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Relationship between the geometric properties and the shear modulus of the adhesive, and optimization of mechanical behavior of bonded assemblies

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Abstract
The bonding is a method of maintaining solidly and permanently attaching two surfaces, similar or different of materials by adhesive.
It is known that several parameters influence the bounding quality such as the size and the intrinsic properties of the adhesive and the plate. The experimental design methodology is used to investigate the effects of lap length, thickness of the adhesive, the shear modulus of the adhesive and lap width in order to achieve an optimization of the bonding operation. This optimization allows us to identify the most influencing parameters on the bounding performances.
In order to ensure the minimal stress; an interaction study has found different combinations of factors.

1. Introduction

The adhesive bonding plates are experiencing a growing especially in the aviation industry development. If the rivet assembly was dominant in recent years, it is now outclassed by the collage. The level of development achieved in recently in improving the resistance properties of adhesives which allowed the collage technique to be a very important part in the aerospace and other applications [1,2]. The main advantage of gluing riveting is the uniform stress distribution in the adhesive joint. The rivet has a zone of stress concentration that can initiate a crack [3,4].
The evaluation of stress distributions in adhesive joint is very important to know the strength of an adhesive. The tensile test with single or double seals and coats tests were used to characterize the adhesives by determining their shear modulus, the main problem for experimenters is to measure the stress and strain at any point in the adhesive layer. To solve this problem, some theoretical models have been developed. These models calculate analytically the stresses in the joints single or double adhesive. However, they are insufficient because they are one-dimensional in their totalities. The growing development of numerical methods in recent years (finite element and boundary element) has identified fairly accurate shear stresses in the adhesive joints in two-dimensional and three-dimensional case.

2. Selection of influential factors

The experimental design methodology is an interdependent multi-factorial process applied to optimize and to determine the most influencing parameter. In this work, the effect of different parameters of the bonded structure is analyzed using finite element method:
• Length recovery. $20mm \leq L \leq 60mm$
• The thickness of the adhesive. $0.4\ mm \leq e \leq 2mm$
• Jettison recovery. $10mm \leq b \leq 40mm$
• The shear modulus of the adhesive. $200\ MPa \leq G \leq 1000\ Mpa$
• The thickness of the substrates. $ep = 2\ mm$
• The module Yong substrates. $E = 73100MPa$, $\nu = 0.33$
For a good understanding of the collage and the interdependence between these parameters, it is interesting to study the maximum parameters at once.

The breaking of adhesively bonded structures requires analysis of the stress distribution in the adhesive layer. Structures single adhesive joint, known for their simplicity and efficiency, are widely used to argue many assertions and have become a standard test for determining the mechanical properties of adhesives.
Fig. 1 shows the modeling by finite element method [5] of the specimen single lap.

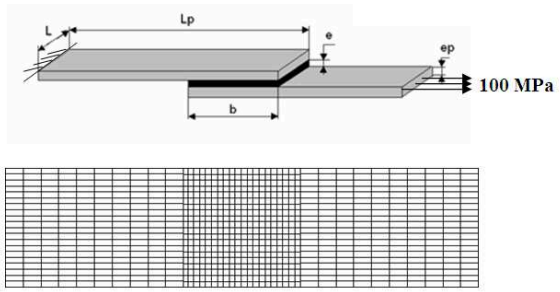

Fig. 1 Modeling the test piece by the finite elements method

The numerical results obtained by the fatigue calculation software (FRANC 2DL) [5], the results of 27 experiments according to the experimental design are shown in Table 1.
The adhesive element is analyzed as elastic members subject to shear forces. The shear force is distributed to all members and not confined to the node in question. When an adhesive joint assembles two surfaces, it must be introduced at the upper layer to enable to make an interpolation to calculate the displacement of the joint and allow the maximum amount of information stored on the database.
It is assumed that the adhesive layer is homogeneous, elastic is isotropic. It is also assumed that only the adhesive deforms in shear and this deformation is uniform through the thickness of the adhesive. It is assumed that parts of the normal stresses acting in the layers of the substrates are transmitted to the adhesive layer in the form of shear stresses.

