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Geometrical parameters optimizations of scarf and double scarf bounded joint

Sidi Mohamed Fekih*, Kuider Madani, Smail Benbarek and Mohamed Belhouari

LMPM, Department of Mechanical Engineering, University of Sidi Bel Abbes, BP 89, Cité Ben M'hidi,
22000 Sidi Bel Abbes, Algeria

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Abstract. The aim of this work is to optimize the geometrical parameters as the adhesive thickness and the beveled angle to reduce the edge effect of the scarf and V bounded joint. A finite element analysis is done to define the generated stresses in the bounded joint. The geometrical optimum is obtained using the Experimental Design Method. Results show that the double scarf (V) joint is better than the simple scarf bounded joint.

Keywords: scarf bounding; V bounding; finite element analysis; stresses distribution; experimental design method; optimization

1. Introduction

The adhesive bounding experienced the first applications in the early 20's when the first nitrocellulose-based adhesives appear and allow the assembly of construction materials (Volkersen 1938); several authors had followed this work as (Goland and Reissner 1944, Matthews *et al*. 1982, Lubkin 1944, Li *et al*. 2000, Assih *et al*. 2001, Xinglei and Wang 2016, Bouchiba and Serier 2016).

After the Second World War, the adhesive bounding took another boom; the development of new chemicals product has brought new properties of adhesion and the setting time of the adhesive. This has made it possible to adapt this assembly technique to other applications. Nowadays; the adhesive bounding has developed greatly in several areas (Aeronautics, automotive, Building, etc.). This technique is used to connect several different materials in order to repair or strengthen them; it also allows the design of mixed structures (Composite patch on Aluminum plate) (Baker *et al*. 1984, Jones 1983, Tarn and Shek 1991, Fekih *et al*. 2012, Yala and Megueni 2009, Elhannani *et al*. 2016, Fioriti 2014).

The adhesive bonding method is an effective alternative solution against the conventional assembly processes; it has many advantages: Homogeneous stress distribution, weight gain, thin materials assembly, Vibration attenuation and Design (From the aesthetic point of view, it is possible to obtain parts with a smooth appearance and the assembly will not very visible).

Assemblies that minimize stress concentrations and do not promote the appearance of the

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*Corresponding author, Ph.D., E-mail: fekih_moh@yahoo.fr

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cleavage are few in number. However, studies carried out on the scarf type of bonded joint show that this sample piece type offers satisfactory mechanical performances in particular under tension and fatigue.

Furthermore, the geometry of the substrates is simple to machine and unlike to some geometries (Double Butt Lap joint, Tongue and Groove Joint and Landed scarf Tongue and Groove Joint) does not predefine the future adhesive bonded thickness. This allows us to study its mechanical performance for an almost unlimited number of geometric configurations.

The double scarf bounded joint type presents a several similitude with that of simple scarf joint but unlike this latter, the double scarf bonded joint still not well known because of the acute or obtuse angles in the vicinity of the edges and at the tip of the V shape joint which makes the study of its mechanical behavior difficult to apprehend.

However, the variation of the beveling angle for these two sample test pieces (scarf and V joint) is a geometric parameter that allows us to study the influence of the geometrical singularity (the V tip) on the first micro-cracks onset in the adhesive joint.

This work consists in optimizing the joint components dimensions and in second time the joint shape optimization (plate and adhesive) in order to reduce the edge effect. To this end, several parameters have been highlighted as the adhesive thickness or the plate beveled angle (angle α).

2. Geometrical and finite element models

The numerical studied models of both simple scarf and double scarf (V) adhesive bonded assembly are shown in Fig. 1.

The assembled Aluminum 2024-T3 substrates are bonded using an Adekit A140 adhesive with a variable thickness (e_a). A uniform load of σ =10 MPa is applied on the edge of the joint with respect to its length direction (x direction) and the opposed edge is fully encastred. The mechanical properties of both plates and adhesive are given in Table 1. The Finite element model is made up with 20 nodes hexahedral elements. The finite element mesh of the 3D model is generated using the ABAQUS (2007) software as shown in Fig. 2. A regular mesh is applied on the entire adhesive joint model (approximately 14365 elements). This mesh is kept the same in all calculus in order to avoid any mesh influence on the obtained results. Both joint plates are considered fully bounded by considering the nodes merging between adjacent elements. The merging of the nodes results in having the same mesh for the whole structure.

