The effect of adhesive thickness on spot weld-bonded joints of dissimilar materials using finite element model

Essam A. Al-Bahkali
Department of Mechanical Engineering
College of Engineering
King Saud University
P.O.Box 800, Riyadh 11421, Saudi Arabia
ebahkali@ksu.edu.sa

ABSTRACT
In present work, the bonded and spot weld-bonded of dissimilar materials joints for three dimensional models using the finite element technique were studied for different adhesive thicknesses. The results show that the stresses in adhesive bonded joints are concentrated at the ends of the overlapped area. When the spot-welding is combined with the adhesive bonding, the stresses are concentrated at the adhesive bond ends and at both ends of the weld nugget. The results show also that the stresses are more concentrated towards the material of the lowest melting point. Changing the thickness of the adhesive layer for various dissimilar material models give us the optimal thickness for each case that one can use in designing lap joints of two dissimilar materials. The results in general show that the thinner the adhesive is, the higher is the peak stresses developed in the weld-bonded joint.

Keywords: Adhesive thickness, Spot Weld, dissimilar material, Finite Element Model

1. INTRODUCTION

Resistance Spot Welding (RSW) has been used for many years as a sheet metal joining process in automotive bodies, aerospace, and other industries applications. It has been widely used because of it is cost effective and easy to operate.

Weld-bonded is a combination of resistance spot welding and adhesive bonding, which has gathered wide acceptance as an effective joining process for significant improvement in static, dynamic and impact toughness properties of sheet metal joints. It also improves the corrosion and noise resistance as well as stiffness of the joint, over those observed in case of conventional resistance spot welding.

In order to reach an optimum welding quality of a spot welded or a weld-bonded joints, different calibration trials have to be conducted to setup the optimum welding parameters, i.e. welding current, electrode force, and welding time [1,2]. In predicting stress distribution, stress concentration and failure modes of a weld-bonded or a spot welded nugget, a finite element modeling does an excellent job in this regard. Boone [3] applied some testing techniques for qualification of the use of adhesives in hybrid connections. He characterized the performance of the adhesive for varying bondline thickness and varying surface preparations.

The subject of weld-bonding of dissimilar materials has been of interest to researchers for long time to study the feasibility of joining two different materials in an efficient and cost-effective way. Given the success of the thermoplastic resistance welding process, the possibility of using the fusion bonding approach to join dissimilar materials was considered. In particular, the joining of light metal becomes more and more common in aerospace and automotive industries and it is felt to hold potential for application of resistance welding. The advantages of resistance welding process include typically short process times and heat focused specifically at the material interfaces. This process is very effective economical since no secondary materials are needed. Resistance welding can easily be automated and in most cases only assistants or robots are needed to supply the material. Two most important parameters that have the largest effect on the geometry and quality of the spot-weld nugget are the welding current and welding time. The effective weld-bonded parameters of stainless steel and the optimum thickness of adhesive bonding also have been reported [4].

Finite element modeling has been widely used in modeling the resistance spot welding and weld-bonded. This is important because it provides the necessary physical insight about the behavior of spot-welded joints, predictive tasks such as design; analysis and evaluation of spot-welded structures. Al-Samhan and Darwish [5] studied weld-bonded joint using two dimensional finite element models. They found in their studied that the strength of weld-bonded joints having square or spew fillet adhesive layer. They also demonstrated the major principle stress predicted in joints have spew fillet adhesive layer is lower than that predicated in joints having adhesive layer with square edges. Darwish [6] analyzed spot-welded of dissimilar material joints using also the finite element method. He showed that the stresses are more concentrated towards the member that has the lowest melting point of the joint. He also used an adhesive layer in conjunction with the spot weld nugget resulted in eliminating the stress concentration and strength ending dissimilar material joints.

Modeling by finite element method will not reach the optimal approximation of mechanical properties unless the plastic properties of the specimen have been taken into consideration [7]. Sometimes, it is important to study the microstructure and mechanical properties at nugget and heat affected zone caused by welding process because the plastic properties of the nugget and heat affected zone are different from the base metal such as in steel and brass [8].

The aim of the present work is to study the effect of changing the adhesive thicknesses on the stresses distribution in the overlapped joint for bonded and spot weld-bonded of dissimilar materials joints using finite element techniques.

2. FINITE ELEMENT MODEL

2.1 GEOMETRY

The art of the finite element analysis lies in the representation of a real mechanical structure and its loading by a mathematical model which then can be analyzed. An accurate and efficient idealization is trying to make the model as similar as possible to the real structure from the geometric and loading point of view. Two finite elements models were considered in the present work. The considered models are a single lap bonded model (bonded at overlap area), and a single lap weld-bonded model (spot weld and bonded at overlap area). Figure 1 shows the configuration, dimensions, constraints and loading conditions for both bonded and weld-bonded models. The total length of the models is 175 mm and each strip has a thickness of 1.5 mm.

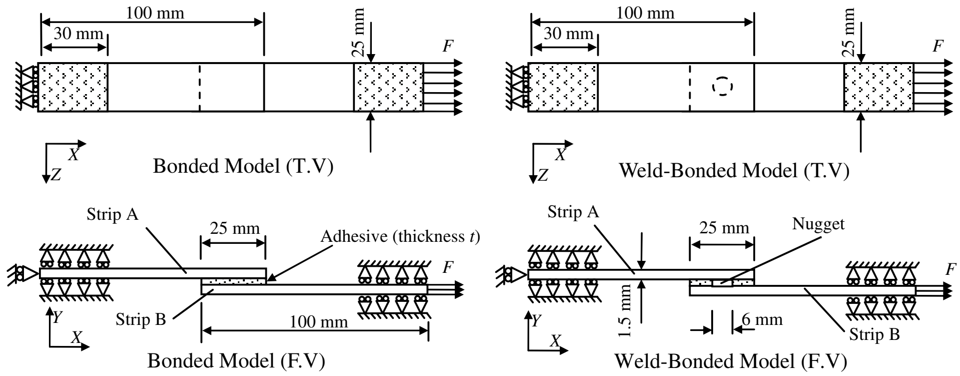

Figure 1 Bonded and weld-bonded models.

