

Optimization of the surface condition of the bonding zone of a bonded assembly

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Abstract: The bonding area is the critical interface where the adhesive is applied to join two plates or surfaces. The shape and size of this area directly influence the strength and rigidity of the assembly. This article presents a comparative study of the shapes of the bonding area to assemble two 2024 aluminum plates for simulation using Abaqus 6.17 software. The objective is to determine the effect of the bonding area geometry on the force-displacement curve to define a better contact surface for bonding the plates under tensile load. To optimize the assembly, we identified correlations between the bonding area surface S and the tensile modulus E of four adhesives using Modde5 software.

Keywords: bonding area surface, tensile modulus, adhesives, maximum force, optimization

1. INTRODUCTION

Geometric modeling and analysis of bonding areas in adhesive plate assemblies are crucial aspects in engineering to assess the structural performance and durability of assemblies. Adhesives offer significant advantages over mechanical joints (Polyakov et al., 2023). They are widely used in various industrial applications to assemble components due to their benefits such as uniform load distribution, weight reduction, and the ability to bond dissimilar materials (Abdelaziz et al., n.d.; Delzendeurooy et al., 2022; Kupski & Teixeira De Freitas, 2021).

In this context, several studies have been cited in the literature. Kupski & Teixeira De Freitas (2021) worked on joint design to improve shear strength. Sousa et al. (2024) studied different factors influencing the fatigue life of bonded structures, including joint geometry (zigzag, sinusoidal), environmental conditions, and loading conditions. This article demonstrates that factors such as adhesive thickness, fillet, and overlap shape impact the fatigue life of bonded assemblies., Shu et al. (2023) studied the long-term performance and optimization of single-lap joints, focusing on evaluating overlap length, adhesive layer thickness, and adhesive changes to indicate shear strength limit subsection.

In another work, Birro et al. (2020) worked on modeling the cohesive zone of adhesives at the initiation of interface cracks. In 2021, Birro, in his thesis, focused on predicting adhesive failure in bonded metal assemblies. In January 2024, Nao-Aki Noda analyzed the effect of adhesive size and surface to achieve high strength (Noda & al., 2024). Kumar et al. (2023) focused on developing a bonding technique with three different joint configurations with epoxy-filled holes in the overlap region (pure epoxy, four drilled holes with a 2 mm diameter, and four drilled holes with a 2 mm diameter). Experimental results showed that different hole configurations significantly improved joint strength compared to pure epoxy.

Zielecki (Zielecki et al., 2017) analyzed the influence of plastic deformation of the adherend material on stress distribution in adhesive joints. Nonlinear finite element analysis results showed that for materials with low yield strength, plastic deformation starts at an adherence load of 50% below the joint's destructive force. This phenomenon causes a rapid increase in stresses in the adhesive layer, significantly reducing the strength of the lap joints of elastic-plastic materials. To improve tensile strength, Akpinar et al. (2024) studied the effect of geometry on joint strength in adhesively bonded joints with the same adhesive area, with single and double lap joints.

Our work involves a numerical two-dimensional approach using the finite element method with Abaqus software, conducting a comparative study of four shapes of bonding areas (flat, rectangular, circular, triangular) with the same size to assemble two aluminum plates to define a better contact area for bonding the plates under tensile. To optimize the assembly, we identified correlations between the bonding area surface S (in mm^2) and the tensile modulus E (in N) of four adhesives, in order to determine the significance of coefficients S and E on the maximum force F

2. GEOMETRIC MODEL AND MECHANICAL PROPERTIES

Our geometric model consists of two aluminum plates measuring $70.2 \times 15 \text{ mm}^2$ and an adhesive joint of 15.2 mm but with different shapes, axially loaded along the X-axis by an imposed displacement of 5 mm . The adhesive joint is for a single lap joint of the two aluminum plates