Table 1: Results of different program execution

Exp. No	Width (mm)	Length (mm)	Thickness (mm)	G adhesive (MPa)	Stress (Mpa) τ_{zymax}
01	10	20	0.4	200	21.86
02	10	20	0.4	1000	27.52
03	10	20	2	200	20.4
04	10	20	2	1000	21.06
05	10	60	0.4	200	22.7
06	10	60	0.4	1000	28.87
07	10	60	2	200	20.7
08	10	60	2	1000	22.7
09	40	20	0.4	200	9.171
10	40	20	0.4	1000	19.68
11	40	20	2	200	5.93
12	40	20	2	1000	9.171
13	40	60	0.4	200	9.71
14	40	60	0.4	1000	20.67
15	40	60	2	200	20.67
16	40	60	2	1000	9.71
17	25	40	1.2	200	9.322
18	25	40	1.2	1000	13.33
19	25	40	0.4	600	16.61
20	25	40	2	600	10.23

21	25	20	1.2	600	11.03
22	25	60	1.2	600	11.7
23	10	40	1.2	600	22.51
24	40	40	1.2	600	9.48
25	25	40	1.2	600	11.47
26	25	40	1.2	600	11.48
27	25	40	1.2	600	11.49

The shear stress in the adhesive is defined by the relationship:

$$\tau = \frac{G}{e}(u_1 - u_2) \quad (1)$$

with:

- τ: Shear stress.
- G: shear modulus of the adhesive
- e: thickness of the adhesive.
- u: displacement in layers 1 and 2.

2.1 Fixed Parameter

• The setting was held constant is the thickness of the substrates.
• The module Yong substrates.

2.2. Variable parameters

For our study, we considered four variable parameters, length of overlap, the thickness of the adhesive, the width of the overlap, and the shear modulus of the adhesive.

2.3. Modeling

As adopted a comprehensive experimental design of 4 factors with 2 levels, the model of the experimenter is quadratic and has the following form [6]:

$$y = a_0 + \sum_{i=1}^{4} a_i x_i + \sum_{1 \le i < j \le 4} a_{ij} x_j + \sum_{i=1}^{4} a_{ii} x_i^2 + e \quad (2)$$

• y is the response
• x_j x_i represents the level assigned to the input i and j.
• a_0 is the value of the response at the center in the field of study.
• a_i a_j is the effect (or principal effect) of factor i and j.
• ij is the interaction between factors i and j.
• e is the standard.

$x_i = (u_i - u_{ic})/\Delta u_i = u_i^*$,

$u_{ic} = (u_{imax} + u_{imin})/2$; $\Delta u_i = (u_{imax} - u_{imin})/2$ (3)

MODDE the software is used to make various statistical calculations. There are two ways to do the regression MODDE: regression 'PLS' (Partial Least Squares) or regression 'MLR' (Multiple Linear Regression) used when there is a lack of data. The method used is PLS; least squares regressions on several factors [6].

2.4. Choice of experimental design

After an initial study of the various factors that influence delay, we will now try to establish a relationship between the input variables and output variables. For this we propose a plan of second degree called "face-centered composite design" which offers a modeling response surface (RSM), in addition to the mathematical model. The results of 27 experiments in the composite design of experiments are reported in Table.1.

3. Preliminary tests for the study the influence of the variables

To investigate the influence of variables (length L - width w - thickness e - Modulus G), we must fix three parameters and vary the fourth; each factor has a significant influence on the performance criteria of overlap.

The influence of each factor on responses is obtained from the mathematical model by plotting the variation of responses depending on the chosen factors. After calculating the coefficients of the regression model, one of them has to check the validity of this model. "Normal probability plot" residue answers or N-plot are the first methods to control the relevance of the model. The residue "e" is the difference between the value of the model $\hat{y}$ and the test value y with e = y - $\hat{y}$.

This graphical technique is used to check if the residuals have a normal distribution or not to detect off point model [6] (Fig. 2).