The following assumptions were considered throughout the idealization process: The problem is three-dimensional FE model and because of symmetry half of the model will be considered to save computation time. The adhesive layer is isotropic and there is no adhesive layer in a zone 1 mm around the circumference of the weld nugget and the depth of the indentation assumed to be 0.1 mm for both strips [9]. This indentation caused by the electrode of the spot weld machine. A small applied load of 500 N to study the stress distribution at the overlap area.

2.2 MODEL ANALYSIS

A standard elastic finite element formulation is used. The type of simulation analysis would be carried out through this model is based on a structural engineering mechanics theories that depend on the force method. The solution would be achieved when solving a system of equations on the form:

$$\boldsymbol{KQ} = \boldsymbol{F} \tag{1}$$

Where $\boldsymbol{K}$ represents the stiffness matrix coefficient, $\boldsymbol{Q}$ is the global nodal displacement vector and $\boldsymbol{F}$ is the nodal forces vector.

The mechanical boundary conditions associated with finite element model can be summarized as the following:

On the edges X = 0, a clamped boundary conditions are imposed

$$u_x\Big|_{X=0} = u_y\Big|_{X=0} = u_z\Big|_{X=0} = 0 \tag{2}$$

Whereas both strips are subject to a fixed y-direction boundary condition at the beginning 30 mm segment of strip A (X = 0 to 30 mm) and at the end 30mm segment of strip B (X = 145 to 175 mm).

$$u_y\Big|_{X=0-30} = u_y\Big|_{X=145-175} = 0 \tag{3}$$

In the overlap area a tie constraints are imposed between components of welded joints; i.e. strip A, strip B, adhesive layer, and weld nugget. By doing so, the translational and rotational boundary conditions of tied surfaces are made identical, regardless of the way these parts are meshed.

The model is subjected to a constant tensile force of 500 N at the right edges of strip B.

$$F_x\big|_{X=175} = 500N \quad (4)$$

2.3 FINITE ELEMENT MESH

The finite element computation was carried out using ABAQUS software [10]. The finite-element meshes of these models are generated using eight-node-linear brick reduced integration elements. Figures 2 and 3 show the FE meshes for both bonded and weld-Bonded models respectively. The mesh of bonded model is straight forward and simpler because of the absence of spot welding, which leads to only the overlap area need to be divided into a finer mesh. However, the weld-bonded model needs additional finer mesh on the edges of spot weld and adhesive layer to avoid error analysis. The numbers of elements for the different models that are going to be used in current study, after several refined meshes to insure the conversion of FE results, are given in Table 1.

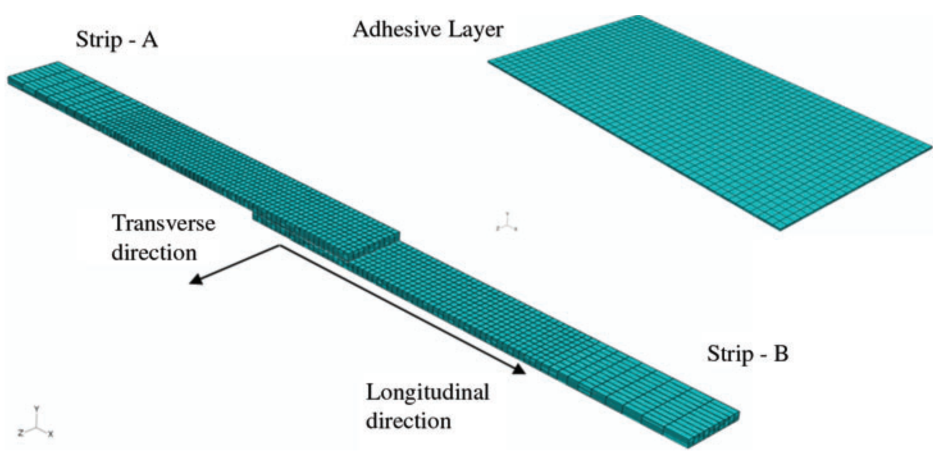

Figure 2 The finite element mesh for bonded model.

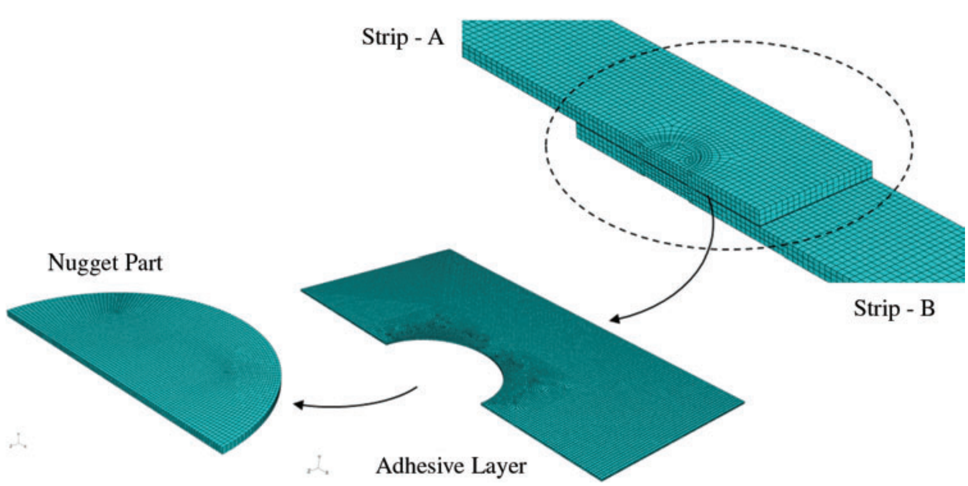

Figure 3 Partial of the finite element mesh for weld-bonded model.