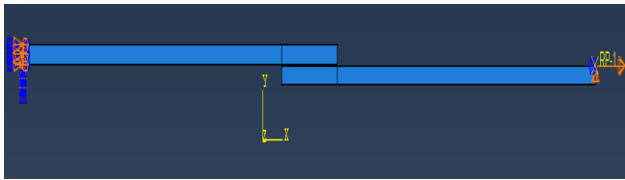


Figure 1: Geometric Model

The modeling was conducted using the Abaqus finite element simulation software. Four bonding area configurations were studied:

- Flat bonding area
- Rectangular bonding area
- Circular bonding area
- Triangular bonding area

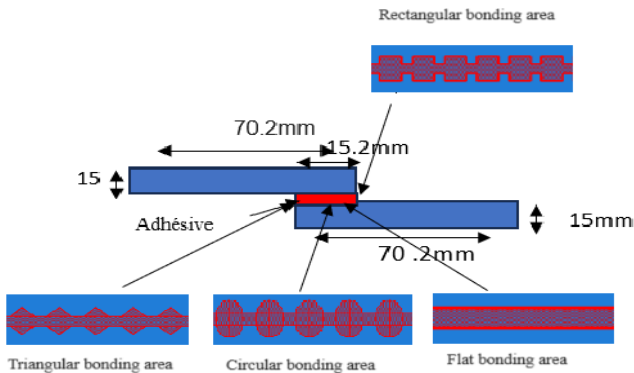


Figure 2: Geometric Modeling of Four Bonding Areas in Abaqus

Aluminum, a widely used material in the industry, is characterized by mechanical properties that influence its response to applied loads. The Young's modulus is 75000 MPa , and the Poisson's ratio (ν) is 0.33 . The following table represents the chosen adhesive properties.

Table 1: material properties

Materials	properties							
	E (Mpa)	Poisson's ratio (ν)	E/En (N/m)	G1/Ess (N/m)	G2/Ett (N/m)	Normal-only mode (Mpa)	First Direction (Mpa)	Second Direction (Mpa)
Aluminum	75000	0,33						
Adhesive (Adekit)			10000	10000	10000	35.9	30.9	30.9

3. RESULTS AND DISCUSSION

Force and Displacement

During a tensile test, a force as a function of displacement curve is created by recording the applied force and the displacement of the specimen under tension. This curve provides information on the elastic-plastic behavior and tensile strength of a material.

3.1 Flat Bonding Area

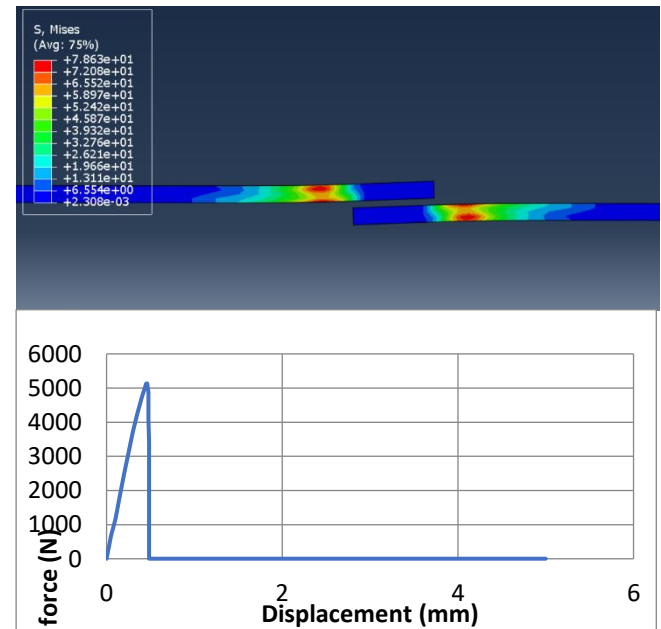


Figure 3: Flat Bonding Area

The figure shows the evolution of force as a function of displacement for the two plates bonded with adhesive. It is noted that in the displacement interval between 0 and 0.42 mm , the relationship between force and displacement is linear (elastic domain), and the maximum force reaches 5130 N .

