic devices, electronic circuit boards, and sports equipment. Therefore, many journals published in the last two decades attest to the fact that there has been a major effort to develop composite material systems, and analyze and design structural components made from composite materials [2]. That's why mechanically fastened joints are frequently used in composite structures [3]. They present a number of characteristics that make them well suited for joining composite laminates. For instance, mechanically fastened joints are relatively low-cost to produce and can be disassembled [4]. In the meantime, adhesive bonding technology is frequently used in almost all the industries fields of the world and this is mainly due to its high strength-weight ratio, low cost and high efficiency nowadays [5].

According to the authors, based on the result of a literature review, lots of researchers have studied either adhesively bonded or pinned single lap joints, double lap joints, etc. However, the analysis of hybrid joints constructed from both adhesively bonded and pinned single lap joints for metal and composite sheets under both thermal loads and tensile loads has not been investigated so far. A transient thermal and thermal stress analysis of an adhesively bonded and laser-spot welded joint was performed based on a thermal model developed for the laser-spot welding of multi-layered sheets using a pulsed Nd:YAG laser. The material non-linear properties of adhesive and metal sheets were considered with the non-linear finite element method in the thermal stress analysis [6]. Sen and Aldas [7] created a thermoplastic composite disc model with central hole using FEM. Linear temperature loadings were applied to the disc for observing thermal stress distribution on it. It was observed that thermal stresses occurred because of the material nonlinearity of the thermoplastic composite. Sen [8] studied the thermal stresses based on uniform temperature loading in a thermoplastic composite plate with a circular hole in its center. The elastic-plastic stress analysis was carried out using FEM. Silva and Adams [9] tested a mixed adhesive joint. Experiments were performed for titanium/titanium and titanium/composite double lap joints. According to the results they obtained, 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. In another study, Silva and Adams [10] analyzed adhesive joints with dual adhesives to be used over a wide temperature range theoretically. A numerical analysis was applied using FEM to determine the stress distribution in a mixed adhesive joint. According to numerical analysis results, for a joint with dissimilar adherents, the combination of two adhesives gives a better performance over the temperature range considered than the use of a high-temperature adhesive alone.

Sen and Sayman [11] studied the effects of the geometrical parameters such as the edge distance-to-hole diameter ratio (E/D) and plate width-to-hole diameter ratio (W/D) on the failure response of bolted-joint aluminum glass-epoxy sandwich composite plates. The failure modes and bearing strengths were determined for different applied preload moments, experimentally. Sayman *et al.* [12] determined the effects of a number of preload moments on the bearing strength in fiber reinforced laminated composite single pinned/bolted-joints. The laminated plates were initially tested experimentally and then bearing strengths were calculated with maximum failure loads. Pakdil *et al.* [13] investigated the effect of preload moments on the failure response of glass-epoxy laminated composite single bolted/pinned joints with hole clearance. To determine the effects of fastener geometry and the stacking sequence of laminated plates on the bearing strength and failure mode, parametric analysis was performed experimentally.

In this study, a stress analysis was done for pinned and adhesively bonded joints of different metal sheets with a composite sheet. For this purpose, three dimensional finite element models were designed to determine stresses based on both tensile loading and temperature loading.

2. Problem Statement

A hybrid joint was considered as seen in Figure 1. The lower adherent is assumed to be aluminum, steel, copper or titanium, whereas the upper adherent is modeled as an aluminum metal matrix composite. The metal sheet and aluminum sheet were bonded together with both epoxy adhesive and a single pin. Consequently, a hybrid joint was designed. The epoxy resin was used in many real applications owing to its good bonding properties.

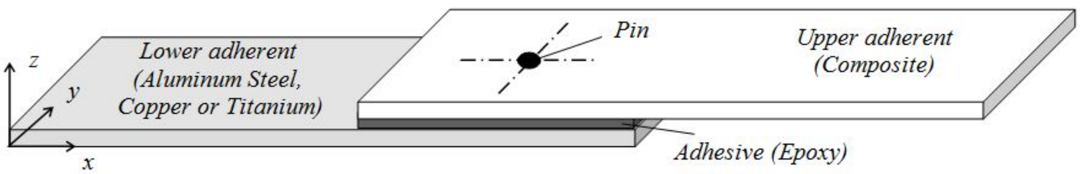


FIGURE 1. Illustration of the hybrid joint.

