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Effect of modifying the thickness of the plate at the level of the overlap length in the presence of bonding defects on the strength of an adhesive joint

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Abstract. Adhesive bonding is currently widely used in many industrial fields, particularly in the aeronautics sector. Despite its advantages over mechanical joints such as riveting and welding, adhesive bonding is mostly used for secondary structures due to its low peel strength; especially if it is simultaneously exposed to temperature and humidity; and often presence of bonding defects. In fact, during joint preparation, several types of defects can be introduced into the adhesive layer such as air bubbles, cavities, or cracks, which induce stress concentrations potentially leading to premature failure. Indeed, the presence of defects in the adhesive joint has a significant effect on adhesive stresses, which emphasizes the need for a good surface treatment. The research in this field is aimed at minimizing the stresses in the adhesive joint at its free edges by geometric modifications of the ovelapping part and/or by changing the nature of the substrates. In this study, the finite element method is used to describe the mechanical behavior of bonded joints. Thus, a three-dimensional model is made to analyze the effect of defects in the adhesive joint at areas of high stress concentrations. The analysis consists of estimating the different stresses in an adhesive joint between two 2024-T3 aluminum plates. Two types of single lap joints (SLJ) were analyzed: a standard SLJ and another modified by removing 0.2 mm of material from the thickness of one plate along the overlap length, taking into account several factors such as the applied load, shape, size and position of the defect. The obtained results clearly show that the presence of a bonding defect significantly affects stresses in the adhesive joint, which become important if the joint is subjected to a higher applied load. On the other hand, the geometric modification made to the plate considerably reduces the various stresses in the adhesive joint even in the presence of a bonding defect.

Keywords: adhesive; bonding defect; modified lap joint; single lap joint; stresses

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1. Introduction

Due to its advantages over traditional joining processes, adhesive bonding is widely used in different industrial fields, especially aerospace and automotive (Hara and Özgen 2016). This joining technique is easy to implement, presents a more uniform stress distribution, and offers the possibility to efficiently join materials of different nature (Wu 1997). The single lap joint (SLJ) is the most used to characterize the adhesive under a tensile loading, and it presents different stresses in the adhesive as a result of the non-linearity of the applied load, which creates a bending moment. Adams (1997) showed that the edges of the joint experience a high concentration of shear and peel stresses due to geometric and material discontinuities, in addition to the bending effect caused by the load eccentricity. Several methods have been suggested by researchers (Matthews 1982, Shang 2019, Nemati 2018) to optimize the SLJ performance. These modification methods can be material and/or geometric. Material modification is aimed at optimizing the adhesive stiffness and type. However, attempts at geometric modification involve altering both the plate and adhesive edges (adhesive beading and/or plate bevelling (Shishesaz 2013, Elhannani 2016, Mokhtari 2013).

Da Silva (2006), Tang (2013), Banea (2018) highlighted various joint design parameters taking into account bond stiffness, adhesive type and thickness, overlap length, and bond-adhesive interface properties.

Among the ideas regarding material modification, Kim (2004) proposed a stepped lap joint for a composite structure. It was concluded that cracking was initiated at the end of the lap portion producing delamination of the composite. On the other hand, the average tensile load of the joint increased for higher number of steps and bond edge angle, while shear stresses decreased at the overlap ends.

Adams (1997) characterized the strength of an adhesive joint in the presence of a fillet, and the influence of the adhesive bead angle was highlighted. The results clearly showed that the major stress concentrations at the edges of the adhesive can be reduced if the bead angle is optimized. On the other hand, Da Silva and Adams (2007) took into consideration the effect of internal bevelling of the plates with a bead of adhesive to reduce the high peel stress concentrations. The joint strength could be improved by varying the bevelling angles of the adhesives and the adhesive bead if the thermal stresses were not significant.

Da Silva and Campilho (2015) proposed methods to improve the joint strength by using adhesive fillets to reduce peeling or cleavage stresses. Akpinar (2013) investigated the effect of adhesive fillets on the flexural strength of the assembly. Different SLJ types (with and without fillets) were tested. The numerical results showed that the adhesive fillet reduced the maximum stress at the lap ends.

Doru (2014) showed that the presence of an adhesive fillet can considerably improve the SLJ load capacity by highlighting different widths of the plates to be joined. In this same context, Zielecki (2017) tested a SLJ under fatigue loading by varying the bevel angle of the plates and the adhesive fillet angle. The authors showed that the fatigue strength of the joint is significantly affected by modifications made to the plates' edges and the adhesive. Stress distributions in the adhesive joint were addressed by Belingardi (2002), highlighting several variations in adhesive fillet angles. The authors also testified that the bead angles affected the joint strength. The use of two adhesives with variable modulus is considered one of the techniques to improve the SLJ strength. Fitton (2005) were able to show, through experimental tests, a strength improvement of an adhesive joint in the presence of a double adhesive system, when compared to a single adhesive

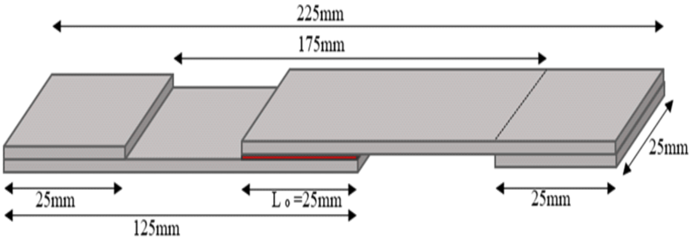


Fig. 1 Geometric model of a SLJ

joint. The proposed solution showed significant changes in the failure mode and reduction of stress concentrations.

The techniques proposed by different researchers have shown their effectiveness in relation to the joint strength, while mainly reducing the concentration of stresses in the adhesive joint. However, if the structure is exposed to environmental factors during service, this can easily lead to modifications of the mechanical properties of the adhesive, which negatively affect the joint strength. Furthermore, if the adhesive has defects, the load transfer between the substrates can be considerably reduced, leading to major stress concentrations in the adhesive joint. Subsequently, the joint strength becomes very low. Recently, research in the field of bonding has been carried out to analyse the effect of the shape, size, and position of defects in the adhesive layer on the SLJ strength. It was demonstrated that stresse increases in the adhesive joint in the presence of the bonding defect (Benchiha and Madani 2015, Kaddouri 2019, Elhannani 2017). This behaviour is significantly affected by the shape and size of the defect. In fact, the numerical analysis showed that the significant stress concentrations at the overlap edges can reach excessive values if the defect is present at these locations.

The present work is part of this context, aiming to analyse, by the finite element method, the variation of the different stresses in an Adekit A140 type adhesive joint used to join two aluminium 2024-T3 plates. To reduce the stress concentrations in the adhesive joint at the overlap edges, a modification was made to the overlap part by removing the material by 0.2mm according to the thickness of a one of the two plates. So that part of the applied load will be transmitted to the modified plate. On the other hand, the evaluation of stresses is considered taking into account the presence of a bonding defect of square or circular shape in positions with high stress concentrations in the adhesive layer. The results found in the modified joint were compared with those of a SLJ by highlighting the applied load, the position, size and shape of the defect.

2. Geometric model and mechanical properties

Two 2024- T3 aluminium plates bonded with the Adekit A-140 adhesive were considered. The SLJ has the dimensions presented in Fig. 1.

Stresses in the adhesive joint depending on the modifications made to the substrates were compared to those resulting from the SLJ, which is considered as the basic model.

A change in the thickness of a plate was made at the overlap region by removing 0.2 mm of material to ensure that the adhesive was fully introduced into the plate (Fig. 2). The material removal of 0.2 mm represents 10% of the plate thickness. This configuration has already been numerically studied, and showed higher strength than a conventional SLJ (Bezzerrouki 2019).