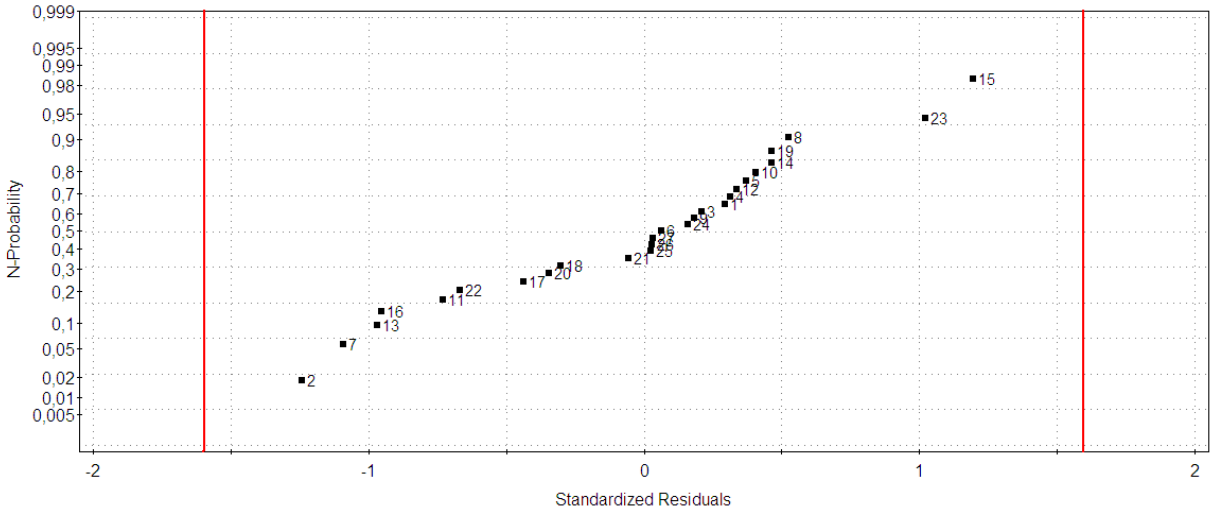

Fig. 2 Confidence Interval Model

4. Analysis with a single effect

4.1. Effect of shear modulus of adhesive

We studied the influence of the shear modulus of the adhesive, in this study the effect of adhesive properties on the variation of the maximum stress (tangential τ_{ZY}). The geometric characteristics of the seal used in this study are part of the following:

Width of 25 mm, a length of 40 mm and thickness 1.2 mm. Fig. 3 shows the variation of the maximum stress for different shear modulus of the adhesive (200 to 1000 MPa). To reduce travel and therefore the maximum stress (tangential τ_{ZY}) in the glue joint, you must choose adhesives having a weak shear modulus.

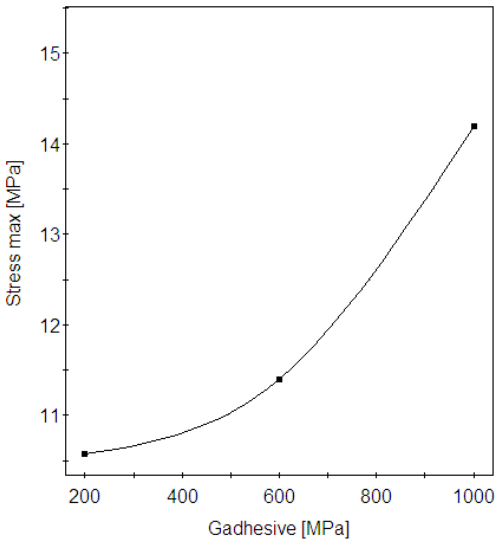

Fig. 3 Influence of shear modulus of the adhesive on the maximum stress distribution

Increasing this module's level leads to an increase in the maximum stress (tangential τ_{ZY}) in the collection, so we can conclude that the best quality of adhesives is characterized by low shear modular allowing them to withstand tangential stresses.

4.2. Influence of adhesive thickness

Another important parameter is the geometric thickness of the adhesive layer. We varied the thickness of 0.4mm to 2 mm and a length of 40 mm, width 25 mm. Fig. 4 shows that the value of the maximum stress (tangential τ_{ZY}) decreases when the thickness of the adhesive increases. Therefore, membership is better when increasing the thickness of the adhesive layer; it allows us to say that the strength of the adhesive is brittle at low thicknesses. It is better to increase the thickness of the adhesive layer to improve the strength of the bond, for cons if excessively increases the thickness of the adhesive layer, it may act as a third material which separate the mechanical properties when they are low. In addition, the increase in the thickness of the adhesive increases the risk of its lamination. Plasticization involves a degradation of the mechanical properties of the adhesive, thus generating adhesive ruptures. The thickness of the adhesive must be optimized to enhance the adhesion and to prevent the adhesive layer acts as a separate material having mechanical properties of low resistance [7].