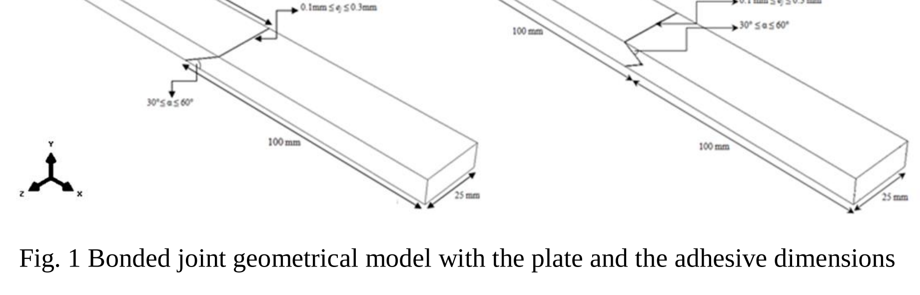


Fig. 1 Bonded joint geometrical model with the plate and the adhesive dimensions

Table 1 Material properties of a typical repair

	A (%)	E (GPa)	G (GPa)	υ
Aluminum 2024-T3	2.4	68	26.46	0.33
Adékit A140	5	2.69	1.035	0.3

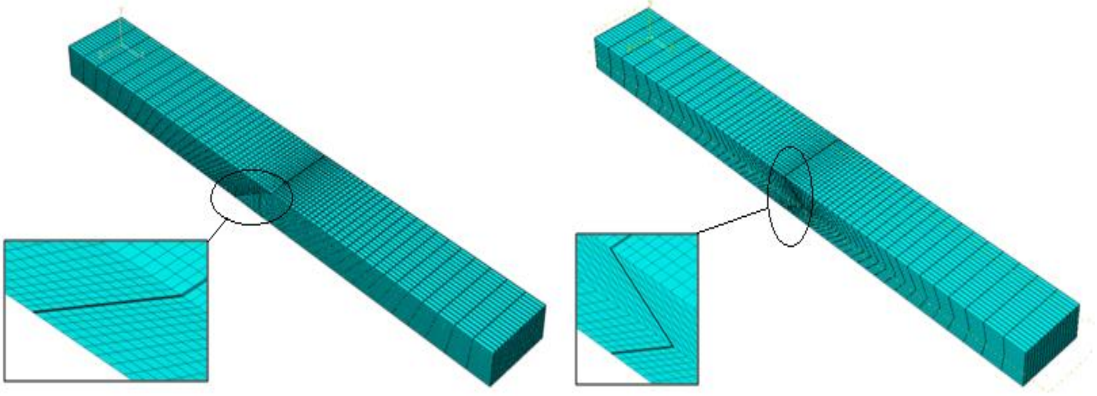


Fig. 2 Typical mesh model of the global structure

3. Experimental design method

The complete tests plans of 2 to 3 level is adopted, the experimenter model is quadratic having the following form

$$y = a_0 + \sum_{i=1}^{2} a_i x_i + \sum_{1\le i<j\le 3} a_{ij} x_j + \sum_{i=1}^{2} a_{ii} x_i^2 \tag{1}$$

Different statistics calculations are carried out using MODDE software. There are two ways to do the regression in this software: ‘PLS’ (Partial least Square) Regression is used when there is lacks of data and ‘MLR’ regression (Multiple Linear Regression).

The chosen method is MLR; least squares regressions on several factors. We try to establish a relationship between the input and the output data. For this we propose a second-order plane called Complete factorial plan with 3 levels » which offers a response using surface modeling (RSM) (Frigon 1996, Eriksson *et al*. 2000, Ali *et al*. 2017, Ugur *et al*. 2017).

4. Result and discussion

For this study, we consider tow variables parameters, the adhesive thickness (e_a) and the substrate bevelling angle α. The study range of different factors is chosen from the preliminary tests.

Results of $2^3 = 09$ made tests according to the experimental design factorial are reported in Table 2. We choose the study ranges for both factors as follow

$$\begin{aligned} &0{,}1\ \text{mm} \le e_a \le 0{,}3\ \text{mm} \quad \text{(Adhesive thickness);} \\ &30° \le \alpha \le 60° \quad \text{(Substrate bevelling angle);} \end{aligned} \tag{2}$$

The kept constant parameters are the mechanical properties of the adhesive and the substrate.