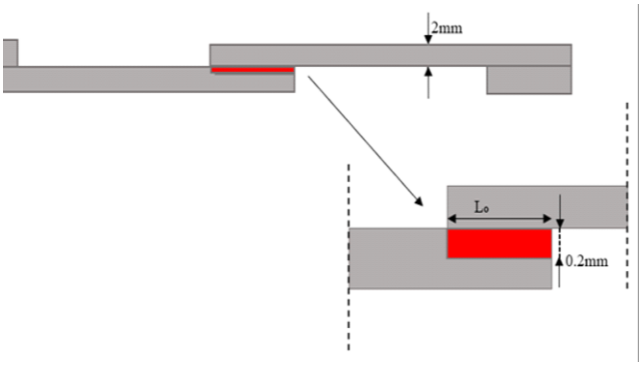
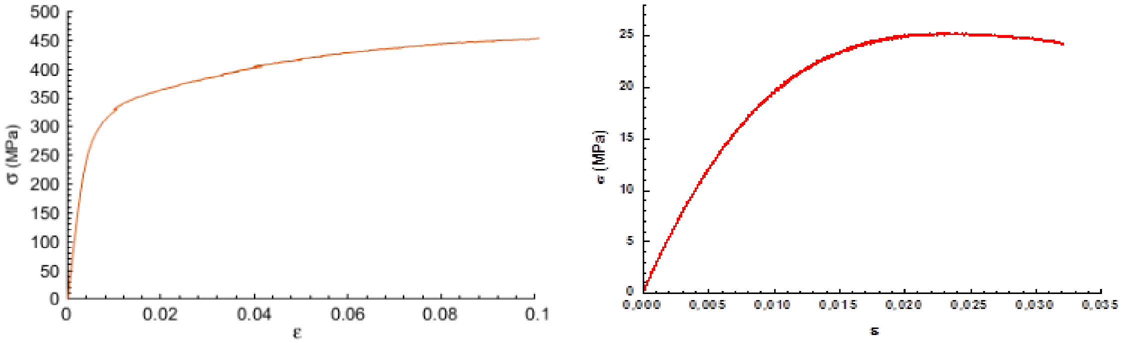


Fig. 2 Modified geometrical model (material removal of 0.2 mm from the plate thickness)



(a) Aluminium plate (b) Adekit A140 adhesive (Madani *et al.* 2010)

Fig. 3 Tensile stress-strain

The curves shown in Fig. 3 result from tensile testing carried out on the aluminium plate (Fig. 3(a)) and Adekit A-140 adhesive (Fig. 3(b)). The Adekit A140 adhesive was chosen for this study due to its good mechanical performance at high temperatures and resistance to aging and aggressive environments. This structural adhesive is atwo-component epoxy based on modified epoxy resin, marketed in France by the company Axson and Hexcel composite. This adhesive comes in the form of a very viscous liquid packaged in cartridges.

Modelling these two materials in the ABAQUS software (Smith 2009) requires the introduction, in addition to the Young's modulus and the Poisson's coefficient, of the plastic curve (stresses and strains associated at the plastic zone) (Madani 2010).

3. Loading and boundery conditions

The applied boundary conditions are classical for SLJ models under a tensile load. The joint is oriented along the x direction, y is the width direction, and z is the normal direction to the joint plane. It is well known that the results from a numerical finite element model differ with the imposed boundary conditions. The work of Waheb (2002) suggests different boundary conditions for a SLJ model.

For the current model, clamping the edge of plate 1 and applying a tensile stress at the edge of plate 2 were considered.

4. Mesh descriptions

For the analysis, two SLJ models (Figs. 1 and 2) were modelled with the Abaqus commercial code (Smith 2009). The structure has been meshed differently depending on the joint location, with a refined mesh along the overlap length and adhesive layer regions. The density of mesh elements in the two substrates at the overlap is the same as that at the adhesive layer. Far from the joining region, the mesh is coarsened (Fig. 5). The mesh density is of great importance for the analysis of the structure. The element type chosen for the two structures is of type C3D8R, which is the most favourable for meshing bonded structures.

The joint is made up of three substrates (adhesive and two plates), each considered as an independent three-dimensional structure subjected to a state of plane stress with elastoplastic behaviour. The adhesive layer is considered to be a third homogeneous and isotropic material with elastoplastic behaviour.

In the SLJ, the adhesive layer deforms mostly under shear stress and, given the non-collinearity of the two applied load, it is also subjected to peel stresses. The contact between the adherends and adhesive is considered to be perfect. In the overlap length, the nodes between the different joint components are common to ensure continuity of deformation and stress. By modelling the adhesive layer in the form of a third material allow to introduce its traction curve presented in Fig. 3. The idea of modelling the adhesive as being a third material was the idea of Naboulsi and Mall (1996) and recently by several authors such as (Benchiha 2015, Kaddouri 2019, Elhannani 2017, Bezzerrouki 2019, Madani 2010).

On the other hand, to evaluate the effect of the load applied on the value of the different stresses in the adhesive joint, it was subjected to a stress of 15 MPa and 20 MPa.

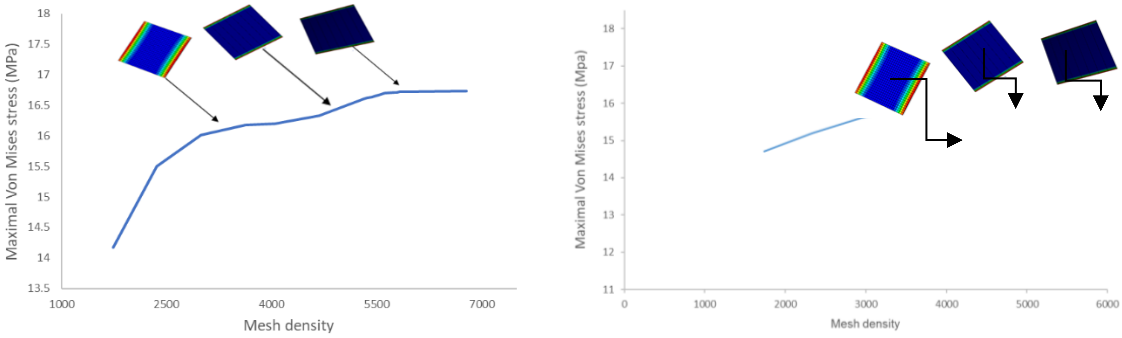
4.1 Mesh sensitivity

The density of mesh elements has an impact on the estimation of stresses in the adhesive joint and, consequently, on the magnitude of stress concentrations. To arrive at a reliable model, the density of mesh elements was varied essentially at the overlap to achieve a well refined structure. For each mesh density, the maximum value of von Mises stresses in the adhesive joint was assessed. Fig. 4 shows the variation of von Mises stresses for different densities, for both basic SLJ and modified joints.

For the basic model, the von Mises constraints increase with the density of the mesh elements, until stable stress values are reached. For our two chosen models, an average mesh was considered so that the surface presents a well-refined mesh and at the same time ensures optimal calculation time.

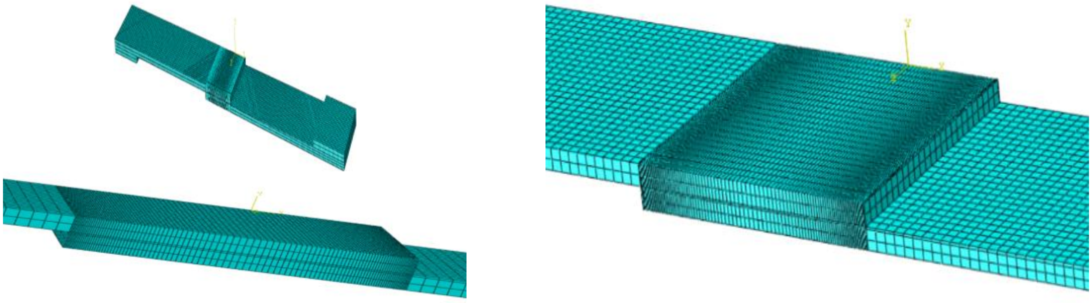
4.2 Element type

Once we made the choice on the type of elements which is the C3D8R for modelling the structures, The total number of elements is 15825 for the base model and 15750 for the modified model. The geometrical model of the joint is presented in Fig. 5.