Additionally, it is known that epoxies have an excellent combination of mechanical properties, corrosion resistance, dimensional stability, good adhesion, relatively low cost and good electrical properties [14]. During the modeling process, the thickness of both metal adherents and the composite adherent were selected as 2 mm, while the thickness of the epoxy adhesive was 0.2 mm. The lengths of each of the adherents and the adhesive were 100 mm and 50 mm, respectively. In other words, the length of the bonding surface of the adhesive with the adherents was 50 mm. The hybrid joint problem was considered as three dimensional, so the width of both the adherents and adhesive was 25 mm. In addition, the pin diameter was preferred as 5 mm. After the modeling process, both the edge distance-to-hole diameter ratio (E/D) and the plate width-to-hole diameter ratios (W/D) were modeled as 5 for the single pinned structure. These ratios were suggested from previous experimental studies for a good single pinned joint [15, 16]. The material properties of the metal adherents and epoxy adhesive are given in Table 1 [6, 14], whereas the mechanical properties of the aluminum metal matrix composite are presented in Table 2 [17]. It is assumed that the material properties were not changed, because the analyses were done in a uniform temperature, and they were not carried out at higher temperatures.

TABLE 1. Material properties of metal sheets and epoxy adhesive [6,14].

Property	**Copper**	**Aluminum**	**Steel**	**Titanium**	**Epoxy**
ρ (kg/m^3)	8940	2707	7780	4570	1264
c_p (J/kgK)	386	896	460	523	1046
k (W/mk)	398	204	80.3	20.4	0.179
E (GPa)	110	66	207	116	3.3
ν	0.34	0.33	0.29	0.34	0.30
α (μm/m°C)	17.0	23.6	12.6	8.9	43.3

Table 2. Mechanical properties of aluminum metal matrix composite material [17].

E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	ν_{12}	α_1 (1/°C)	α_2 (1/°C)
85000	74000	30000	0,29	$18,5 \times 10^{-6}$	21×10^{-6}

For the solution, the finite element method (FEM) was preferred to determine stresses in the hybrid joint. Therefore, three dimensional FEM models were created in this work. Most researchers used 2D FEM models rather than 3D FEM models in previous studies, since the 2D models are computationally efficient. However, the results from 2D models can be deceptive, particularly for thermal loading conditions [18]. Both the modeling and solution processes were done using ANSYS [19] software. It is accepted as powerful FEM code for both scientific studies and commercial applications. During the mesh structure, the SOLID45 element type was chosen. The geometry, node locations, and the coordinate system of this element are plotted in Figure 2 [19]. The SOLID45 element is used for the 3-D modeling of solid structures. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions [19].

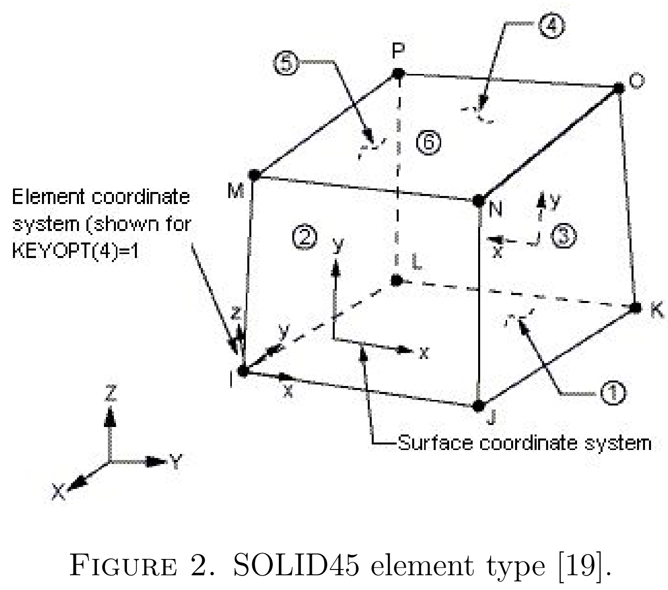


Figure 2. SOLID45 element type [19].