Table 2 Results of different program execution

		$\sigma_{\text{V.Mises}}$ (MPa)	
Thickness (mm)	Angle (°)	Scarf	Double Scarf
0.1	30	8.262	8.155
0.2	30	8.971	8.76
0.3	30	9.584	9.265
0.1	45	9.278	8.7
0.2	45	9.617	8.537
0.3	45	9.897	8.426
0.1	60	8.549	7.777
0.2	60	9.069	7.599
0.3	60	9.433	7.595

4.1 Scarf joint

In order to study the influences of variables (Adhesive thickness (e_a) and the bevelling angle α), we must keep constant one variable and vary the second; we will see latter that each factor has a significant influence on the assembly performance criterion.

From the obtained mathematical model given by Eq. (3), one can determine the influence of each factor on the response by plotting the Von-Mises stress variation with respect to the chosen factors. If for example we want to determine the influence of a factor (xi) on the Von-Mises stress, we plot the variation for the three chosen factor.

$$\sigma_{V.Mises} = 2.1349174 + 10.066618 * e + 0.26493237 \propto - 5.18322 * e^2 - 0.00275258 * \propto^2 - 0.073 * e * \propto \qquad (3)$$

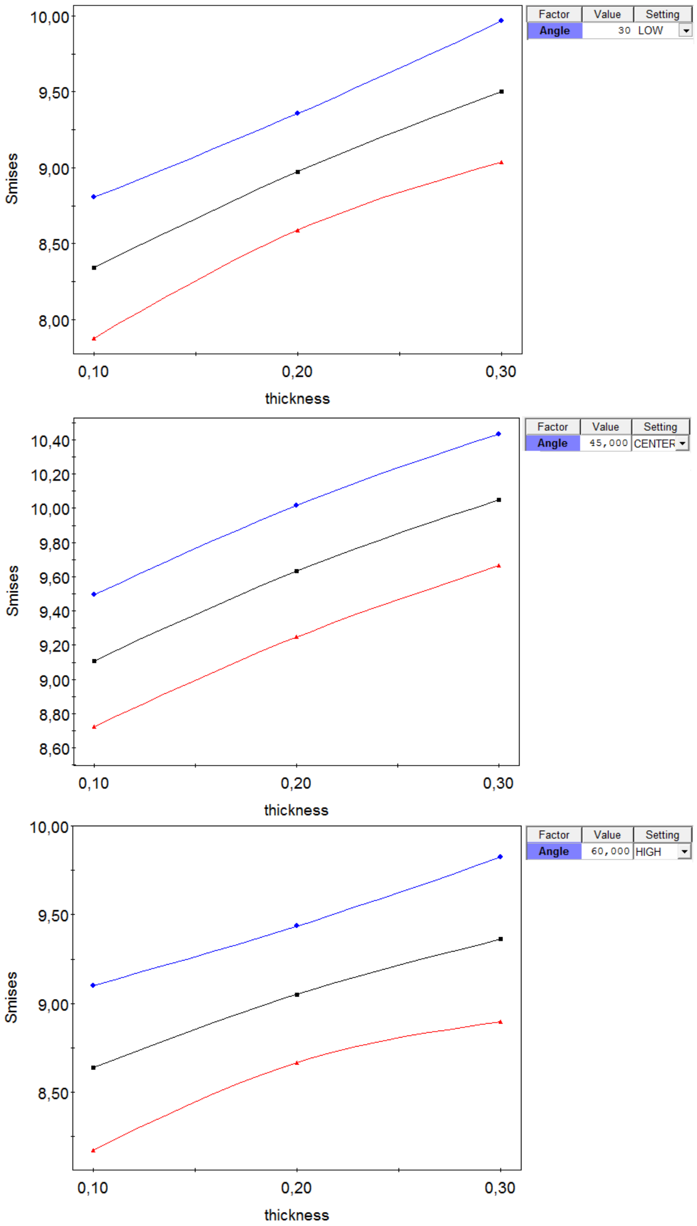
4.1.1 Adhesive thickness (ea) effect

The goal of this study is to study the influence of the adhesive thickness (e_a) for a bonded joint assembly of tow simple scarf Aluminum plates. The increase of the lifespan of this structure is analyzed in terms of Von-Mises stress concentration minimization. We consider several bevelling angles varying between 30° and 60°. The study using the experimental design method is carried out to analyze the (e_a) thickness effect on the equivalent stresses (Fig. 3). The analysis of this figure show that the growth of the thickness (e_a) level leads to a growth of the Von-Mises stresses for any bevelling angle (α). Von-Mises stresses are more important for the bevelling angle around 45°.