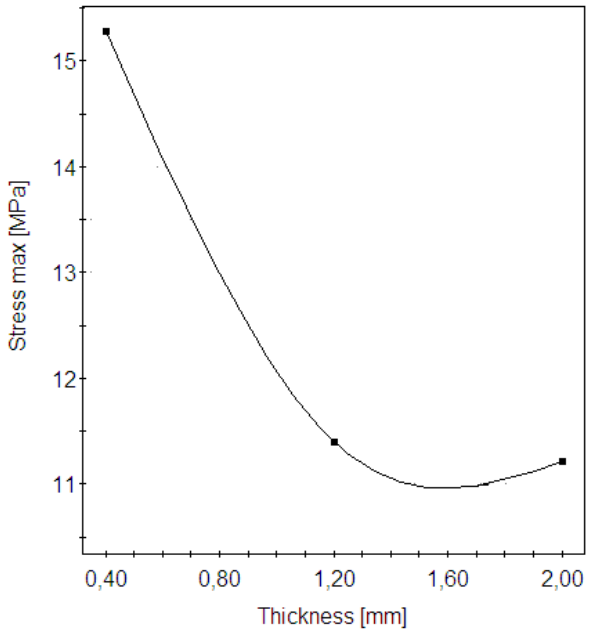

Fig. 4 Influence of the thickness of the layer of adhesive on the maximum stress distribution

4.3. Influence the recovery length

We studied the influence of the length of overlap varying from 20 mm to 60 mm, a width of 25 mm, a thickness of 1.2 mm and a shear modulus G = 600 MPa, Fig. 5 illustrates the influence in which we see an increase in the length of the overlap increases the maximum stress (tangential τ_{ZY}) in the bonded joint. We can conclude that increasing the length of overlap leads to an increase of the maximum stress (tangential τ_{ZY}). [7,8,9]

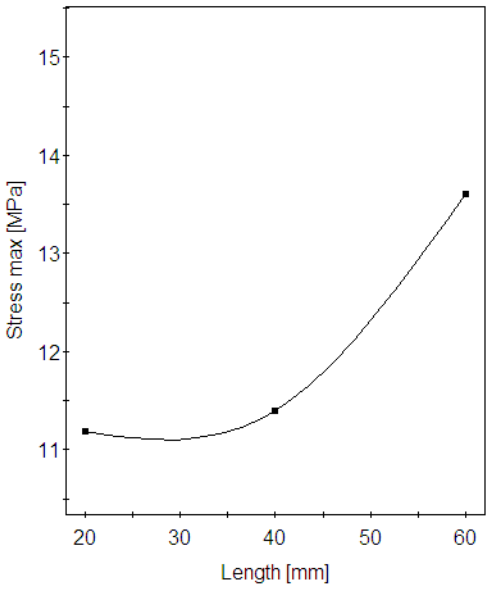

Fig. 5 Influence of the length of the recovery on the maximum stress distribution

4.4. Influence the overlap width

In this section, we will study the influence of the overlap width varying from 10 mm to 40 mm, a length of 40 mm, a thickness of 1.2 mm, the mechanical characteristics of the assembly single lap. Fig. 6 shows the influence of the overlap width on the maximum stress distribution (tangential τ_{ZY}) in the adhesive seal. It was found that the maximum stress (tangential τ_{ZY}) overlaps following increases while the overlap width decreased. Increasing the width of overlap causes a decrease in the maximum stress, under the effect of increasing the bonding surface. However, there is a cap to cover width optimal because only the ends of the seal actually work while the center barely supports any effort [10,11].