(a) for basic SLJ model (b) for modified model (applied load of 15 MPa)

Fig. 4 Variation of the maximum von Mises stresses according the density of mesh elements in the adhesive layer



(a) for basic SLJ model (b) for modified model (applied load of 15 MPa)

Fig. 5 Variation of the maximum von Mises stresses according the density of mesh elements in the adhesive layer

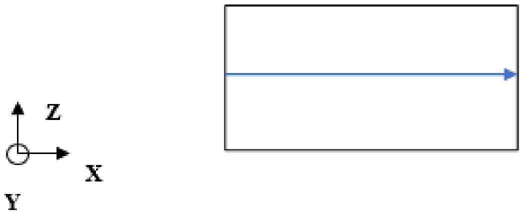


Fig. 6 Line of the stress distribution (path)

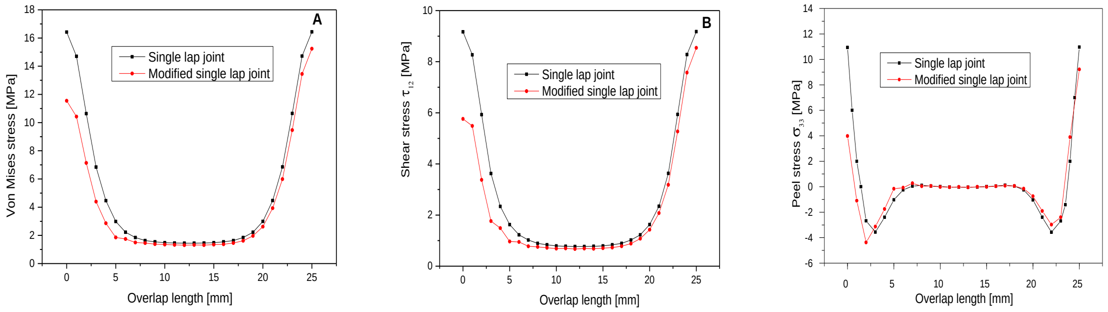
5. Results and discussion

5.1 Stress distribution in the adhesive layer

To analyse the stress distributions in the adhesive layer, the mid-width of the adhesive was considered (Fig. 6).

5.1.1 Applied stress 15 MPa

To evaluate the effect of the modification made to the joint by removing 0.2 mm from a single



(a) von Mises (b) Shear (c) Peel

Fig. 7 Stress distribution in the adhesive joint along the overlap length for a 15 MPa stress (comparison between basic and modified 0.2 mm model)

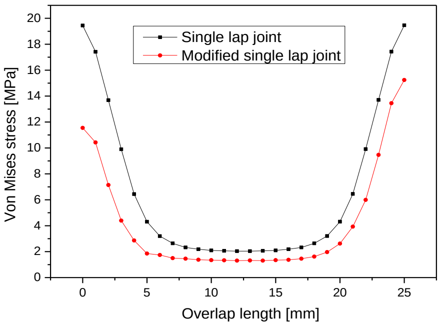


Fig. 8 von Mises stress distribution in the adhesive joint along the overlap length (comparison between basic and modified 0.2 mm model)

plate, a comparison of the different stresses in the adhesive along the overlap length is presented in Figs. 7 and 8.

5.1.2 Applied stress 20 MPa

It is clearly seen that the gradient of the stress distribution in the adhesive joint is identical irrespectively of the joint type, and that the maximum stresses are always located at the overlap edges, while the overlap core is practically inactive. However, for the modified joint design, there is a difference in the stresses at the two edges when compared to the basic SLJ. The modification made to the plate considerably reduces the different stresses in the adhesive joint. A reduction of almost 2 MPa is observed between the two models for the von Mises stresses and varies from one edge to the other.

The removal of material from the plate generates a slight concentration of stress in the plate, which reduces the transfer of the applied load to the adhesive and, consequently, there is a slight increase of von Mises stress in the plat (Figs. 7 and 8).

5.2 Effect of the bonding defect presence

Load while the core remains in most cases inactive. Therefore, the four positions of the defect are located at the overlap edges (Fig. 9). Two defect positions are on side A of the adhesive, which

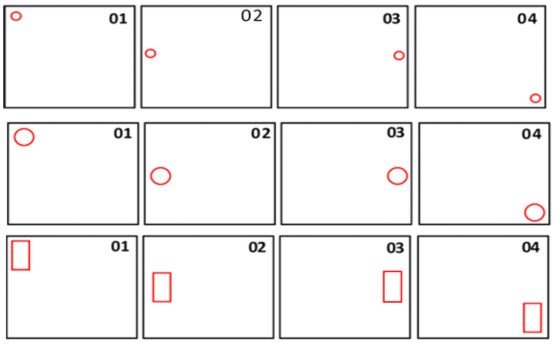


Fig. 9 The four positions of the defect-square and circular shape

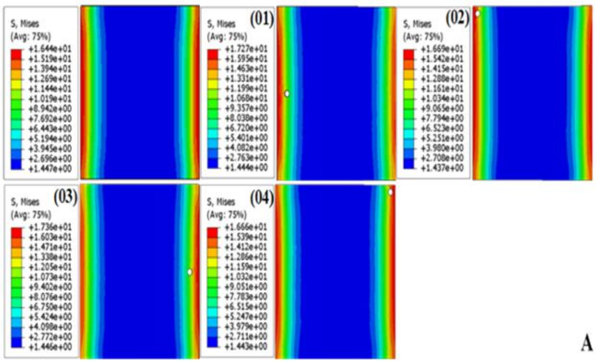


Fig. 10 von Mises stresses in the adhesive joint in the presence of circular bonding defect (*D*=1 mm) and applied load of 15 MPa (four selected positions1, 2, 3, and 4)

is in contact with the free edge of the plate (position 1 and 2), and two others are on side B, which is in contact with the plate (positions 3 and 4).

In all tested configurations, the geometric model of the different joints is always the same, apart from the presence of a bonding defect in the adhesive layer.

5.2.1.1 Basic model

Circular bonding defect of 1 mm diameter

In this case, the basic SLJ was evaluated, subjected to a stress of 15 MPa in the presence of a circular defect with diameter *D*=1 mm.

The different stresses in the adhesive joint are shown in Fig. 10.

The stresses in the adhesive joint clearly show that the von Mises stress concentration (Fig. 10A) is always at the overlap edges, even in the presence of the bonding defect and whatever is its position. On the other hand, the length of the inactive zone in the overlap is very important compared to the most stressed zones. Even in the presence of a bonding defect, the core of the adhesive is still inactive.

von Mises stresses vary depending on the position of the defect, with a maximum value when the defect occurs in position 3. An increase of 0.8 MPa is observed for a circular defect of 1 mm in diameter. Whatever the position of the defect at the edge, the stress value at the middle of the overlap remains unchanged.

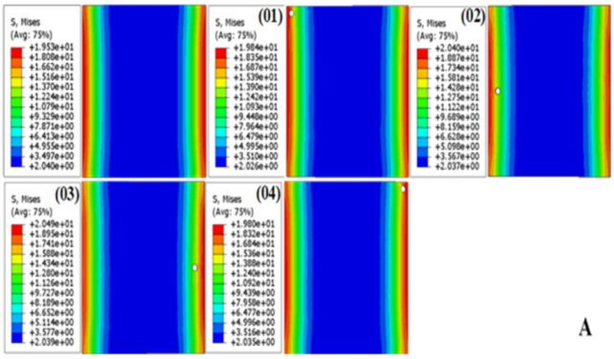


Fig. 11 von Mises stresses in the adhesive joint with the presence of circular defect (1 mm) and load of 20 MPa (four selected positions 1, 2, 3, and 4)

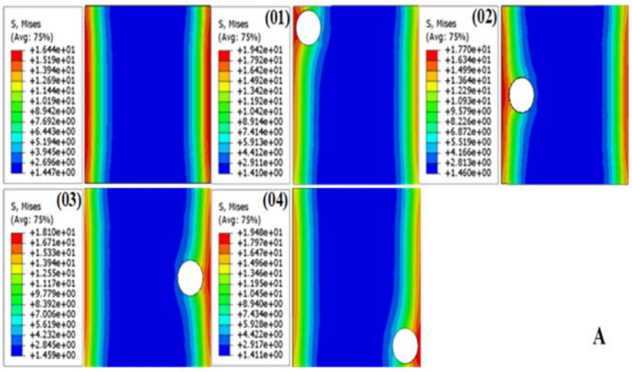


Fig. 12 von Mises stresses in the adhesive joint with the presence of circular defect (5 mm) and load of 15 (MPa) (four selected positions 1, 2, 3, and 4)

By increasing the applied stress to 20 MPa, the stress concentration in the adhesive layer with and without defect remains almost the same at both edges with an inactive core, although the value of the different stresses increases (Fig. 11).