Table 1 Number of elements used in different models

Model	Bonded model	Weld-bonded model
Strip A	2700	6426
Strip B	2700	6426
Adhesive Layer	2500	20034
Nugget	—	16128

3. RESULTS

In this section, the results of ABAQUS finite element simulations for bonded and weld-bonded dissimilar joints will be examined for different adhesive thickness. Normal, shear, and Von Mises stresses were analyzed along the longitudinal directions. These stresses were developed along the mid-layer of overlapped area. The combination dissimilar materials that are going to be used in the analysis are Steel-Aluminum, Steel-Brass and Brass-Aluminum joints. Their material properties used throughout the present work are given in Table 2. These properties where obtained in the lab.

Table 2 Material properties of strip and adhesive

Material	Adhesive	Steel	Aluminum	Brass
Young's Modulus E(GPa)	2.2	210.9	64.03	100
Possion's Ratio ν	0.38	0.30	0.35	0.34
Yield Stress S_y(MPa)	32	337.4	111.5	244.5
Ultimate Stress S_{ut}(MPa)	39	409.7	116.3	407.5

Five adhesive thicknesses are used in the analysis. These thicknesses are 0.12, 0.42, 0.72, 1.02, and 1.32 mm respectively. And for easy representation it will be written as $t_1 = 0.12$mm, $t_2 = 3.5t_1$, $t_3 = 6t_1$, $t_4 = 8.5t_1$, and $t_5 = 11t_1$. The selections of these thicknesses are within the range of automobile and aircraft industries in which the thicknesses are less than 1.524 mm [3].

3.1 STRESSES DEVELOPED IN STEEL-ALUMINUM MODELS

The stresses distributed in bonded and weld-bonded joints were comparatively studied in order to investigate the role of changing the adhesive thickness. Figure 4 shows the predicted stresses (σ_{xx}, σ_{yy}, and σ_{xy}) along with the Von Mises (V.M.) stresses developed through the mid-layer of the adhesive thickness. The single overlap joint is subjected to large shear stresses resulting from joint deflection, rotation, and induced peel stresses. The effect of peel stresses on the strength of the bonded joints and the consequences of bending deflections of the joint are caused by load path eccentricity. It is observed from Figure 4 that the predicted stresses through the mid-layer of the adhesive boned joints are concentrated at the far ends of the overlapped area. When adhesive thickness increases 3.5 times the original adhesive thickness, stresses σ_{xx}, σ_{yy}, and σ_{yx} are reduced by 52%, 28%, and 45% respectively. The overall reduction in $\sigma_{V.M.}$ stress is 41%. When adhesive thickness increases 6 times the original adhesive thickness, stresses σ_{xx}, σ_{yy}, and σ_{yx} are reduced by 69%, 37%, and 58% respectively and the overall reduction in $\sigma_{V.M.}$ stress is 51%. Increasing thickness over than 6 times, leads to a general reduction in stresses. However, the percentage reduction in stresses becomes more and more small as shown clearly in Table 3.