FEM structure with details of the hybrid joint is shown in Figure 3. This figure illustrates the fact that a good mapped mesh structure was developed on the hybrid model together with the pin hole zone and adhesive layer.

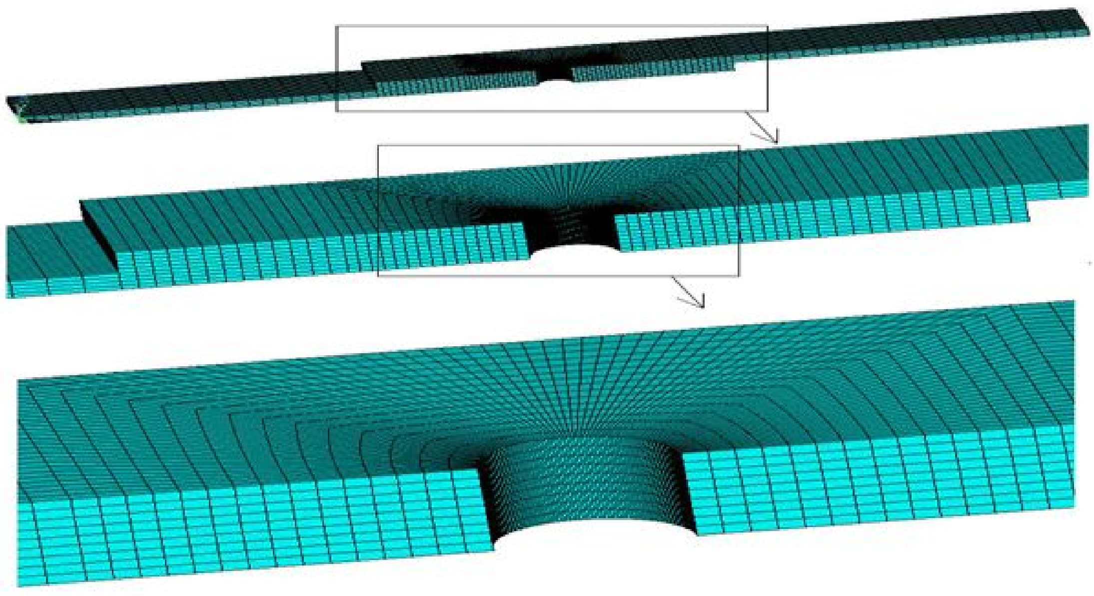
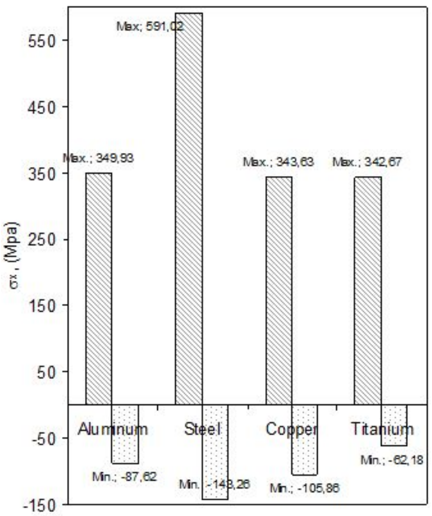


FIGURE 3. FEM structure of hybrid joint with details.