In the presence of the defect, an increase in von Mises stresses from 19.53 to 20.49 (MPa) has been observed.

Circular bonding defect of 5 mm diameter

By increasing the size of the defect up to 5 mm in diameter and under a stress of 15 MPa, von Mises stresses increase sharply to a high value. This difference in value between von Mises stresses for the case without and with defect depends on the position of the defect. The highest value is always noted for the defect in position 4. For this size of defect and whatever its position, high concentration of stresses is found, whose value clearly exceeds the elastic limit of the adhesive (Fig. 12).

By increasing the applied stress to 20 MPa, and in the presence of the large defect, von Mises stresses can be close to that at the failure of the adhesive, which can cause the joint failure. A difference of 4 MPa is noted for the position 4 of the defect, on the other hand whatever the position of the defect the values of the Von Mises stress are high (Fig. 13).

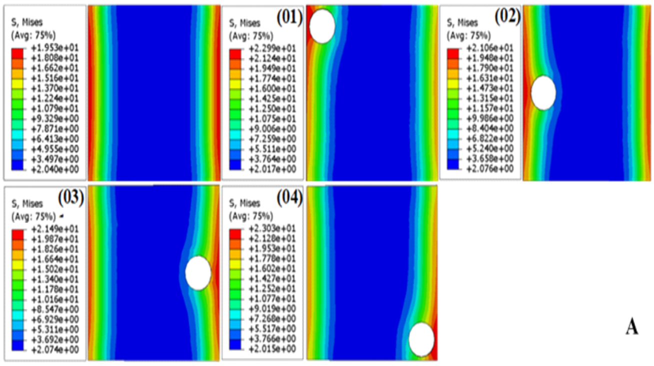


Fig. 13 von Mises stresses in the adhesive joint with the presence of circular defect (5 mm) and load of 20 MPa (four selected positions1, 2, 3, and 4)

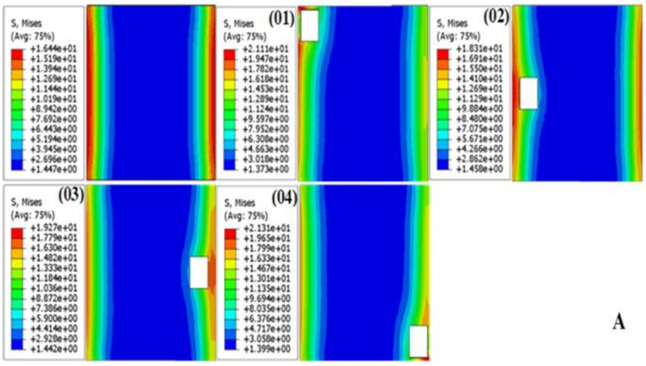


Fig. 14 von Mises stresses in the adhesive joint with the presence of rectangular defect and load of 15 MPa (four selected positions1, 2, 3, and 4)

Rectangular defect in the adhesive layer

To check the effect of the defect shape on the joint strength, the defect shape was changed to a rectangular shape so that the same area as the circular defect shape was kept. The different stresses are shown in Fig. 14.

von Mises stresses considerably increase, and the difference in stress value with a bonding defect reaches 32% if the defect is at positions 1 and 4, and 15% for the other positions. The size of the high stress zone considerably decreases compared to the no defect condition, and the joint is at risk of failure in the assembly since von Mises stresses are well above the elastic limit of the material. High stress concentrations are located at the vicinity of the defect (position 2 and 3) and especially when there is an interaction between the free edge of the adhesive and the defect (position 1 and 4).

By increasing the applied stress to 20 MPa, von Mises stresses increase sharply to high values at the adhesive edges (Fig. 15). A difference of more than 25% is observed if the defect is located at the edge end (positions 1 and 4). von Mises stresses reach the material strength. As a result, the joint strength is negatively affected and becomes reduced.

The square shape defect of the joint in positions close to the overlap edges lead to significant von Mises stresses.

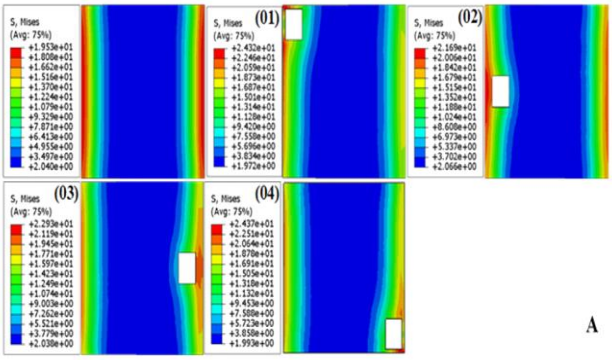


Fig. 15 von Mises stresses in the adhesive joint with the presence of rectangular defect and load of 20 MPa (four selected positions 1, 2, 3, and 4)

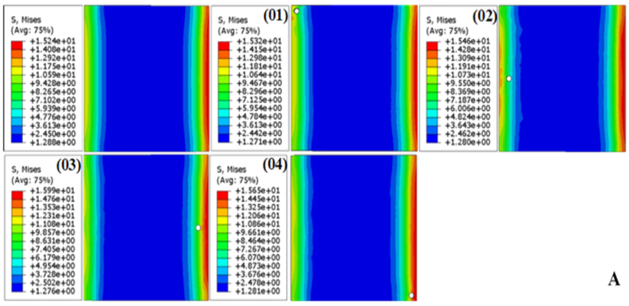


Fig. 16 von Mises stresses in the adhesive layer in the presence of circular defect (1 mm) and load 15 MPa (four positions chosen 1, 2, 3, and 4)

5.2.1.2 Modified model

Circular defect of 1 mm diameter in the adhesive layer

Stresses for this joint configuration are shown in Fig. 16. The stress distributions in the adhesive layer are nearly identical as the basic SLJ except for the stress magnitudes. The highest stresses are found for the basic SLJ, while the modification made to the model induces a reduction of the various stresses.

In the presence of the bonding defect, and for any position, there is a slight increase in von Mises stresses. Thus, for a defect of minimal size and a small load von Mises stresses will not be influenced by a significant amount.

By increasing the applied load (Fig. 17), von Mises stresses sharply increase. Stresses are always concentrated at the edge, whatever the position of the defect. an increase of about 3 MPa in the Von Mises stress is noted.

In the presence of the minimum size defect under an applied stress of 20 MPa, the stresses in the modified model always remain very low compared to those in the basic model.

Circular defect of 5 mm diameter in the adhesive layer

If the size of the defect increases (Fig. 18), the stress concentration varies depending on the position of the defect. The highest stresses are observed at the edges and in the vicinity of the defect. von Mises stresses increase by almost 3 MPa if the defect is located at the edge contacting

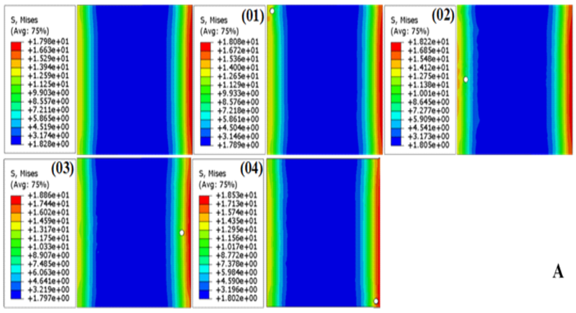


Fig. 17 von Mises stresses in the adhesive joint in the presence of circular defect (1 mm) and load 20 MPa (four positions chosen 1, 2, 3, and 4)

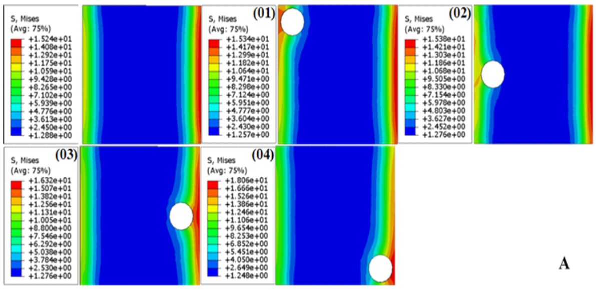


Fig. 18 von Mises stresses in the adhesive joint in the presence of circular defect (5 mm) and load 15 MPa (four defect positions chosen 1, 2, 3, and 4)

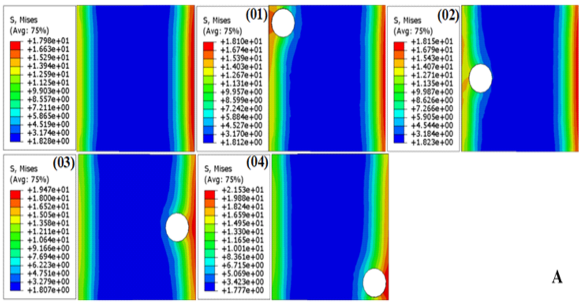


Fig. 19 von Mises stresses in the adhesive joint in the presence of circular defect (5 mm) and load 15 MPa (four defect positions chosen 1, 2, 3, and 4)

the free edge of the plate. On the other hand, for the other positions, a slight increase is observed. Position 4 of the defect always presents the highest von Mises stresses, which clearly exceed the elastic limit of the adhesive. The length of stress concentrations at the overlap edges varies and becomes just concentrated near the defect, which is at position 4.