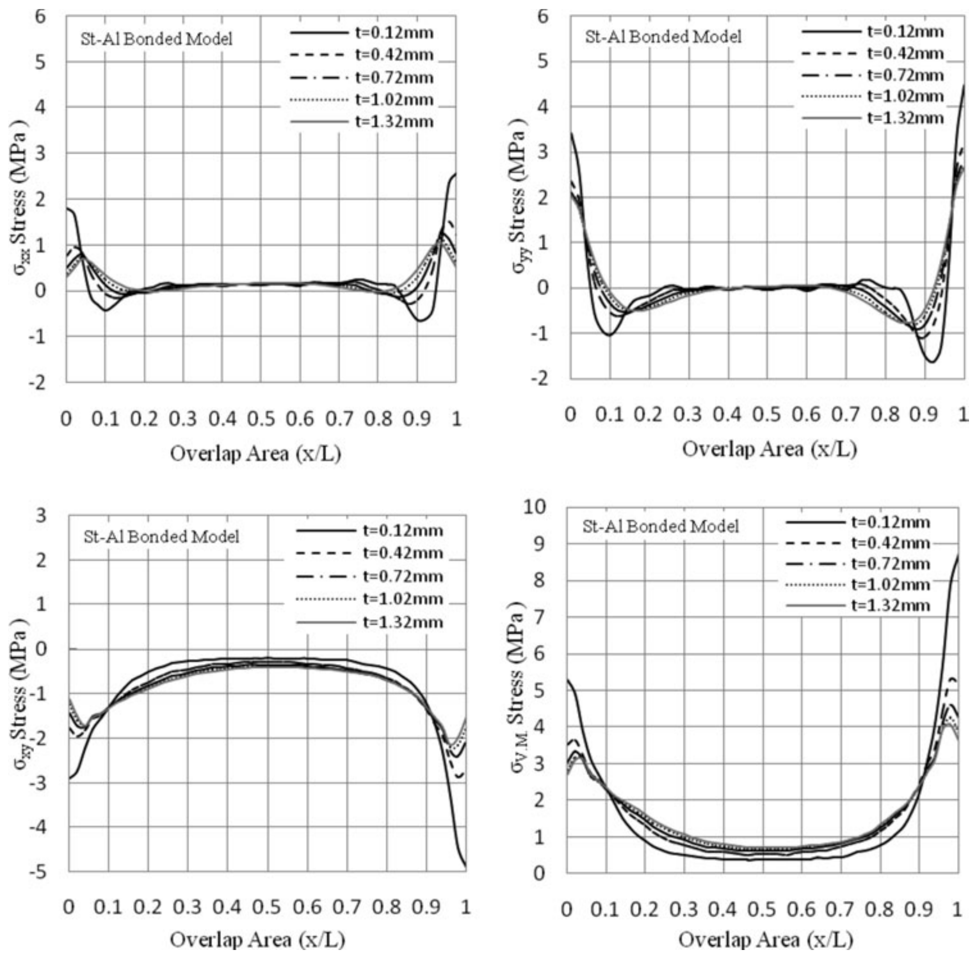

Figure 4 Stresses developed in steel-aluminum bonded joint along a layer at adhesive mid-thickness in the longitudinal direction.

Table 3 Approximate changes in stresses for steel-aluminum bonded Model

Adhesive thickness (mm)	**%change in σ_{xx} stress**	**%change in σ_{yy} stress**	**% change in σ_{xy} stress**	**% change in $\sigma_{V.M.}$ stress**
t_2=3.5t_1	–52	–28	–45	–41
t_3=6.0t_1	–69	–37	–58	–51
t_4=8.5t_1	–76	–40	–62	–57
t_5=11t_1	–80	–41	–65	–59

Figure 5 shows contour plot of V.M. stress for Steel-Aluminum model developed in the overlapped bonded joint. It also shows that the stresses are constant across the transverse direction (z-direction).

Figure 6 predicted stresses through the mid-layer of the weld-boned joints. The stresses in general are higher at the far ends for both weld nugget and adhesive bonded.

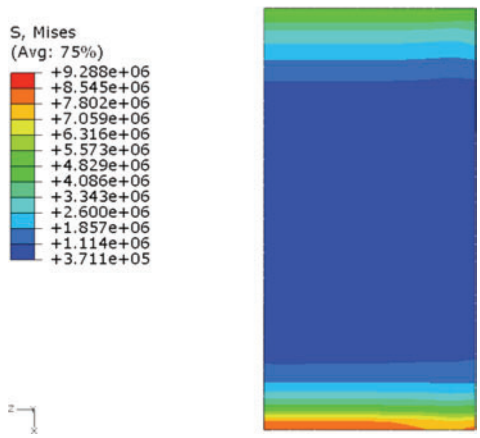

Figure 5 Contours plot of V. M. stress for St-Al bonded model (adhesive thickness t_1).

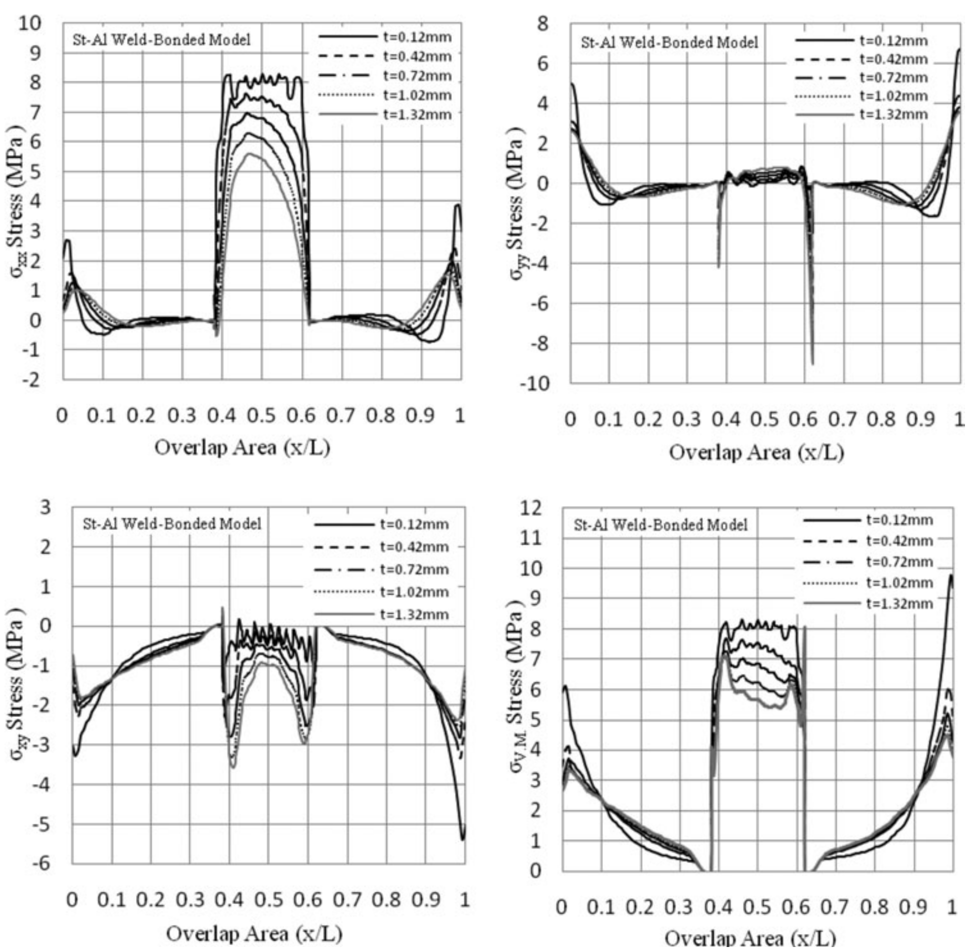

Figure 6 Stresses developed in steel-aluminum weld-bonded joint along a layer at adhesive mid-thickness in the longitudinal directions.