After the rupture point, in the interval of 0.42 to 5 mm, the force sharply decreases

3.2 Rectangular Bonding Area

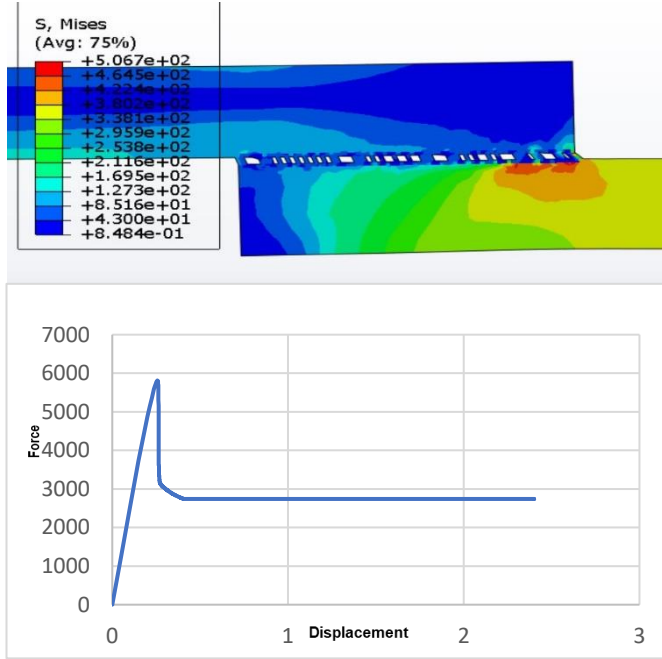


Figure 4: rectangular bonding area

The figure represents the variation of force as a function of displacement. It is noted that in this case, the maximum force is 5813 N, corresponding to tensile strength. After 0.32 mm, the force decreases to 2800 N during displacement.

3.3 Circular Bonding Area

In the third test, we changed the geometry of the bonding area and performed the tensile test.

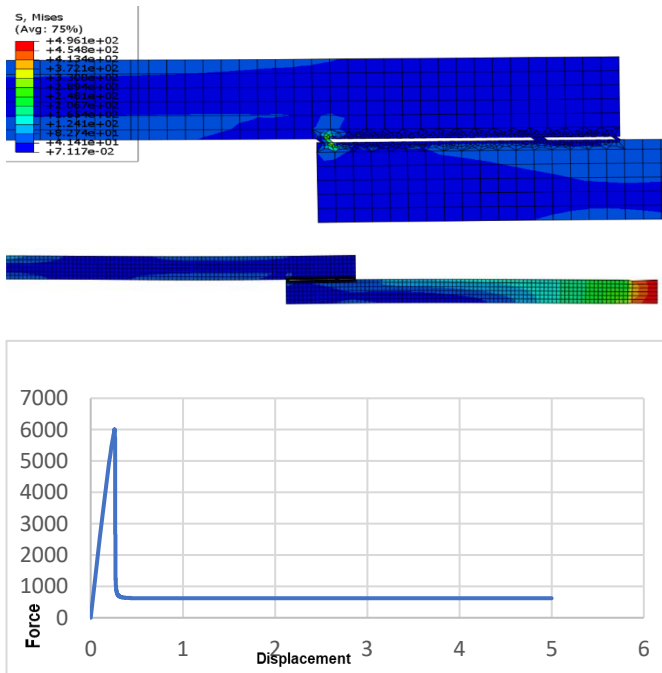


Figure 5: Circular Bonding Area

The figure represents the variation of force as a function of displacement. In this case, the maximum force is 6007 N, and the relationship between force and displacement is linear in the interval of 0 to 0.2 mm. After the rupture point, the force decreases to 800 N during displacement.