Even by increasing the value of the applied stress, the modified model still presents lower von Mises stresses than the base model (SLJ).

By increasing the applied load (Fig. 19); von Mises stresses abruptly increase The difference in the stress value can reach 3 MPa for a defect position at the overlap edges (position 4). Unlike the basic SLJ, a slight increase of stresses is noted for the modified joint.

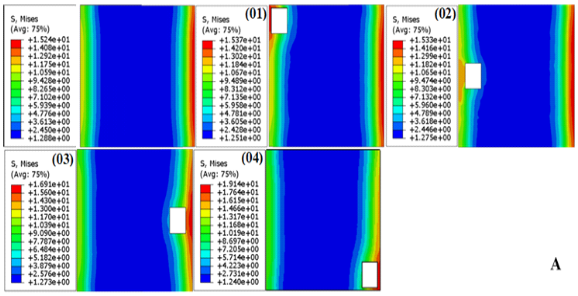


Fig. 20 von Mises stresses in the adhesive joint in the presence of a rectangular defect for a load of 15 MPa (four positions selected 1, 2, 3, and 4)

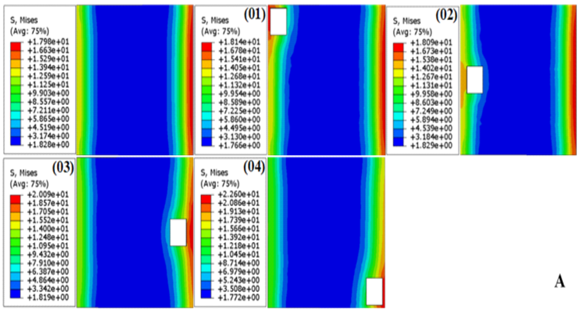


Fig. 21 von Mises stresses in the adhesive joint in the presence of a rectangular defect for a load of 20 MPa (four positions selected 1, 2, 3, and 4)

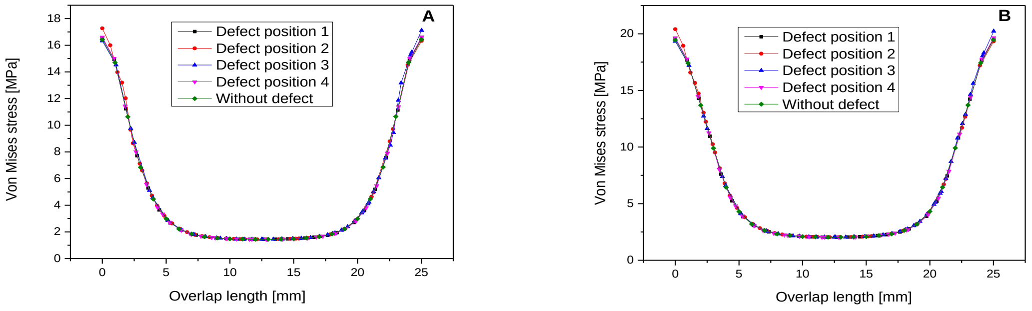
Rectangular defect

For the modified joint, the same positions of the square shape defect were highlighted (Fig. 20). For an applied stress of 15 MPa, an increase in von Mises stresses of almost 4 MPa is noted but only for the defect in position 4. For the other positions, only a slight increase is noted. This difference clearly shows that the modification made to the plate provides a higher reduction of von Mises stresses in the presence of a defect in the different positions. Contrary to the basic SLJ, the zone of high concentration always remains in the adhesive along a higher length, except for position 4, in which case the stress concentration is localized only near the defect.

By increasing the applied stress (Fig. 21), von Mises stresses increase but do not reach the limit at failure as for the case of the basic SLJ. The zone of high stress concentration remains existing at only one overlap edge, and near the defect. An increase of almost 30% on von Mises stresses is noted compared to the defect in position 4. The modified joint presents higher strength compared to the basic SLJ even for a significant applied stress.

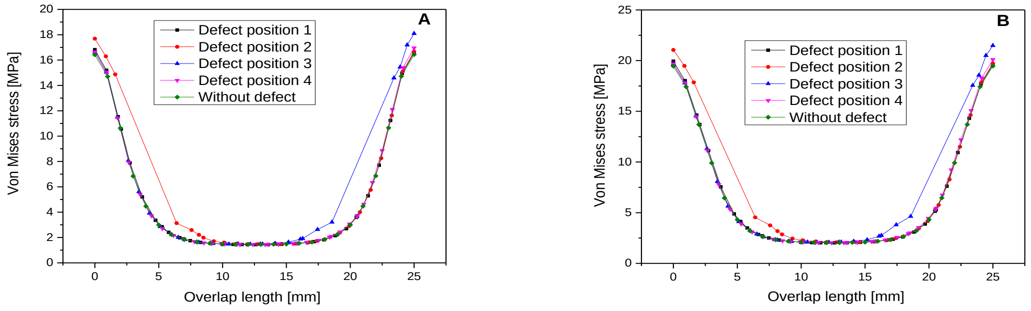
5.3 Stress distribution

The analysis of von Mises stress distributions is shown in Fig. 22. von Mises stresses are high at both adhesive edges while its core remains inactive. For the applied stress of 15 MPa regardless the defect position., the curves of von Mises stresses are practically the same, although a slight difference is to be noted at the edges depending on the position of the defect (Fig. 22A). However, if the applied stress increases; the adhesive absorbs more stress and therefore shows a slightly



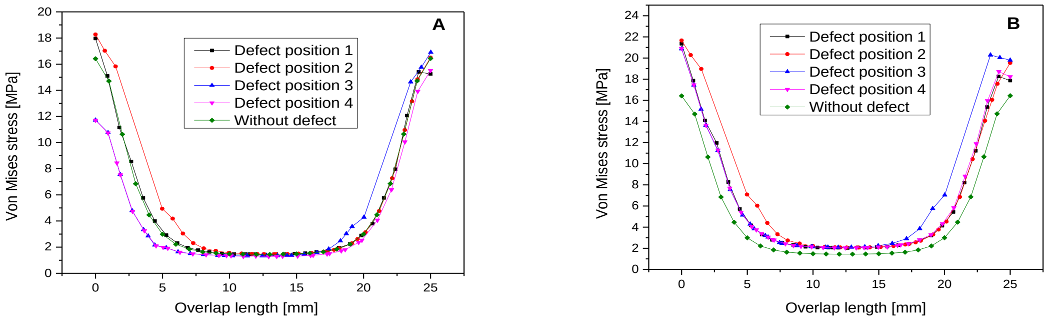
(a) 15 MPa (b) 20 MPa

Fig. 22 Variation of von Mises stresses along the overlap length, in joints with circular defect of diameter 1 mm (basic model)



(a) 15 MPa (b) 20 MPa

Fig. 23 Variation of von Mises stresses along the overlap length, in joints with circular defect of diameter 5 mm (basic model)