When adhesive thickness increases 3.5 times the original adhesive thickness, the change in stresses σ_{xx}, σ_{yy}, σ_{yx}, and $\sigma_{V.M}$ at the far end of the weld nugget are –11%, +155%,+57%, –13% respectively, whereas the changed in stresses σ_{xx}, σ_{yy}, σ_{yx} , and $\sigma_{V.M}$ at the end of the overlapped bonded area are –66%, –36%, –54%, –46% respectively. Table 4 summarized the change in stresses for different thickness of adhesive layer.

Table 4 Approximate changes in stresses for steel-aluminum weld-bonded model

Adhesive thickness (mm)	**% change in σ_{xx} stress**		**% change in σ_{yy} stress**		**% change in σ_{xy} stress**		**% change in $\sigma_{V.M.}$ stress**	
	Adhesive	Nugget	Adhesive	Nugget	Adhesive	Nugget	Adhesive	Nugget
t_2=3.5t_1	–66	–11	–36	+155	–54	+57	–46	–13
t_3=6.0t_1	–79	–17	–43	+233	–69	+91	–56	–8
t_4=8.5t_1	–85	–25	–46	+262	–76	+128	–59	–7
t_5=11.t_1	–88	–32	–47	+267	–80	+146	–60	–4

The result of Table 4 demonstrates that σ_{yy} and σ_{xy} become too large as the adhesive thickness increases. Increasing the thickness tends to reduce the peak stress over the overlapped area. In addition, it exaggerates the peel stress distribution. One of the reasons that the peel stress (σ_{yy}) and the Shear stress (σ_{xy}) become very high as the adhesive thickness increased is due to the absent of adhesive layer in a zone of 1mm around the circumference of the weld nugget.

Figure 7 shows contour plot of V. M. stress developed in the weld-bonded joint for steel-Aluminum configuration. The contour illustrates that the stresses are higher at both end of adhesive layer compare with its center. In the nugget region, the stress is higher at the center of the nugget and across the transverse directions (z-direction).

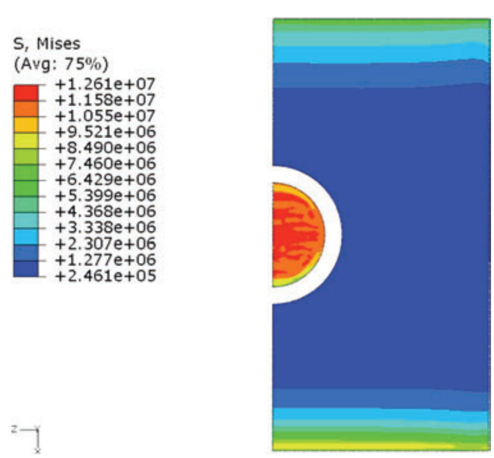

Figure 7 Contours plot of V.M. stress for St-Al weld-bonded model (adhesive thickness t_1).

3.2 STRESSES DEVELOPED IN STEEL-BRASS MODELS

The predicted stresses through the mid-layer of the adhesive boned joints are concentrated at the far ends of the bonded as shown in Figure 8. When adhesive thickness increases 3.5 times the original adhesive thickness, stresses σ_{xx}, σ_{yy}, and σ_{yx} are reduced by 45%, 32%, and 40% respectively. The overall reduction in $\sigma_{V.M.}$ stress is 37%. When adhesive thickness increases 6 times the original adhesive thickness, stresses σ_{xx}, σ_{yy}, and σ_{yx} are reduced by 56%, 40%, and 49% respectively and the overall reduction in $\sigma_{V.M.}$stress is 46%.