4.1.2 Bevelling angle (α) effect

The second geometric parameter studied is the angle of bevelling, this parameter is predominant because it conditions at the same time: The overlap length (Lr), ratio between the normal stresses σ_{11}, the shear stresses σ_{12} and angular singularities. The angle of bevelling varies from $\alpha = 30$ ° to $\alpha = 60$ °.

Fig. 4 shows the evolution of the Von-Mises stresses. Results show that the decreasing of the bevelling angle (α) and consequently the increasing of the overlap length increases significantly the mechanical strength of the bonded joint.



Factor	Value	Setting
Angle	30	LOW

Factor	Value	Setting
Angle	45,000	CENTER

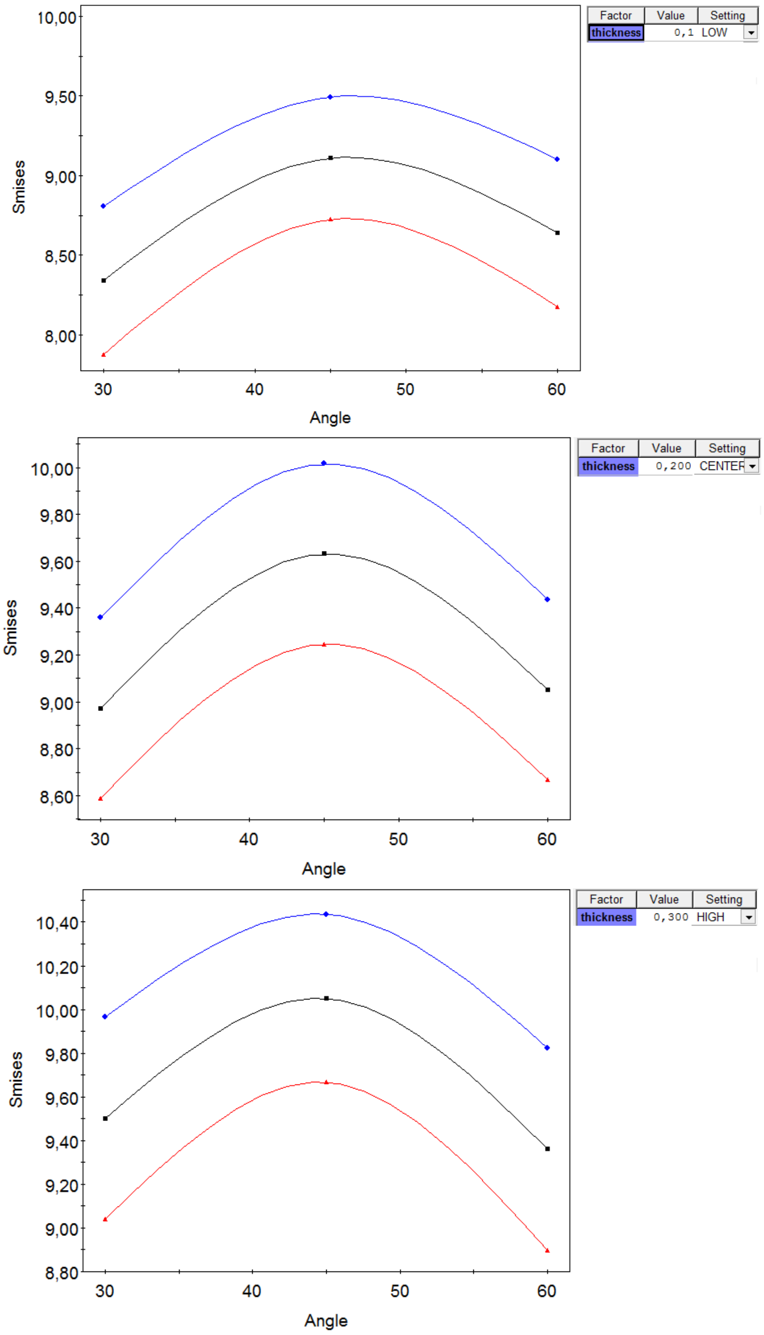
Factor	Value	Setting
Angle	60,000	HIGH

Fig. 3 Evolution of $\sigma_{\mathrm{V.Mises}}$ with respect to adhesive thickness (e_a) for the three level

4.1.3 Effect of interaction between the thickness of the adhesive (ea) and the angle of bevelling (α)

Assemblies that minimize stress concentrations and do not promote the appearance of the show that this type of sample offers satisfactory mechanical performances especially in tension.