3.4 Triangular Bonding Area

In the last test, we modified the geometry of the area. (triangular surface)

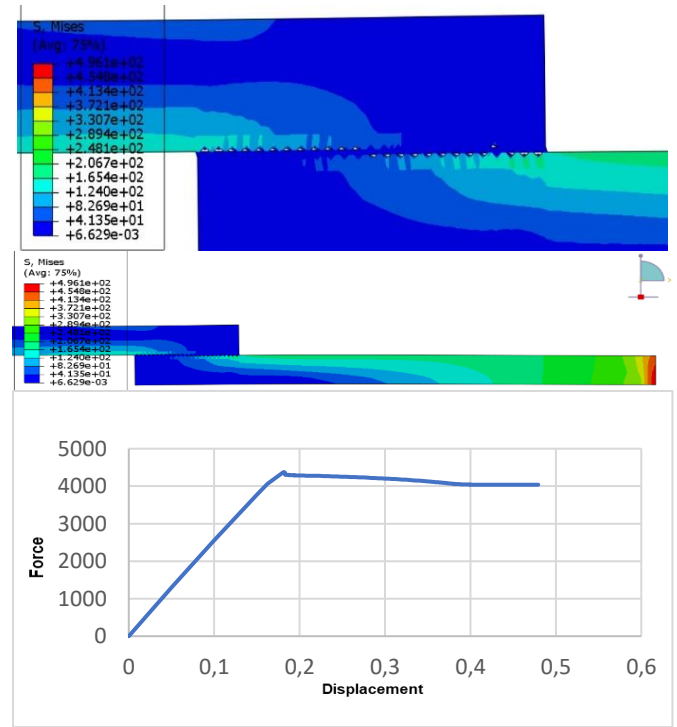


Figure 6: Triangular bonding area

The figure represents the variation of force as a function of displacement. It is noted that in this case, the maximum force is 4376 N, corresponding to tensile strength.

4.COMPARISON

The figure represents the variation of force as a function of displacement for the four different bonding areas and the same loading.

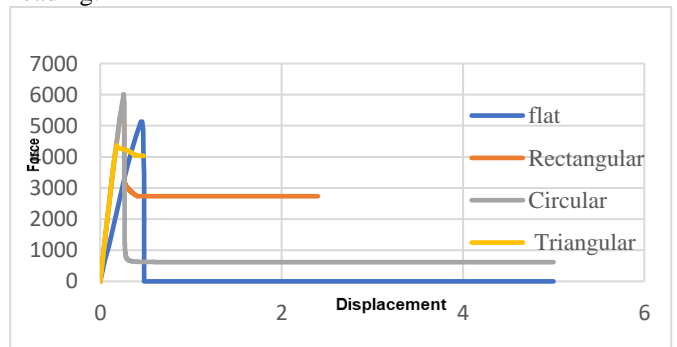


Figure7: the variation of force as a function of displacement for the four different areas under the same loading conditions

On the graph, we notice. The maximum force peak and stability are:

- The semicircular area reaches the highest maximum force (6007 N), followed by the rectangular area (5813 N), the flat area (5130 N), and finally the triangular area (4376 N).
- The rectangular area shows the greatest stability.
- The semicircular area shows relatively high but less stable force.
- The flat area shows a very high initial force but drops rapidly to a much lower level.
- The triangular area, although having an initial force, fails quickly, which could limit its usefulness in applications requiring durable force

5. FORCE OPTIMIZATION

To optimize the assembly, we identified combinations between the bonding area surface S (in mm²) and the tensile modulus E (in N) of four adhesives. The following table presents four geometric surfaces of the bonding area and four tensile moduli of the adhesives.

Table 2: Geometric Surfaces of the Bonding Area

	Geometric Zone			
	Flat	Rectangular	Circular	Triangular
Surface (mm ²)	3.04	7.2	6.3	5.12

The tensile moduli (in MPa) of the adhesives are as follows: Adekit = 10000, Araldite = 8000, FM 73 = 9000, FM 300 = 11500.

Table 3: The tensile moduli (in MPa) of the adhesives

adhesives	tensile moduli (Mpa)
Adekit	10000
Araldite	8000
FM 73	9000
FM 300	11500

This approach aims to determine the optimal configurations to achieve maximum force for the assemblies studied using the optimization software MODDE 5.

The following figure represents the Input factors and Response in MODDE 5.