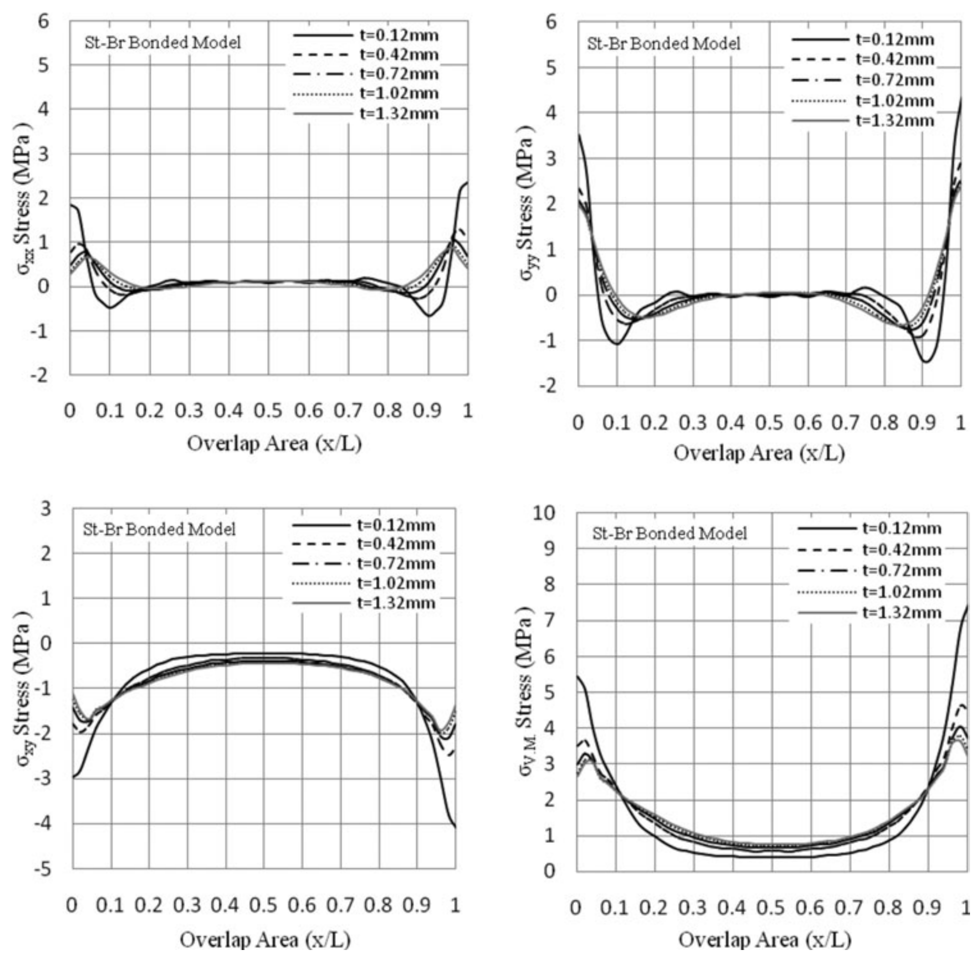

Figure 8 Stresses developed in steel-brass bonded joint along the mid-layer of overlapped in the longitudinal directions.

As the thickness increases more than 6 times, the stresses in general decrease however the ratio of decreasing becomes slighter. Table 5 summarized the reduction in stresses for a variety of adhesive thickness.

Table 5 Approximate changes in stresses for steel-brass bonded model

Adhesive thickness (mm)	% change in σ_{xx} stress	% change in σ_{yy} stress	% change in σ_{xy} stress	% change in $\sigma_{V.M.}$ stress
$t_2=3.5t_1$	–45	–32	–40	–37
$t_3=6.0t_1$	–56	–40	–49	–46
$t_4=8.5t_1$	–60	–43	–52	–49
$t_5=11t_1$	–63	–44	–53	–51

Figure 9 predicted stresses through the mid-layer of the Steel-Brass weld-boned joints. The stresses in general are higher at the far ends for both weld nugget and adhesive bonded. When adhesive thickness increases 3.5 times the original adhesive thickness, the maximum change in stresses σ_{xx}, σ_{yy}, σ_{yx}, and $\sigma_{V.M}$ at the weld nugget edges are –9%, +141%, +61%, –5% respectively, whereas the maximum changed in stresses σ_{xx}, σ_{yy}, σ_{yx},

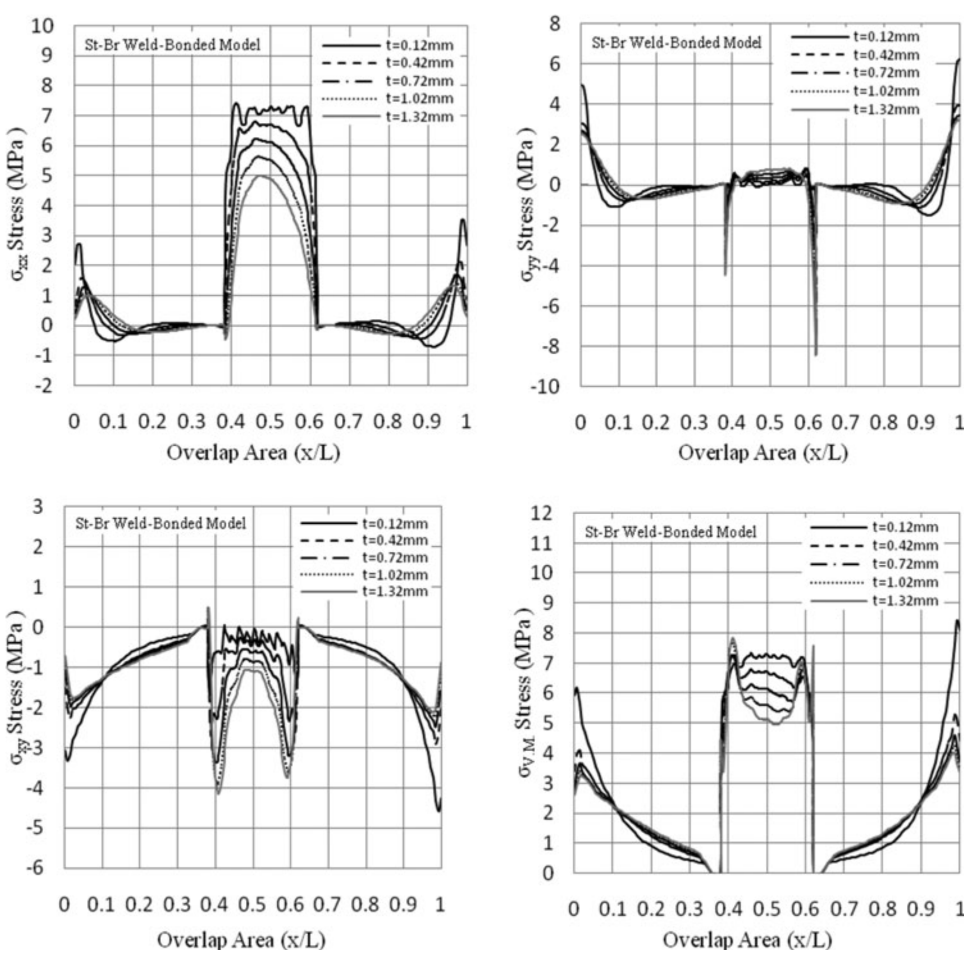

Figure 9 Stresses developed in steel-brass weld-bonded joint along a layer at adhesive mid-thickness in the longitudinal directions.

and $\sigma_{V.M}$ at the end of the overlapped bonded area are –40%, –37%, –37%, –37% respectively. Table 6 summarized the maximum change in stresses for different thicknesses of adhesive layer.