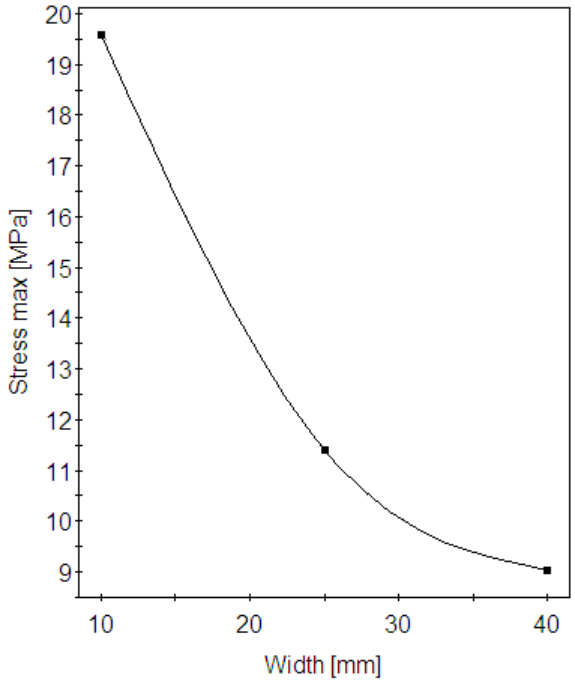

Fig. 6 Influence of the overlap width on the maximum stress distribution

5. Effects of interactions on the response

The MODDE 5.0 software (modeling and DEsign) is a Windows executable program for the development and statistical evaluation of experiments. It predicted responses based on the parameters: width, length, thickness and shear modulus.

5.1. Interaction between thickness and modulus G

In the following analysis we expand our comments taking into account the time of an interaction between two factors we keep the three factors constant. This decision allows us to visualize the variation of maximum stress by a graph in three dimensions.

Fig. 7, usually called “Iso curves” and that is the projection of the surface 6 of the plan, In this curve analysis shows that the increase of the shear modulus of the adhesive has a negative influence on the response (maximum stress of the adhesive), we find that the range of shear modulus between 200 and 600 MPa, but the thickness of the adhesive plays the opposite role, more the thickness increases more stress in the adhesive decreases and the shear deformation is small ($\tau = G\,\gamma$).

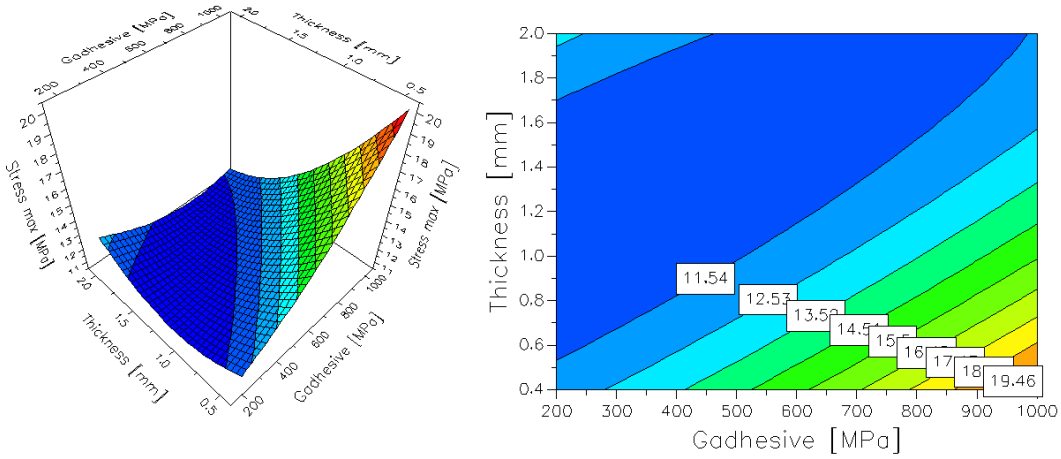

Fig. 7 Effect of interaction between modulus G and the thickness of the maximum stress

5.2. Interaction between thickness and length

The method in this case is to fix the shear modulus of the adhesive and the joint width and to vary the length and thickness of the adhesive joint (Fig. 8). It is observed that the interaction between the adhesive thickness and the overlap length provides an area of adhesive; the thickness varies between 1.4 and 2 mm, and the length between 20 and 35 mm.