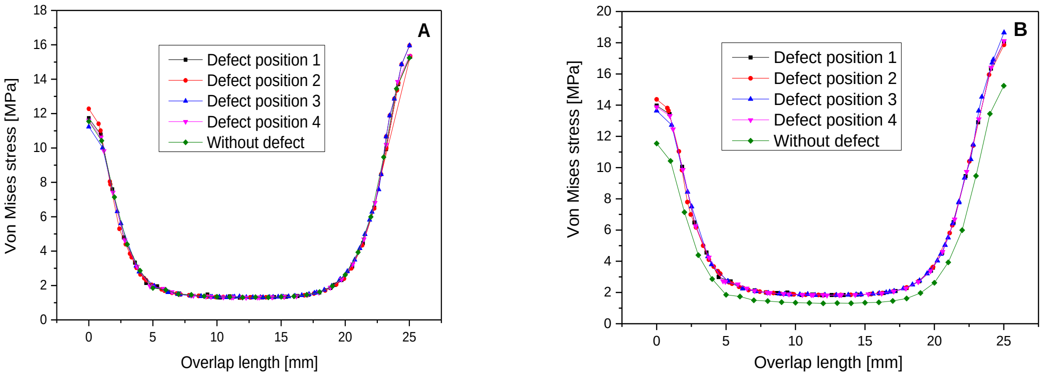
(a) 15 MPa (b) 20 MPa

Fig. 24 Variation of von Mises stresses along the overlap length, in joints with rectangular defect (basic model): (a) 15 MPa (b) 20 MPa

higher concentration than for the case of 15 MPa stress. With the defect, von Mises stresses increase and a difference is to be noted compared to the joint without defect.

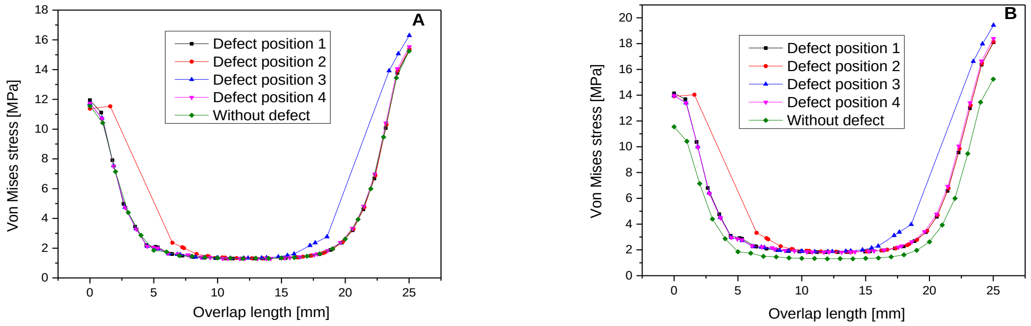
On the other hand, if the load increases, the stresses at the overlap edges considerably increase and the adhesive core becomes more and more active.

By increasing the size of the defect (Fig. 23), von Mises stresses slightly increase and vary



(a) 15 MPa (b) 20 MPa

Fig. 25 Variation of von Mises stresses along the overlap length, in joints with circular defect of diameter 1 mm (Modified model)



(a) 15 MPa (b) 20 MPa

Fig. 26 Variation of von Mises stresses along the overlap length, in joints with circular defect of 5 mm diameter (Modified model)

depending on the position of the defect and the applied stress.

If the shape of the defect changes (Fig. 24), von Mises stresses slightly increase depending on the value of the applied stress. von Mises stresses depend on the defect position.

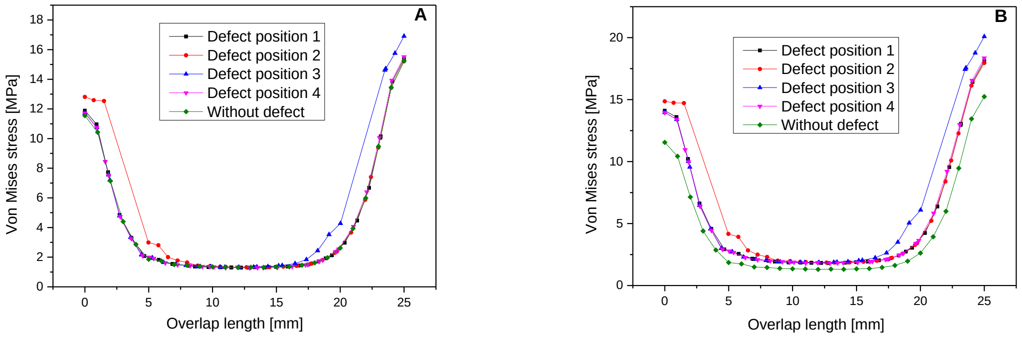
5.3.1 Modified model

For the modified model, the same remark should be noted, for a stress of 15 MPa (Fig. 25A), i.e., the position of the defect slightly affects von Mises stresses, particularly at the overlap edges. If the applied stress is increased (Fig. 25B), then von Mises stresses increase and the difference in magnitude differs depending on the position of the bonding defect. If the diameter of the defect increases to 5 mm, von Mises stresses in the adhesive layer increase, especially at the overlap edges contacting the free edge of the plate.

The core of the adhesive becomes increasingly active if the applied load is 20 MPa (Fig. 26B).

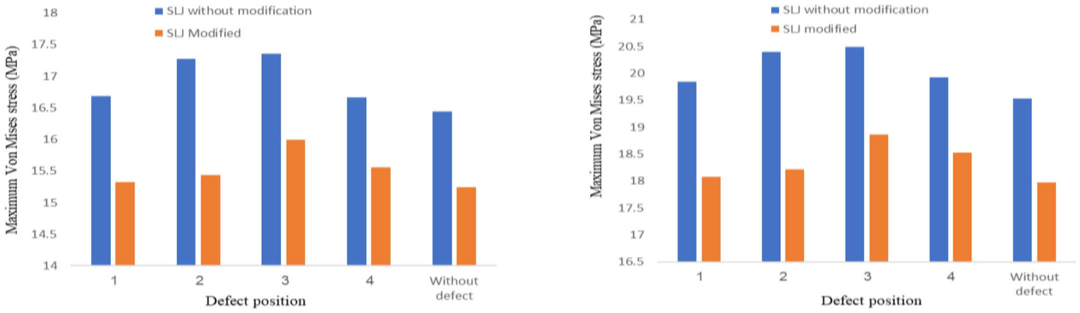
If the shape of the defect becomes rectangular (Fig. 27), von Mises stresses slightly increase and vary according to the applied load and the position of the defect.

Irrespectively of the shape or the size of the defect, von Mises stresses remain low in the modified model compared to the basic SLJ.



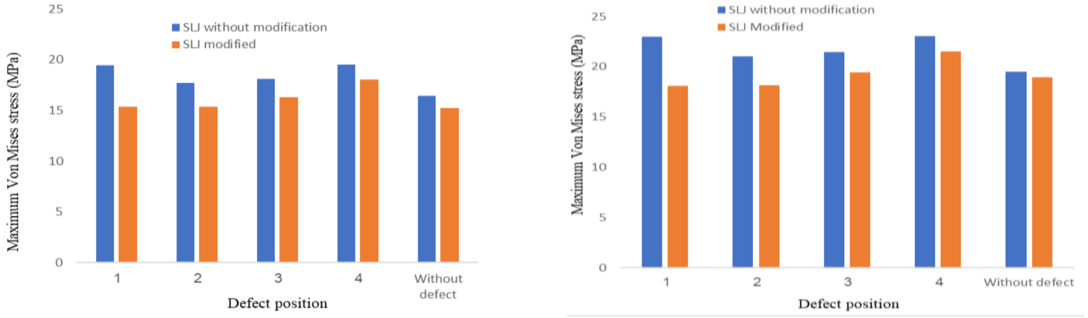
(a) 15 MPa (b) 20 MPa

Fig. 27 Variation of von Mises stresses along the overlap length, in joints with circular defect of 5 mm diameter (Modified model)



(a) 15 MPa (b) 20 MPa

Fig. 28 Maximum values of von Mises stresses along the different positions of the circular defect (defect size 1 mm diameter)