Table 6 Approximate changes in stresses for steel-brass weld-bonded Model

Adhesive thickness (mm)	% change in σ_{xx}stress		% change in σ_{yy} stress		% change in $\sigma_{xy.}$ stress		% change in $\sigma_{V.M.}$ stress	
	Adhesive	Nugget	Adhesive	Nugget	Adhesive	Nugget	Adhesive	Nugget
t_2=3.5t_1	–40	–9	–37	+141	–37	+61	–37	–5
t_3=6.0t_1	–52	–16	–44	+217	–46	+100	–45	–1
t_4=8.5t_1	–58	–24	–47	+248	–52	+132	–50	+5
t_5=11.t_1	–62	–32	–48	+258	–54	+146	-53	+7

It appears from Table 6 that the peel and shear stresses at the edges of the nugget become sever as the adhesive thickness becomes too large. These results are agreed with the first Steel-Aluminum configuration. And as a rule, increasing the thickness tends to reduce the peak stress over the overlapped area. But it exaggerates the peel stress distribution.

3.3 STRESSES DEVELOPED IN BRASS-ALUMINUM MODELS

The predicted stresses through the mid-layer of the adhesive boned joints are concentrated at the far ends of the bonded as shown in Figure 10. Increases the adhesive thickness 3.5 times the original thickness reduce the stresses σ_{xx}, σ_{yy}, and σ_{yx} by 42%, 28%, and 39% respectively. The overall reduction in $\sigma_{V.M.}$ stress is 39%. Table 7 summarized the reduction in stresses for different adhesive thicknesses.

Figure 11 predicted stresses through the mid-layer of the Brass-Aluminum weld-boned joints. The stresses in general are higher at the far ends for both weld nugget and adhesive bonded. As we did before, Table 8 summarized the maximum change in stresses for different adhesive thicknesses. It also appears from Table 8 that the peel and shear stresses at the edges of the nugget become sever as the adhesive thickness becomes too large.

4. CONCLUSION

Stresses in adhesive bonded joints are concentrated at the ends of the overlapped area. When the spot-welded is used together with the adhesive bonded, the stresses are concentrated at the adhesive bond ends and at both ends of the welding nugget. Stresses are more concentrated towards the soft material. The results in general shows that the thinner the adhesive is, the higher is the peak stresses developed in the weld-bonded joint. Increase the adhesive by at least 3~4 times will reduce the stress in general by more than 35%. The results in Tables 4, 6, and 8 demonstrate that when the melting point of both dissimilar materials are very close to each other, the peel and shear stresses decreases and hence one can increase the adhesive thickness more than 3.5 time the original thickness. The absent of adhesive layer around the circumference of the weld nugget has an effect on the stress concentration at the ends of the weld nugget. It is very important to note that although increasing the adhesive thickness will result in high peel and shear stress,