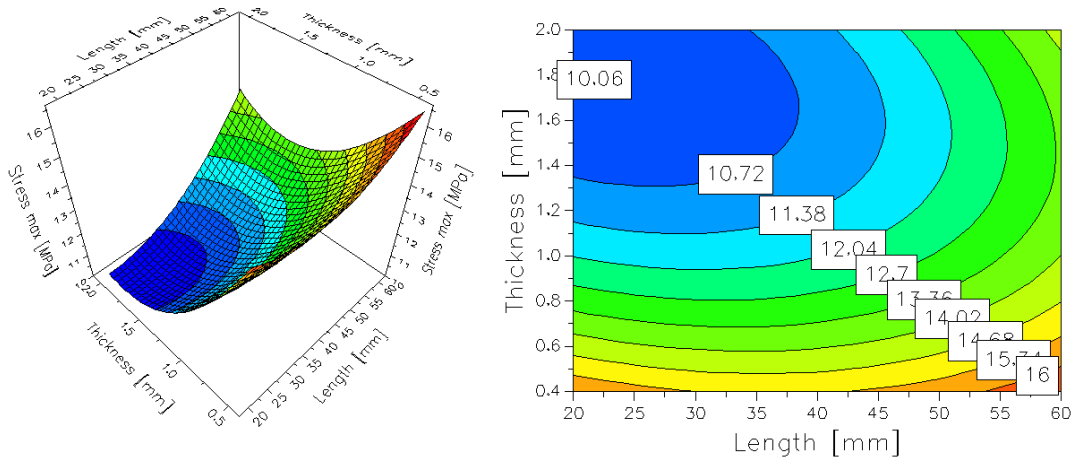

Fig. 8 Effect of the interaction between length and thickness of the maximum stress

5.3. Interaction between thickness and width

Figure 9 illustrate the variation of the stress in the adhesive function of thickness and width factor of the bonded joint. In This case the thickness has no effect on the constraint but increasing the width decreases the stress to a minimum value 10.2 MPa.

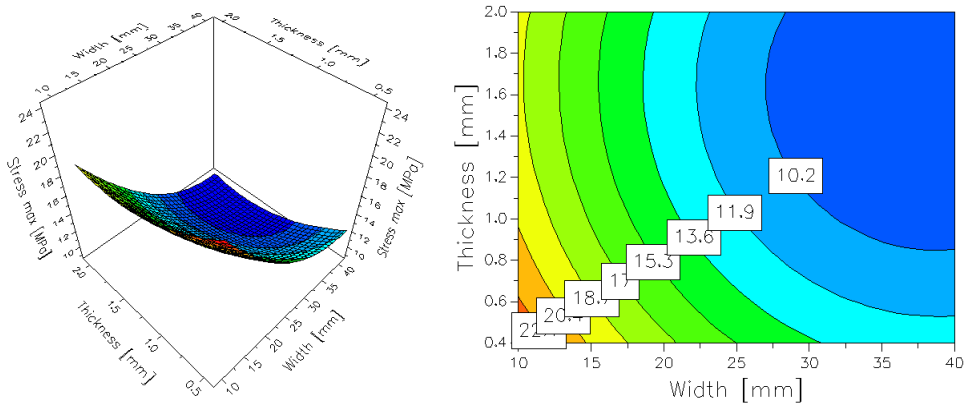

Fig. 9 Effect of interaction between width and thickness of the maximum stress

5.4. Interaction between length and width

Fig.10 shows the effect of two factors length and width of the overlap. For values of the length measured between 20 and 60 mm, the stress remains max if the width varies between 10 and 20 mm. If this value is exceeded it means that the width varies between 25 and 40 mm and the stress decreased to reach the minimum value 9. 3 MPa.

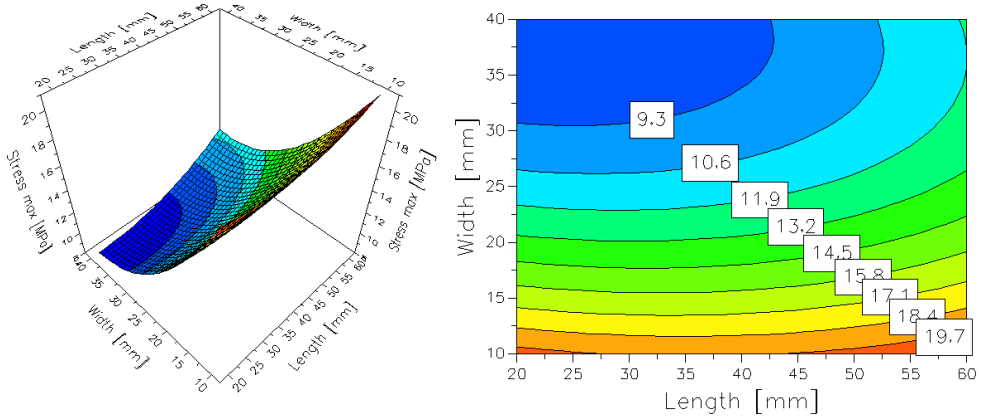

Fig. 10 Effect of interaction between width and length on the maximum stress

6. Effect of different factors on overlap

It is significant to study the effect of the various factors on joining. It is initially necessary to know which factors have the greatest influences and then how the sizes react to these factors.