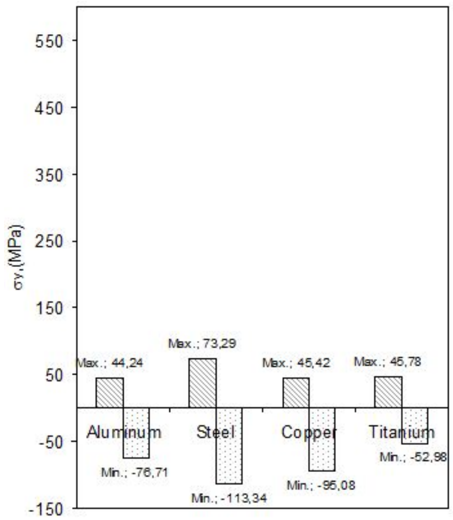
In other words, a mapped mesh structure was built on the model as this has some advantages compared to the free mesh, for a superior FEM solution. After the mesh generation process, 34350 elements and 42290 nodes were created in the 3D-model. Because of the symmetry of the hybrid joint, half of the whole hybrid joint was modeled as seen in Figure 3. As a result, the element and node numbers were decreased. One side of the model was fixed for all directions. Later, two different loadings were applied on the model, namely −15 MPa pressure at a 42.5°C uniform temperature. Thus, both mechanical loading and thermal loading were applied to the model, since in practice adhesive joints can suffer thermal loads as well as structural loads. These thermal loads play an important role in the strength of the adhesively bonded joint [20].

3. Results and Discussion

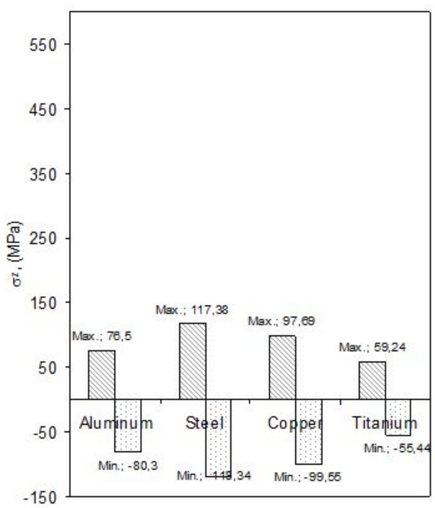
The maximum normal stresses for all directions on the hybrid joint related to the adherent material are shown in Figure 4. The stresses for x-direction (σ_x) are higher than both y and z-directions. The reason of this is tensile loading through x-direction. The highest stresses are calculated for the steel-composite joint for all directions.



(a) For x-direction



(b) For y-direction

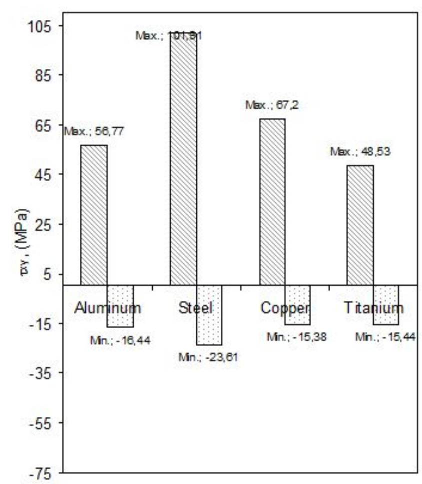


(c) For z-direction

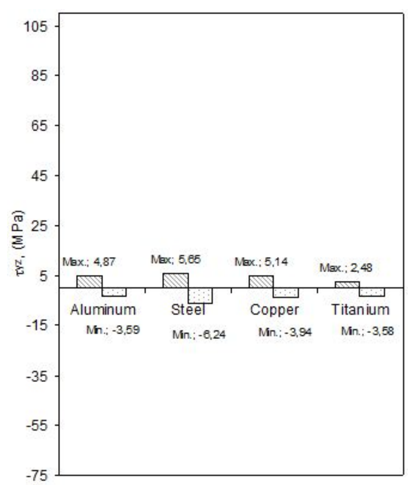
FIGURE 4. Maximum normal stresses on the hybrid joint.

The uppermost value stresses are computed as 591.02 MPa tensile and −143.26 MPa compressive forms for x-direction and steel-composite hybrid joints. It is seen that stresses for z-direction are higher than y-direction. If the analysis is done in two dimensions, the stresses for z-direction cannot be calculated. But they are very important for a real hybrid joint. According to Figure 4, the lowest normal stresses are obtained for the titanium-composite hybrid joint. In other words, the suitable adherent material which is analyzed in this study for an aluminum metal matrix composite plate can be said to be titanium because of the lowest stress concentrations.