	1	2	3	4	5	6	7
	Exp No	Exp Name	Run Order	Incl/Excl	surface	E	force
1	1	N1	7	Incl	3,04	8000	5110
2	2	N2	6	Incl	3,04	8000	5110
3	3	N3	16	Incl	6,3	8000	6019
4	4	N4	8	Incl	7,2	8000	5763
5	5	N5	3	Incl	3,04	9000	5122
6	6	N6	4	Incl	5,12	9000	4347
7	7	N7	10	Incl	7,2	9000	5751
8	8	N8	11	Incl	5,12	10000	4376
9	9	N9	13	Incl	6,3	10000	6007
10	10	N10	17	Incl	7,2	10000	5813
11	11	N11	14	Incl	3,04	11500	5148
12	12	N12	5	Incl	3,04	11500	5148
13	13	N13	9	Incl	5,12	11500	4449
14	14	N14	2	Incl	6,3	11500	5990
15	15	N15	12	Incl	7,2	11500	5831
16	16	N16	18	Incl	7,2	11500	5831
17	17	N17	15	Incl	7,2	11500	5831
18	18	N18	1	Incl	7,2	11500	5831

Figure8: Input Factors and Response in MODDE 5

The figure represents the values of the surfaces S and the tensile modulus E as factors, and the force F as the response, using Abaqus

Upon entering the data, the software can use optimization algorithms to adjust the model and predict the force based on the inputs. the following figure represents optimal surface and tensile modulus for maximum force.

The screenshot shows the MODDE 5 Optimizer interface. It includes a toolbar with icons for play, refresh, and other functions. Below the toolbar is a table for factors:

	Factor	Role	Value	Low Limit	High Limit
1	surface	Free		3,04	7,2
2	E	Free		8000	11500

Below this is a table for the response:

	Response	Criteria	Weight	Min	Target	Max
1	force	Maximize	1	6025,24	6157,27	

The interface also shows 'Iteration: 5003' and an 'Iteration slider'. At the bottom, there is a table of optimization results:

	1	2	3	4	5
	surface	E	force	iter	log(D)
1	3,04	8000	5132,31	4435	1,7801
2	7,2	8000	6091,26	1609	-0,6021
3	3,04	11500	5082,88	4401	1,821
4	7,2	11500	5932,29	4738	0,4629
5	7,2	11500	5932,29	5003	0,4629

Figure9: Optimal Surface and Tensile Modulus for Maximum Force

After 5003 iterations, the optimal surface is 72 mm², corresponding to a rectangular bonding area with a tensile modulus of 8,000 N (Araldite adhesive), yielding a maximum force of 609,126 N.

5.1 OPTIMIZATION FUNCTION

The force F is proportional to the surface S and the tensile modulus E. The relationship can be simplified as:

$$F = k \cdot S \cdot E$$

where k is a proportionality constant

The following figure represents the optimization function

	1	2	3	4	5
1	force	Coeff. SC	Std. Err.	P	Conf. int(±)
2	Constant	4774,58	237,414	1,30771e-010	517,279
3	sur	452,089	126,005	0,00372803	274,54
4	E	-52,0988	130,216	0,696118	283,716
5	sur*sur	597,488	260,36	0,0405738	567,273
6	E*E	187,619	256,897	0,479205	559,727
7	sur*E	-27,3869	142,305	0,850606	310,053
8					
9	N = 18	Q2 = 0,180	Cond. no. = 4,8176		
10	DF = 12	R2 = 0,624	Y-miss = 0		
11		R2 Adj. = 0,468	RSD = 422,2676		
12			Conf. lev. = 0,95		

Figure 10: Optimization Function in MODDE 5

Based on the following figure, the function for the maximum force is:

$$F = 4774,58 + 452,089 \cdot S - 52,0988 \cdot E + 597,488 \cdot S^2 + 187,619 \cdot E^2 - 27,3869 \cdot S \cdot E$$

5.2 Coefficient Analysis

The significant coefficient in determining the maximum adhesive force is indicated below. The following figure represents the significant coefficients impacting the force