We present the effects of factors using a bar graph. This diagram shows the effects in descending order of importance in absolute terms.

Figure 11 shows the effects of all the factors under (linear, quadratic and cross).

	1	2	3	4	5
1	Stress max	Coeff. SC	Std. Err.	P	Conf. int(±)
2	Constant	11,3968	1,05468	1,54035e-007	2,29793
3	G	1,50543	0,561278	0,0199576	1,22291
4	e	-1,69086	0,561279	0,0108124	1,22292
5	L	1,00872	0,561279	0,0974979	1,22292
6	W	-4,39417	0,561279	4,68836e-006	1,22292
7	G*G	0,682936	1,2356	0,590605	2,69212
8	e*e	1,2801	1,2356	0,320621	2,69212
9	L*L	0,694057	1,2356	0,584647	2,69212
10	W*W	2,01443	1,2356	0,128981	2,69212
11	G*e	-1,67616	0,495341	0,00542931	1,07925
12	G*L	-0,520005	0,495341	0,314497	1,07925
13	G*W	-0,0323364	0,495341	0,949025	1,07925
14	e*L	0,589921	0,495341	0,256702	1,07925
15	e*W	0,102253	0,495341	0,839916	1,07925
16	L*W	0,554001	0,495341	0,285276	1,07925
17					
18	N = 27	Q2 =	0,642	Cond. no. =	6,1592
19	DF = 12	R2 =	0,910	Y-miss =	0
20	Comp. = 2	R2 Adj. =	0,806	RSD =	2,8620
21				Conf. lev. =	0,95

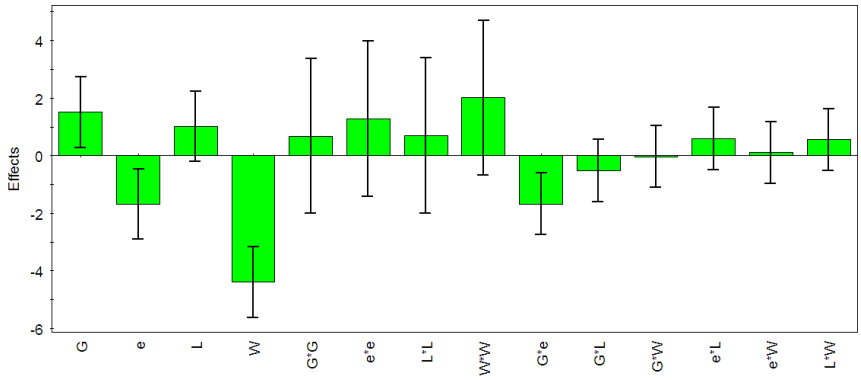

Fig. 11 Effects of factors on the maximum stress

Mathematical model: The experimental designs used in this study is a quadratic complete plan, which one treats with a mathematical model of the second degree, the mathematical model is then expressed as follows