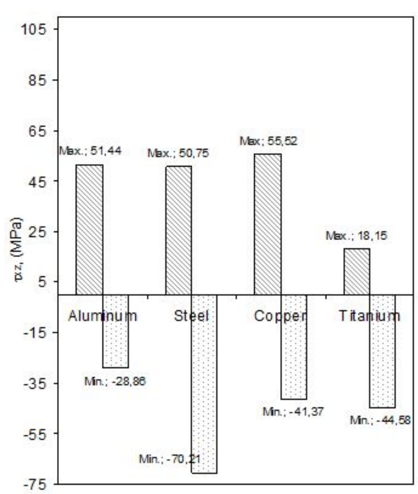
Maximum values of shear stresses on the hybrid joint are given in Figure 5. Shear stresses for the steel-composite joint are also higher that other material combinations like normal stresses. The highest value of tensile shear stress is 101.91 MPa for the steel-composite combination as τ_{xy}, whereas the uppermost value of compressive shear stress is -70.21 MPa for steel-composite combination as τ_{xy}. The lowest values of shear stresses are also calculated for the titanium-composite combination except τ_{xy}.



(a)



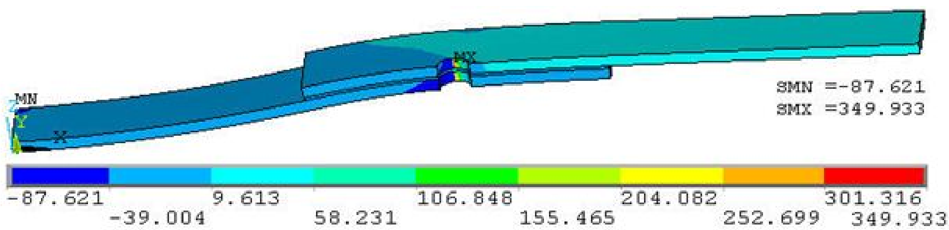
(b)



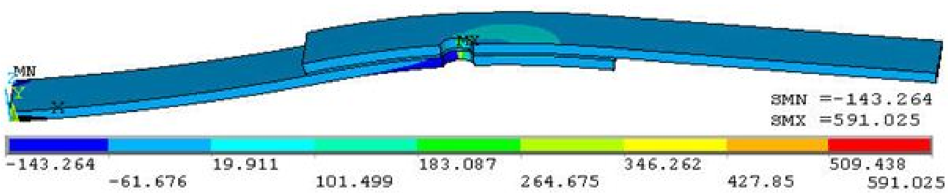
(c)

FIGURE 5. Maximum shear stresses on the hybrid joint.

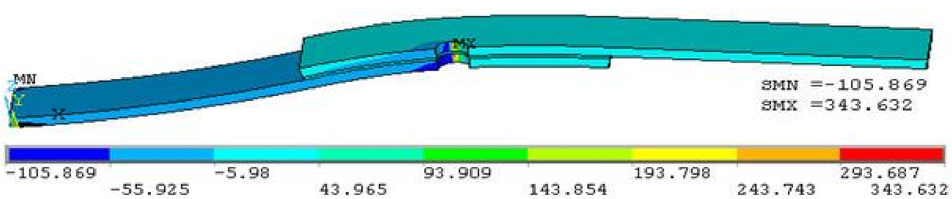
The ANSYS software provides color contours for a good evaluation of the results. Stress distributions on the whole joint for x-direction are plotted in Figure 6. It is clearly seen that the deformation shape of the joint is certainly affected by the material combination. Additionally, the magnitudes of the stresses and spreading on the joint change in relation to the material combination. Figure 6 points out that the stresses are concentrated around the pin hole. It can be seen that the uppermost value of normal stresses for x-direction is calculated for the steel-composite system.