Fig. 5 shows the interaction effect of both dimensions, adhesive thickness (e_a) and the bevelling angle (α). By simultaneously acting on the two geometric parameters from their minimum value to their maximum value, it is noted that the minimum values of the maximum equivalent stress



Factor	Value	Setting
thickness	0,1	LOW

Factor	Value	Setting
thickness	0,200	CENTER

Factor	Value	Setting
thickness	0,300	HIGH

Fig. 4 Evolution of the $\sigma_{\text{V.Mises}}$ stresses with respect to the bevelling angle (α) for the three thickness (e_a) level

correspond to the values of the thickness comprised between 0.1 mm and 0.15 mm and bevelling angle α between 30° and 34°. For this interaction effect, we obtain a good resistance when the values of these two factors are minimal.

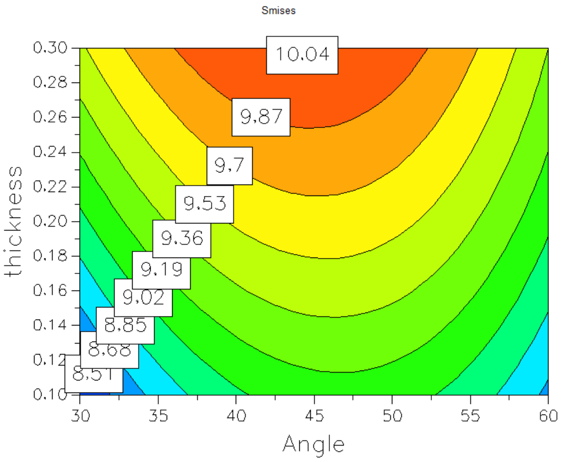
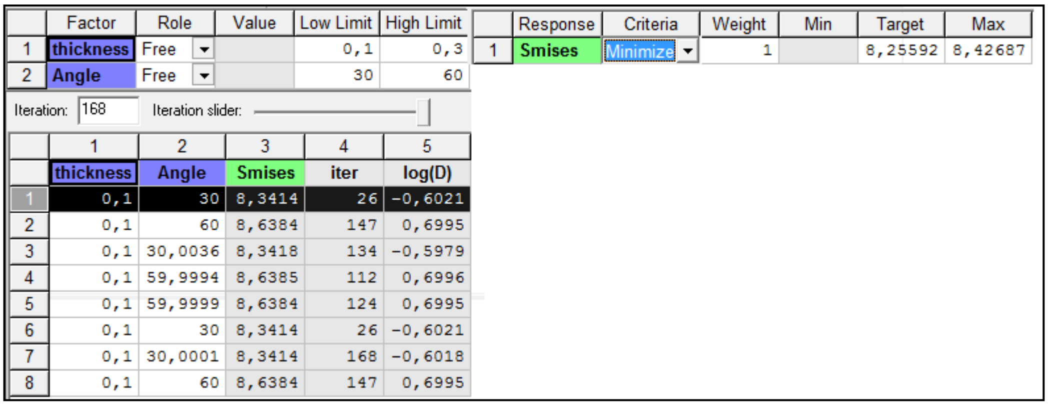


Fig. 5 Thickness e$_a$ - angle α interaction effect



	Factor	Role	Value	Low Limit	High Limit
1	thickness	Free		0,1	0,3
2	Angle	Free		30	60

	Response	Criteria	Weight	Min	Target	Max
1	Smises	Minimize	1		8,25592	8,42687

Iteration: 168 Iteration slider:

	1	2	3	4	5
	thickness	Angle	Smises	iter	log(D)
1	0,1	30	8,3414	26	-0,6021
2	0,1	60	8,6384	147	0,6995
3	0,1	30,0036	8,3418	134	-0,5979
4	0,1	59,9994	8,6385	112	0,6996
5	0,1	59,9999	8,6384	124	0,6995
6	0,1	30	8,3414	26	-0,6021
7	0,1	30,0001	8,3414	168	-0,6018
8	0,1	60	8,6384	147	0,6995