$$\begin{aligned}\tau_{zy} &= 11.3968 + 1.50543\left(\frac{G-G_{moy}}{\Delta p_G}\right) - 1.69086\left(\frac{e-e_{moy}}{\Delta p_e}\right) + 1.00872\left(\frac{L-L_{moy}}{\Delta p_L}\right) - 4.39417\left(\frac{w-w_{moy}}{\Delta p_b}\right) \\ &+ 0.682936\left(\frac{G-G_{moy}}{\Delta p_G}\right)^2 + 1.2801\left(\frac{e-e_{moy}}{\Delta p_e}\right)^2 + 0.694057\left(\frac{L-L_{moy}}{\Delta p_L}\right)^2 + 2.01443\left(\frac{w-w_{moy}}{\Delta p_b}\right)^2 \\ &- 1.67616\left(\frac{G-G_{moy}}{\Delta p_G}\right)*\left(\frac{e-e_{moy}}{\Delta p_e}\right) - 0.520005\left(\frac{G-G_{moy}}{\Delta p_G}\right)*\left(\frac{L-L_{moy}}{\Delta p_L}\right) - 0.0323364\left(\frac{G-G_{moy}}{\Delta p_G}\right)*\left(\frac{w-w_{moy}}{\Delta p_b}\right) \\ &+ 0.589921\left(\frac{e-e_{moy}}{\Delta p_e}\right)*\left(\frac{L-L_{moy}}{\Delta p_L}\right) + 0.102253\left(\frac{e-e_{moy}}{\Delta p_e}\right)*\left(\frac{w-w_{moy}}{\Delta p_b}\right) + 0.554001\left(\frac{L-L_{moy}}{\Delta p_L}\right)*\left(\frac{w-w_{moy}}{\Delta p_b}\right)\end{aligned} \quad (4)$$

7. Checking the optimum focus

According to the analysis by the "modde5.0" software, we find that the optimal verification point is simple, according to Figure 12, the values given by the program, we note that the maximization of the stress in the adhesive can be achieved by experience that includes the values of the thickness equal to 1.78mm, its width is equal à40mm, its length is equal to 20mm, and its shear modulus is equal to 437 MPa.

Iteration: 573 Iteration slider:

	1	2	3	4	5	6	7
	module G	Epaisseur	Longueur	Largeur	contrainte max	iter	log(D)
1	437,312	1,7833	20,0167	39,9997	6,8626	181	-10
2	766,487	1,9998	20,0322	35,2979	7,6656	145	-0,9231
3	624,326	1,9995	23,4097	39,2617	7,3105	307	-1,4357
4	200,324	1,26	20,1514	39,9924	6,4816	387	-10
5	464,818	1,6696	20,0025	38,2725	6,8466	149	-10
6	586,422	1,9999	20,01	35,3885	7,4357	208	-1,2189
7	201,762	1,3592	20,0076	40	6,4992	573	-10
8	464,818	1,6696	20,0025	38,2725	6,8466	149	-10

Fig. 12 Search the optimal values using the 5.0 software MODDE

8. Validation of the model

Figure 13 compares the results calculated by the finite element method (stress measured) and those calculated by the experimental design (stress optimized). Note that the results calculated from the proposed model are in agreement with the experimental results. This model allows us to obtain a better prediction of the maximum stress (tangential τ_{ZY}) single seal cover.

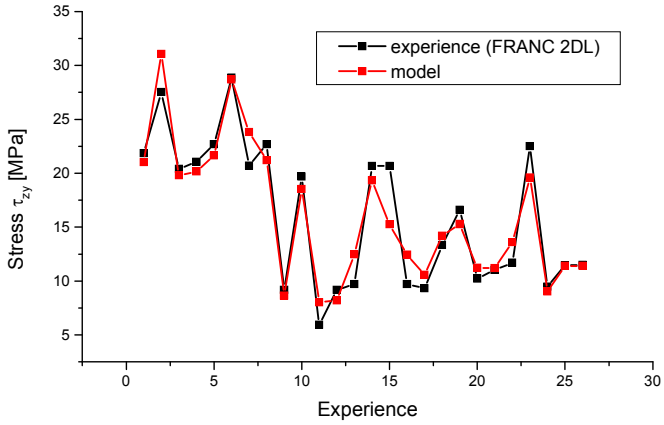

Fig. 13 Comparisons between numerical stress values and those obtained by the model

9. Conclusion

As a conclusion, we can say that these studies focused mainly on the influence of four factors which are the length of the overlap, the thickness of the adhesive, the width of the overlap and the shear modulus of the adhesive G. It is therefore to understand and explain how to act on them and the link between each other and also, we have seen. To study the influence of these factors on the maximum stress one call upon the methodology of the experimental designs which make it possible to reach a better knowledge of the phenomena observed by a minimum of tests. The essential advantage of this method, it is fast and unambiguous interpretation results of the tests. The main advantage of this method is rapid and unambiguous interpretation of test results. This study has shown that the most influential parameters are in order: length, thickness, width and the shear modulus G, The plans given by the experience model allows us to get maximum stress which decreases the bonded joint.

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