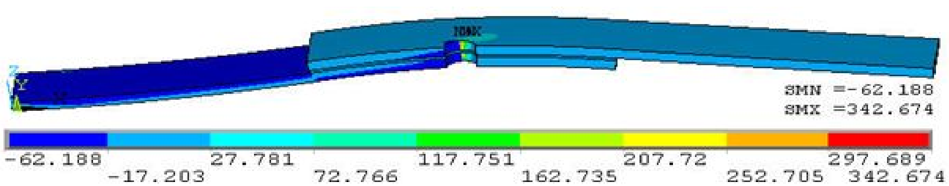
(a) Aluminum-Composite



(b) Steel-Composite



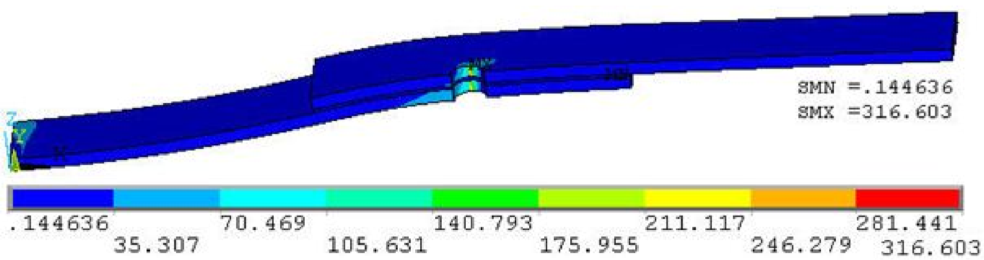
(c) Copper-Composite



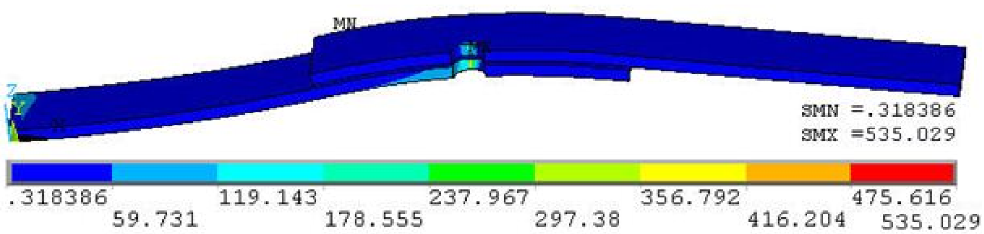
(d) Titanium-Composite

Figure 6. Stress distributions on whole joint for x-direction (all stresses in MPa).

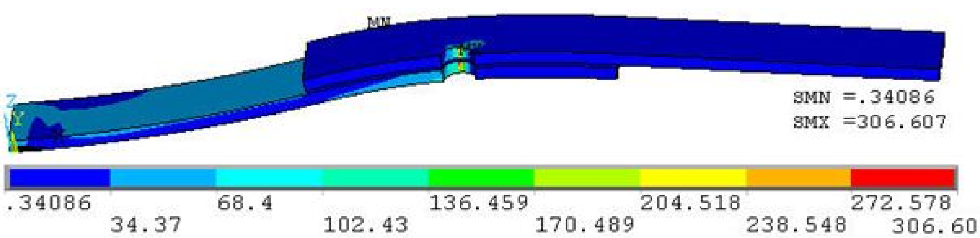
This result is also suitable for both tensile and compressive stresses. The von Mises stress distributions on the whole joint are drawn in Figure 7. According to this figure, the highest value of von Mises stresses is calculated as 535.029 MPa for steel-composite joint.