Fig. 6 Optimal values research using MODDE 5.0 software

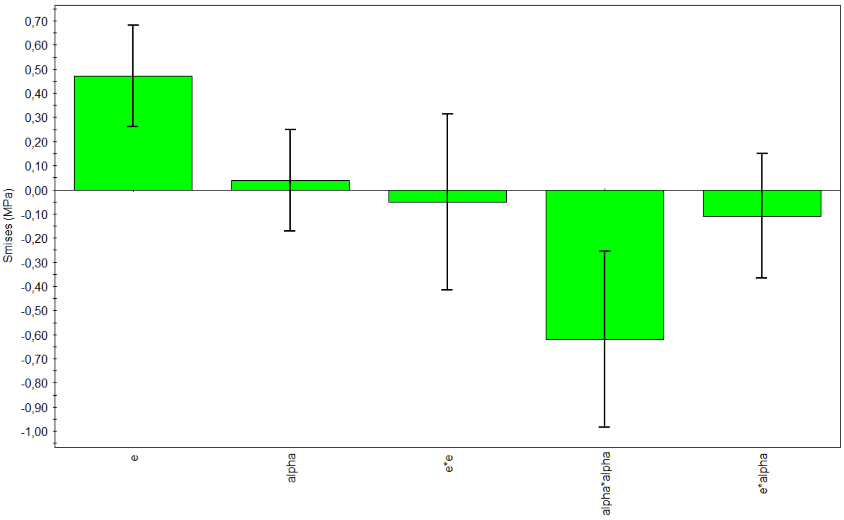


Fig. 7 Effects of different parameters on the $\sigma_{\text{V-Mises}}$ with their interactions

The iso-curves confirm the results of Figs. 3 and 4. Indeed, the stresses decrease with the bevelling angle α and the adhesive thickness e_a.

4.1.4 The optimum point verification

Fig. 6 illustrates the optimal point of the MODDE 5.0 software. In fact, the lowest values of the equivalent stress ($\sigma_{V.Mises}$ = 8.3414 MPa) are obtained for the adhesive thickness e_a = 0.1 mm and bevel angle $\alpha = 30°$.

Therefore, the procedure consists of minimizing the thickness of the adhesive and the angle of bevelling.

4.1.5 Effects of various factors on assembly

It is important to study the effect of different factors on the performance of the scarf joint. It is necessary to determine firstly the most influencing factors and then observe how quantities respond to these factors. These effects are plotted by a histogram. This diagram gives the effects of their importance in absolute value (Fig. 7). The analysis of this diagram shows that thickness e_a is the most important factor and the most dominant on the assembly geometrical parameters optimization.

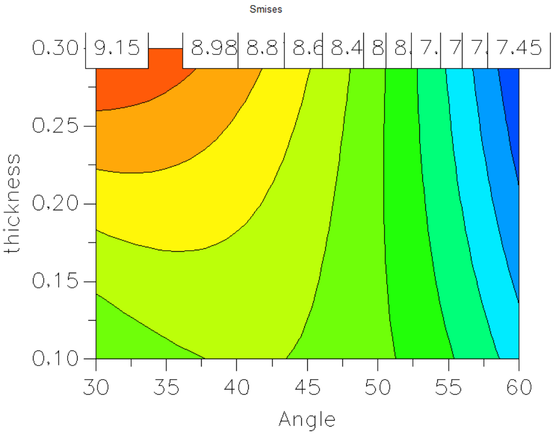
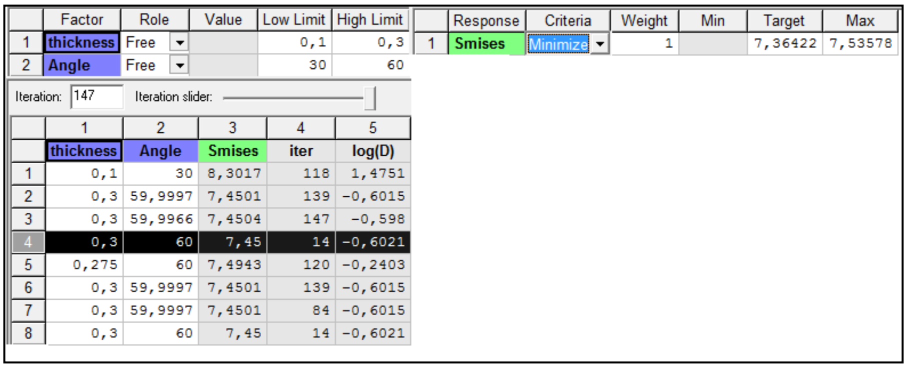