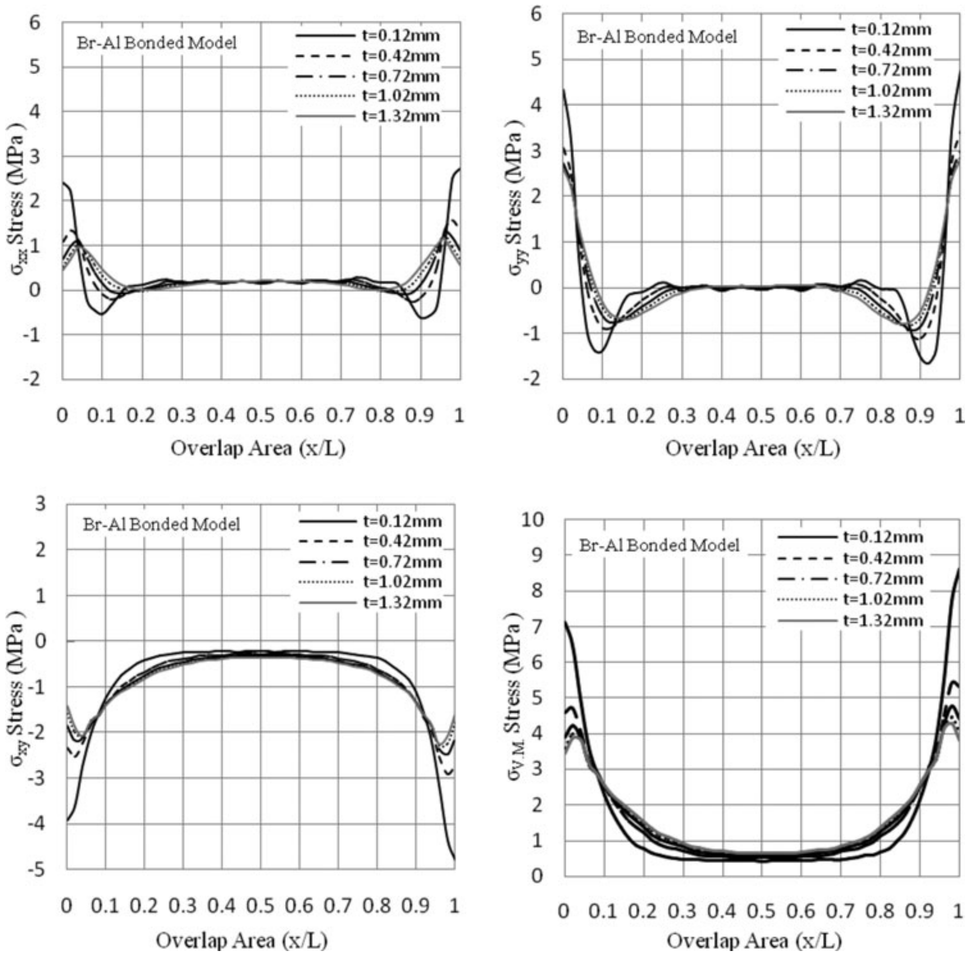

Figure 10 Stresses developed in brass-aluminum bonded joint along a layer at adhesive mid-thickness in the longitudinal directions.

Table 7 Approximate changes in stresses for brass-aluminum bonded model

Adhesive thickness (mm)	% change in σ_{xx} stress	% change in σ_{yy} stress	% change in σ_{xy} stress	% change in $\sigma_{V.M.}$ stress
$t_2=3.5t_1$	–42	–28	–39	-39
$t_3=6.0t_1$	–53	–36	–49	-49
$t_4=8.5t_1$	–56	–39	–52	-54
$t_5=11t_1$	–58	–40	–53	-56

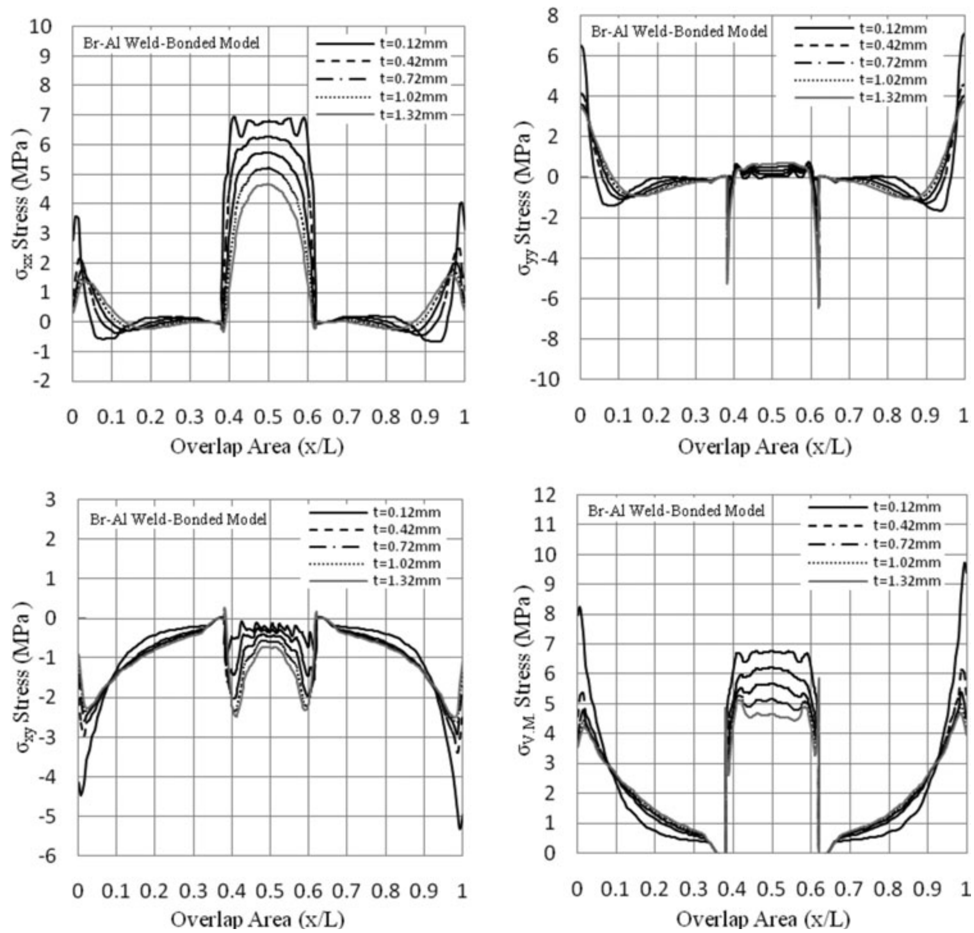

Figure 11 Stresses developed in brass-aluminum weld-bonded joint along a layer at adhesive mid-thickness in the longitudinal directions.

Table 8 Approximate changes in stresses for brass-aluminum weld-bonded model

Adhesive thickness (mm)	**% change in σ_{xx} stress**		**% change in σ_{yy} stress**		**% change in σ_{xy} stress**		**% change in $\sigma_{V.M.}$ stress**	
	Adhesive	Nugget	Adhesive	Nugget	Adhesive	Nugget	Adhesive	Nugget
t_2=3.5t_1	−39	−10	−36	+113	−36	+36	−37	-8
t_3=6.0t_1	−51	−17	−44	+177	−45	+74	−45	-16
t_4=8.5t_1	−57	−25	−46	+201	−51	+100	−49	-18
t_5=11.t_1	−61	−33	−47	+205	−53	+112	−51	-15

however these stresses are still less than the highest stresses that appear at the adhesive bond ends

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