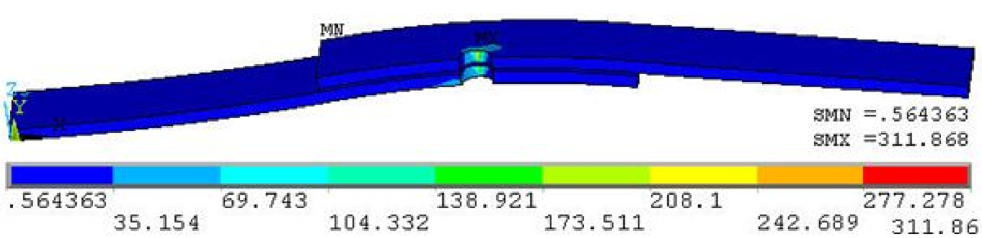
(a) Aluminum-Composite



(b) Steel-Composite



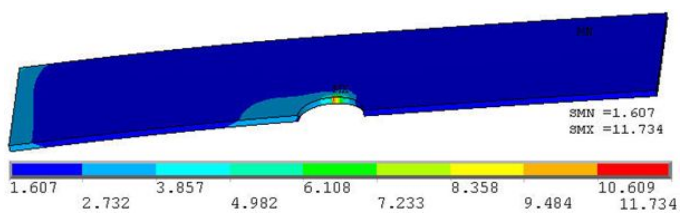
(c) Copper-Composite



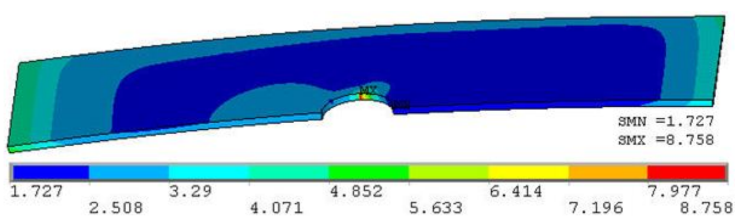
(d) Titanium-Composite

FIGURE 7. von Mises stress distributions on whole joint (all stresses in MPa).

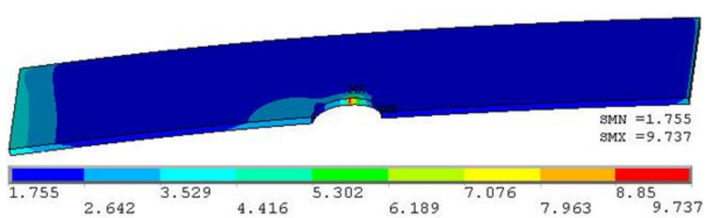
Because of the importance evaluating of stresses in the adhesively bonded joint, von Mises stress distributions on the adhesive layer are plotted in Figure 8. Firstly, the highest values of von Mises stresses are concentrated around pin hole. This zone is seen to be very critical due to fact that failure may occur. Secondly, the highest value of von Mises stresses is computed for the aluminum-composite joint as 11.734 MPA. In other words, the aluminum-composite joint causes higher stresses on the adhesive layer.



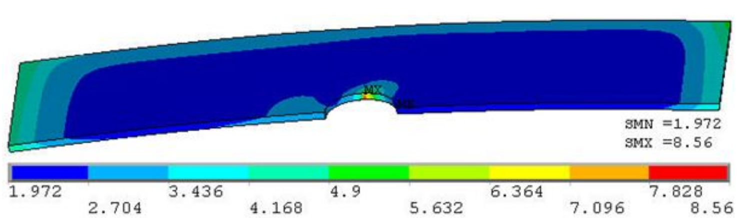
(a) Aluminum-Composite



(b) Steel-Composite



(c) Copper-Composite



(d) Titanium-Composite

FIGURE 8. von Mises stress distributions on adhesive layer (all stresses in MPa).

The main reason for this can be seen from Table 1. The thermal expansion coefficient of the aluminum plate is higher than in other materials and the value is very close to the aluminum metal matrix composite. After the thermal loading, the aluminum and composite plates expand very close to each other compared with the other plates. Consequently, the higher stresses on the adhesive layer occur with the aluminum-composite system.

4. Conclusion

In this study, a numerical stress analysis was carried out for a hybrid joint created using both adhesive and a pin by 3D-FEM. The main purpose was investigating the effect of using different metal plates, such as aluminum, steel, titanium and copper, to bond an aluminum metal matrix composite plate. Results pointed out that the higher stresses on the hybrid joint occurred for the steel-composite system. The lowest stresses were also calculated for the titanium-composite joint. This result was also valid under both normal and shear stresses. The higher stresses on the adhesive were calculated for the aluminum-composite system. As expected, the stresses were concentrated around the pin hole. This zone were seen as very critical because any failure on the joint would start here.

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