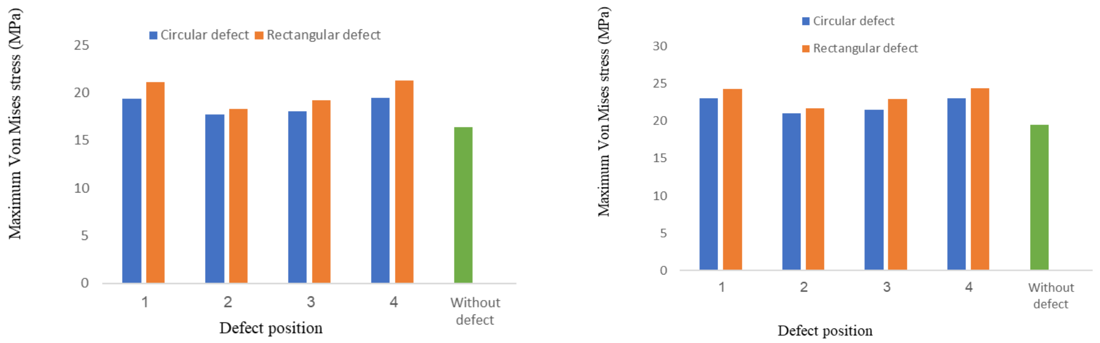
(a) 15 MPa (b) 20 MPa

Fig. 29 Maximum values of von Mises stresses depending on the different positions of the circular defect (defect size 5 mm diameter)

5.3.2 Comparisons between basic and modified models

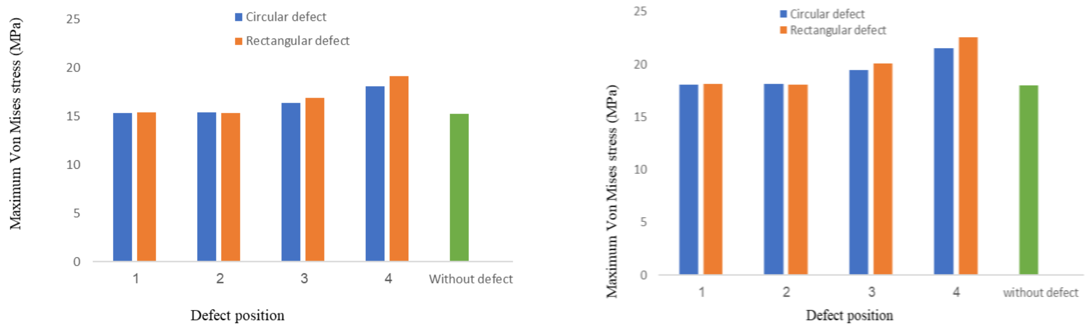
To assess the difference between the basic and the modified models, while taking into account the applied load, and the position and size of the defect, the results have

Fig. 28 represents the maximum von Mises stresses as a function of the different positions of



(a) 15 MPa (b) 20 MPa

Fig. 30 Maximum von Mises stresses depending on the different defect positions (rectangular and circular defect shape, basic SLJ)



(a) 15 MPa (b) 20 MPa

Fig. 31 Maximum von Mises stresses depending on different defect positions (rectangular and circular defect shape, modified model)

the circular defect of diameter 1 mm for a) applied stress of 15 MPa and b) 20 MPa, for the two models (basic and modified). It is clearly been grouped together in Figs. 28 to 31, which present a comparison of the maximum von Mises stresses.

Noticed that the basic model presents higher values compared to the modified model. The difference in value strongly depends on the position of the defect.

By increasing the defect size to 5 mm (Fig. 29), von Mises stresses sharply increase, although with the difference depending on the position of the defect and the joint type. The difference in von Mises stresses between the two joints increases if the size of the defect increases, while also depending on the position of the defect.

By increasing the applied load, von Mises stresses sharply increase and can induce failure for the rectangular defect. A considerable difference is to be noted if the bonding defect is at position 2 for the rectangular shape if the load increases (Fig. 30B).

The presence of the bonding defect in the adhesive layer significantly affects von Mises stresses depending on the position, the shape of the defect and the applied load. If the size of the defect is minimal compared to the bonding surface, regardless the applied stress, von Mises stresses slightly increase (Fig. 32).

However, if the applied stress is high and the defect has a considerable area compared to the

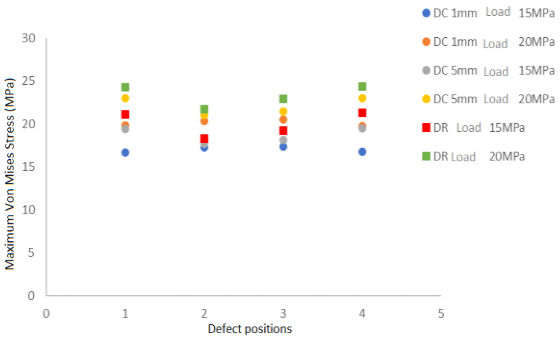


Fig. 32 Maximum von Mises stresses as a function of the position of the defect (basic model) (DC: Circular Defect; DR: Rectangular Defect)

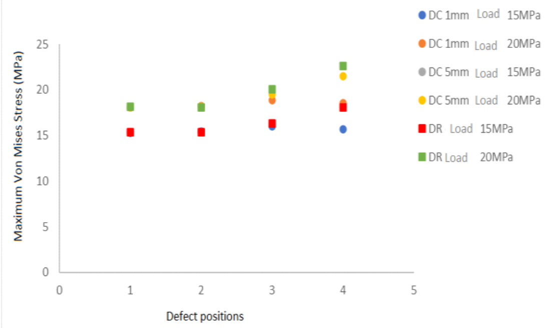


Fig. 33 Maximum von Mises stresses as a function of the position of the defect (modified model) (DC: Circular Defect; DR: Rectangular Defect)

surface of the adhesive; circular and rectangular defects, whatever their position.

By changing the shape of the defect from circular to rectangular so that the surface of the defect remains the same, von Mises stresses increase for rectangular defects, and have high values compared to the case of the circular defect (Fig. 30).

In modified joints with defect (Fig. 31), von Mises stresses are smaller in magnitude compared to the basic SLJ. A slight difference in von Mises stresses is noted between the two values of the applied stress for both circular and rectangular defects, whatever their position.

The value of the von Mises stresses dramatically increases to practically reach the failure limit of the adhesive which naturally causes the failure of the assembly. If the position of the defect is located at the overlap end in contact with the free edge of the plate, then the value of the Von Mises stress in the adhesive joint easily reaches its failure limit.

For the modified model, von Mises stresses are lower in magnitude than for the basic SLJ, whatever the size, the shape of the defect, and the applied load (Fig. 33).

6. Conclusions

This work aimed to analyse the influence of bonding defects on the strength of an adhesive joint used to join two metal/metal type plates by adhesive bonding.

The finite element analysis of the behaviour of the adhesive in the joint enables estimating the different stresses (von Mises and shear) depending on the applied load, the different sizes, shape and position of defect.

- Under an applied load and without the presence of a bonding defect, the adhesive presents good resistance especially in relation to these two edges where a high concentration of stresses is noted
- The presence of bonding defects clearly reduces the strength of the adhesive by increasing the various stresses. This increase varies depending on the position of the defect and, in most cases, a small applied load generates a stress which clearly exceeds the elastic limit of the adhesive.
- The zone of high concentration of stress at the edge of the adhesive along its entire width becomes concentrated just in the vicinity of the defect when this defect is at the undesirable position 4.
- The increase in the applied stress significantly increases the different stresses in the adhesive joint and von Mises stresses can reach the breaking limit of the adhesive.
- The proposed modification to the joint to reduce the stresses in the adhesive joint by removing 0.2 mm of material from the thickness of the plate in the overlap zone clearly shows a drop in the values of the different stresses in the adhesive joint compared to those of the basic model, including in the presence of defects.
- For both joint types, in the presence of the defect and under significant applied stress, the zone of high stress concentration considerably increases, and the adhesive core becomes increasingly active.
- The different stresses in the adhesive joint vary and differ depending on the size, shape, and position of the defect.

References

Abdel Wahab, M.M. (2000), “On the use of fracture mechanics in designing a single lap adhesive joint”, *J. Adhes. Sci. Technol.*, **14**(6), 851-865. https://doi.org/10.1163/15685610051066758.

Abdel Wahab, M.M., Ashcroft, I.A., Crocombe, A.D. and Smith, P.A. (2002), “Numerical prediction of fatigue crack propagation lifetime in adhesively bonded structures”, *Int. J. Fatig.*, **24**(6), 705-709. https://doi.org/1016/S0142-1123(01)00173-6.