Fig. 8 Thickness e_a - angle α interaction effect



	Factor	Role	Value	Low Limit	High Limit
1	thickness	Free		0,1	0,3
2	Angle	Free		30	60

	Response	Criteria	Weight	Min	Target	Max
1	Smises	Minimize	1		7,36422	7,53578

Iteration: 147 Iteration slider:

	1	2	3	4	5
	thickness	Angle	Smises	iter	log(D)
1	0,1	30	8,3017	118	1,4751
2	0,3	59,9997	7,4501	139	-0,6015
3	0,3	59,9966	7,4504	147	-0,598
4	0,3	60	7,45	14	-0,6021
5	0,275	60	7,4943	120	-0,2403
6	0,3	59,9997	7,4501	139	-0,6015
7	0,3	59,9997	7,4501	84	-0,6015
8	0,3	60	7,45	14	-0,6021

Fig. 9 Optimal values research using MODDE 5.0 software

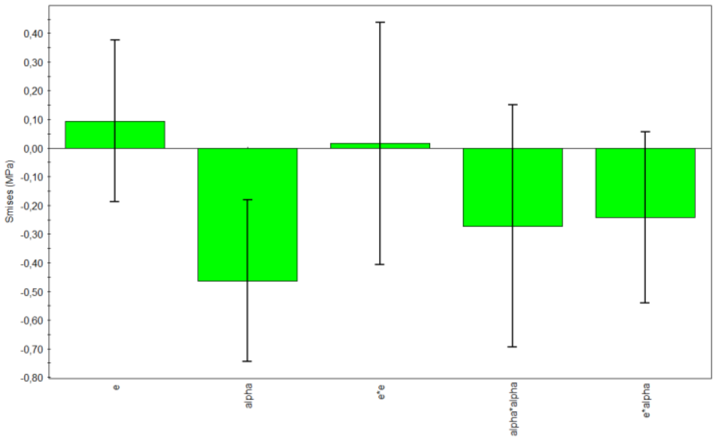


Fig. 10 Different parameters effects on the $\sigma_{\text{V-Mises}}$ with their interactions

Results summary table

Shape of the bonded joint	Dimensions		Stresses
	e_a (mm)	α (°)	$\sigma_{\text{V-Mises}}$(MPa)
Scarf joint	0.1	30	8.3414
Double Scarf joint	0.3	60	7.45

4.2 Double scarf assembly

Fig. 8 shows that a decrease of about 17% of the maximum equivalent stress value when the bevelling angle goes from 30° to 60° for a maximum value of (e_a). On the other hand, the observed thickness e_a effect in this figure is slightly lower except for values of α near 30°. The analysis carried out by the optimization software allows the verification of the optimal point. The minimum value of $\sigma_{\text{V.Mises}}$ (7.45 MPa) can be obtained with an adhesive thickness e_a = 0.3 mm and an angle α = 60° (Fig. 9). Our results show that the angle α is the parameter that influences the most the process of the geometry optimization of a V bonded assembly (Double scarf joint). (Fig. 10).

The mathematical model suggested by MODDE for the double scarf assembly is

$$\sigma_{V.Mises} = 5.9036986 + 7.581465 * e + 0.1101714 * \propto + 1.57501 * e^2 - 0.00120833 * \propto^2 - 0.1615 * e * \propto \quad (4)$$

5. Conclusions

The optimization of bonded joints using the Experimental Methods Design software (MODDE 5.0) are obtained by varying the joint dimensions as the adhesive thickness and the bevelling angle of the plate modifying the geometrical shapes the adherents or the profile of the adhesive.

The lessons to be learned from the dimensions analysis of the joint are that the overlap length and the thickness of the adhesives constitute the main parameters to be modified in order to obtain optimal dimensions i.e., a joint strength increasing related to an economical choice.

In this work, we analyzed a set of results relative to a bonded joint of scarf and double scarf type. All these results make it possible to deduce that there are several parameters that significantly influence the mechanical performance of the adhesive joint. A summary of all numerically carried out tests are given in the following table.

Numerical calculations show that the V-shaped (double scarf) assembly gives satisfactory results compared to the double scarf-bonded assemblies.

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