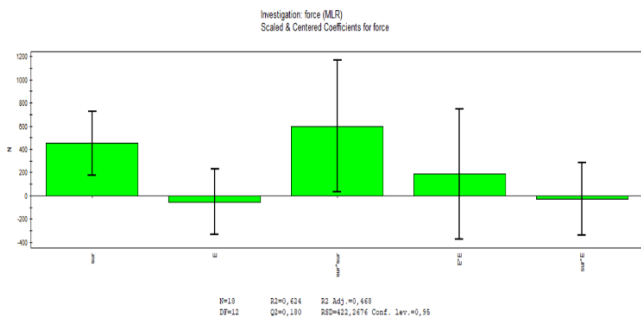


Figure11: Significant Coefficients Impacting the Force

According to the coefficient graph, the bonding area surface significantly impacts the maximum force, while the tensile

modulus E and the interactions E-E and S-E have less pronounced or insignificant impacts.

bonding Surface:

The coefficient for the bonding surface is significantly positive, indicating that increasing the bonding surface area increases the maximum force. This is consistent with the idea that the larger the bonding surface area, the higher the maximum force the adhesive can support.

Tensile Modulus (E):

The coefficient for the tensile modulus is close to zero and the confidence interval crosses zero, suggesting that EEE does not have a significant effect on the maximum force in this specific modeling.

Interaction S×S:

The interaction between surfaces also has a significantly positive coefficient, suggesting that the nonlinear effects of the bonding surface area are important for the maximum force.

Interaction S×E

The interaction between the bonding surface area and the tensile modulus S×E is also not significant, indicating that the combination of these two factors does not have a significant synergistic or antagonistic effect.

5.3 INTERPRETATION AND OPTIMIZATION

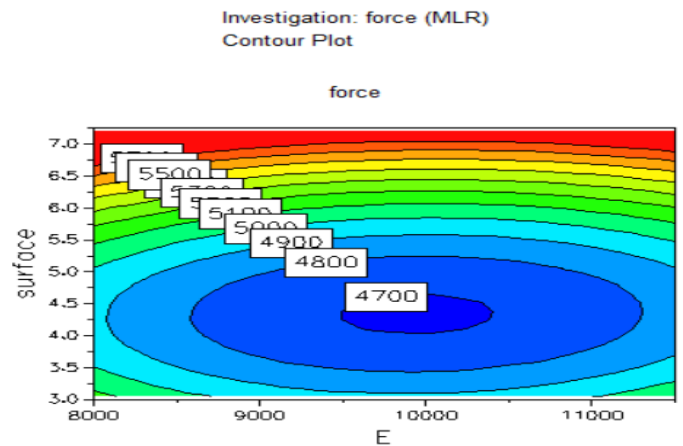


Figure12: Force as a Function of Surface and Tensile Modulus

According to the figure, the bonding area surface S has a more significant impact on the force than the tensile modulus E.

Tensile Modulus: Although E has a lesser impact, it still contributes to the total force, especially when the bonding area surface is already optimized

CONCLUSIONS

The different configurations of bonding areas significantly influence the performance of adhesive assemblies. In this comparative study, we analyze the impacts of rectangular and circular bonding areas on the strength and rigidity of plate assemblies.

- ✓ The shape of the bonding area plays a crucial role in the performance of adhesive assemblies.
- ✓ Circular bonding areas tend to offer better stress distribution and reduce the risk of premature failure compared to flat rectangular and triangular bonding areas
- ✓ The coefficient for the bonding area surface is significantly positive, indicating that increasing the bonding area surface increases the maximum force. This is consistent with the idea that the larger the bonding area, the higher the maximum force the adhesive can support. The coefficient for the tensile modulus is close to zero, and the confidence interval crosses zero, suggesting that EEE does not have a significant effect on the maximum force in this specific modeling.
- ✓ Although Tensile Modulus (E) of adhesive has a lesser impact, it still contributes to the total force, especially when the bonding area surface is already optimized

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