Adams, R.D., Comyn, J. and Wake, W.C. (1997), *Structural Adhesive Joints in Engineering*, Springer Science & Business Media.

Akpinar, S., Doru, M.O., Ozel, A., Aydin, M.D. and Jahanpasand, H.G. (2013), “The effect of the spew fillet on an adhesively bonded single-lap joint subjected to bending moment”, *Compos. B Eng.*, **55**, 55-64. https://doi.org/10.1016/j.compositesb.2013.05.056.

Banea, M.D., Rosioara, M., Carbas, R.J.C. and da Silva, L.F.M. (2018), “Multi-material adhesive joints for automotive industry”, *Compos. B Eng.*, **151**(15), 71-77. https://doi.org/10.1016/j.compositesb.2018.06.009.

Belingardi, G., Goglio, L. and Tarditi, A. (2002), “Investigating the effect of spew and chamfer size on the stresses in metal/plastics adhesive joints”, *Int. J. Adhes. Adhes.*, **22**(4), 273-282. https://doi.org/10.1016/S0143-7496(02)00004-0.

Benchiha, A. and Madani, K. (2015), “Influence of the presence of defects on the stresses shear distribution in the adhesive layer for the single-lap bonded joint”, *Struct. Eng. Mech.*, **53**(5), 1017-1030. https://doi.org/10.12989/sem.2015.53.5.1017.

Bezzerrouki, M., Madani, K., Sahli, A., Touzain, S. and Mallarino, S. (2019), “Innovative geometric design improves the resistance of simple metal/metal lap joint”, *Frattura ed Integrità Strutturale*, **13**(48), 491-

502. https://doi.org/10.3221/IGF-ESIS.48.47.

da Silva, L.F.M. and Adams, R.D. (2007), “Techniques to reduce the peel stresses in adhesive joints with composites”, *Int. J. Adhes. Adhes.*, **27**(3), 227-235. https://doi.org/10.1016/j.ijadhadh.2006.04.001.

da Silva, L.F.M. and Campilho, R.D.S.G. (2015), “Design of adhesively-bonded composite joints”, *Fatig. Fract. Adhes. Bond. Compos. Joint.*, 43-71. https://doi.org/10.1016/B978-0-85709-806-1.00002-1.

da Silva, L.F.M., Rodrigues, T.N.S.S., Figueiredo, M.A.V., de Moura, M.F.S.F. and Chousal, J.A.G. (2006), “Effect of adhesive type and thickness on the lap shear strength”, *J. Adhes.*, **82**, 1091-1115. https://doi.org/10.1080/00218460600948511.

Doru, M.O., Ozel, A., Akpinar, S. and Aydin, M.D. (2014), “Effect of the spew fillet on adhesively bonded single-lap joint subjected to tensile loading: experimental and 3-D non-linear stress analysis”, *J. Adhes.*, **90**(3), 195-209. https://doi.org/10.1080/00218464.2013.777900.

Elhannani, M., Madani, K., Chama, Z., Legrand, E., Touzain, S. and Feaugas, X. (2017), “Influence of the presence of defects on the adhesive layer for the single-lap bonded joint-Part II: Probabilistic assessment of the critical state”, *Aeros. Sci. Techno.*, **63**, 372-386. https://doi.org/10.1016/j.ast.2016.12.020.

Elhannani, M., Madani, K., Legrand, E., Touzain, S. and Feaugas, X. (2017), “Numerical analysis of the effect of the presence, number and shape of bonding defect on the shear stresses distribution in an adhesive layer for the single-lap bonded joint; Part 1”, *Aeros. Sci. Technol.*, **62**, 122-135. https://doi.org/10.1016/j.ast.2016.11.024.

Elhannani, M., Madani, K., Mokhtari, M., Touzain, S., Feaugas, X. and Cohendoz, S. (2016), “A new analytical approach for optimization design of adhesively bonded single-lap joint”, *Struct. Eng. Mech.*, **59**(2), 313-326. https://doi.org/10.12989/sem.2016.59.2.313

Fitton, M.D. and Broughton, J.G. (2005), “Variable modulus adhesives: an approach to optimised joint performance”, *Int. J. Adhes. Adhes.*, **25**(4), 329-336. https://doi.org/10.1016/j.ijadhadh.2004.08.002.

Hara, D. and Özgen, G.O. (2016), “Investigation of weight reduction of automotive body structures with the use of sandwich materials”, *Transp. Res. Proc.*, **14**, 1013-1020. https://doi.org/10.1016/j.trpro.2016.05.081.

Kaddouri, N., Madani, K., Bellali, M.A. and Feaugas, X. (2019), “Analysis of the presence of bonding defects on the fracture behavior of a damaged plate repaired by composite patch”, *Frattura ed Integrità Strutturale*, **13**(49), 331-340. https://doi.org/10.3221/IGF-ESIS49.33.

Kim, J.H., Park, B.J. and Han, Y.W. (2004), “Evaluation of fatigue characteristics for adhesively-bonded composite stepped lap joint”, *Compos. Struct.*, **66**(1-4), 69-75. https://doi.org/10.1016/j.compstruct.2004.04.023.

Madani, K., Touzain, S., Feaugas, X., Cohendouz, S. and Ratwani. M. (2010), “Experimental and numerical study of repair techniques for panels with geometrical discontinuities”, *Comput. Mater. Sci.*, **48**(1), 83-93. https://doi.org/10.1016/j.commatsci.2009.12.005.

Matthews, F.L., Kilty, P.F. and Godwin, E.W. (1982), “A review of the strength of joints in fibre-reinforced plastics. Part 2. Adhesively bonded joints”, *Compos.*, **13**(1), 29-37. https://doi.org/10.1016/0010-4361(82)90168-9.

Mokhtari, M., Madani, K., Belhouari, M., Touzain, S., Feaugas, X. and Ratwani, M. (2013), “Effects of composite adherend properties on stresses in double lap bonded joints”, *Mater. Des.*, **44**, 633-639. https://doi.org/10.1016/j.matdes.2012.08.001.

Naboulsi, S. and Mall, S. (1996), “Modeling of a cracked metallic structure with bonded composite patch using the three layer technique”, *Compos. Struct.*, **35**(3), 295-308. https://doi.org/10.1016/0263-8223(96)00043-8.

Nemati, G.A., Ayatollahi, M.R., Ghaffari, S.H. and da Silva, L.F.M. (2018), “Effect of reinforcements at different scales on mechanical properties of epoxy adhesives and adhesivejoints: a review”, *J. Adhes.*, **94**(13), 1082-1121. https://doi.org/10.1080/00218464.2018.1452736.

Shang, X., Marques, E.A.S., Machado, J.J.M., Carbas, R.J.C., Jiang, D. and da Silva, L.F.M. (2019), “Review on techniques to improve the strength of adhesive joints with composite adherends”, *Compos. Part B: Eng.*, **177**(15), 107363. https://doi.org/10.1016/j.compositesb.2019.107363.

Shishesaz, M. and Bavi, N. (2013), “Shear stress distribution in adhesive layers of a double-lap joint with void or bond separation", *J. Adhes. Sci. Tech.*, **27**(11), 1197-1225. https://doi.org/10.1080/01694243.2012.735914.

Smith, M. (2009), ABAQUS/CAE, User's Manual, Hibbitt, Karlsson & Sorensen, Inc.

Tang, J.H., Sridhar, I. and Srikanth, N. (2013), "Static and fatigue failure analysis of adhesively bonded thick composite single lap joints", *Compos. Sci. Technol.*, **86**(24), 18-25. https://doi.org/10.1016/j.compscitech.2013.06.018.

Wu, Z.J., Romeijn, A. and Wardenier, J. (1997), "Stress expressions of single-lap adhesive joints of dissimilar adherends", *Compos. Struct.*, **38**(1-4), 273-280. https://doi.org/10.1016/S0263-8223(97)00062-7.

Zielecki, W., Kubit, A., Kluz, R. and Trzepiecinski, T. (2017) "Investigating the influence of the chamfer and fillet on the high-cyclic fatigue strength of adhesive joints of steel parts", *J. Adhes. Sci. Technol.*, **31**(6), 627-644. https://doi.org/10.1080/01694243.2016.1229521.

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