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Static and Fatigue Performance Prediction in the Riveted and Hybrid Double Shear Lap Joints

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Abstract: By the present paper, a numerical model was proposed to estimate the fatigue life of hybrid (riveted and bonded) double lap joints. In order to enhance the performances of our double lap joints in particular the equivalent rigidity and the ultimate resistance, initially, a static study was made. From the contour plots of normal, shear and equivalent stresses, a sensitivity study was carried out on the effects of thickness of the substrates, rivet diameter and the overlap length. After that, a numerical model was developed to evaluate the fatigue life of the hybrid double shear lap joint. Comparison between riveted and hybrid joints in term of the distribution of the normal and shear stress was evaluated for two connections configurations. In addition, hysterical normal stress-strains response at critical location showed that the use of the hybrid assembly greatly improves mechanical strength and service life compared to basic double shear riveted joints.

Keywords: Fatigue life; Numerical model; Hybrid joint; Shear stresses; Strength

1. Introduction

In many complex structures, the strength, fatigue life and failure modes of the connection were critically dependent on the joining technique. For this, great attention is given to new assembly techniques in aircraft structures and in multi-material connections. For that, in riveted or bolted assemblies, commonly used in aeronautical structures, the shear strength is considered as an essential factor which must be controlled during static or fatigue stresses [1, 2, 3 and 4].

Rivets are a cheap alternative to welding and metal adhesives. It's manufactured in different shapes and structures according to the needs of construction. They are resistant to corrosion, moisture and even chemicals. On the other hand, bonded joints are regularly used in aerospace applications, the bonding of automotive components and even in the sealing of submarines and surface boats.

Under static or fatigue loading, several parameters influence the quality of the riveting, among which the effect of the complementary adhesive nature, the number, the mechanical and geometric characteristics of the rivets as well as the bonding cover length. Typically, the static strength and fatigue resistance of the different joint configurations depends on the fastener and the materials from which the joints are composed. But, riveting requires more workforces and it gives a concentration of the stresses in the connection zone. Moreover, this process damages the structural

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elements of the assembly, because it creates a hole in the two substrates through which the mechanical fixing will pass. This not only creates additional contamination pathways that can compromise the interior, but creating a hole in the assembly has an effect on structural integrity [5, 6].

For that, several industries have learned to use adhesives because of the cost, time, weight, performance and aesthetic improvements or to unlock new possibilities unattainable when using traditional fasteners. Adhesives distribute the stress of a bond over the entire surface of the bond area while riveting and mechanical fasteners concentrate the stress on specific bond points. But, it requires careful preparation of the surface of the substrate, long mixing and curing time may be required, difficult dismantling of attachments and a long term strength of adhesive bonding depends on various physical and chemical actions in the environment.

In order to ensure a durable assembly and reduce the concentration of local stresses, the hybrid assembly (bonded-riveted) is often adopted as an alternative. The use of a hybrid assembly improves the strength of the assembly by minimizing the number of rivets in the structure. From the literature, several authors have studied the behavior of the riveted and bonded joints under static and fatigue loading, aiming to predict their lifespan especially with the increasing traffic flow [7, 8]. In order to study the mechanical behavior of hybrid joints between aluminum and CFRP, Marannano and Zuccarello [9] and Dhaliwal and Newaz [10] proposed a numerical-experimental study by considering the delamination of the composite material. To analyzed the fatigue life of riveted joints, submitted to variable loadings, Horas [11] presented an innovative numerical fatigue model for assessment of riveted joint. Based on modal superposition principles, this model considers the, local geometrical, material and contact nonlinearities. The fatigue assessment of old riveted structures was investigated experimentally by Bruno [12], to analyze the fatigue behavior and the fatigue resistance of riveted joints. The statistical analysis was performed to propose alternative design S-N curves and numerically by Lehner [13]. Results of the FEM analysis based on the Monte Carlo method shown that the S-N curve for riveted was used to prevent a safe estimation of the residual fatigue life of old riveted joint.

The mechanical behaviors and failure modes of riveted and hybrid joints were investigated experimentally by Chowdhury [14]. They found that the fatigue resistance of a bonded joint is inferior to that of a hybrid joint. Under quasi-static and fatigue behaviors Zhang [15], given an experimental analysis to study the fatigue failures modes and fracture details of Self-piercing riveting joints. The impact damage propagation under quasi-static and cyclic loading of CFRP friction riveted joints was presented by Borba [16]. Two damage types were observed: delamination in the plies of the composite and failure of the rivet-composite interface. In this work, the residual strengths were estimated under different impact damage scenarios. Komorek and Godzimirski [17] tested the impact strength of lap joints, rivet and hybrid rivet-adhesive joints. The comparison of the results showed that the impact strength of the hybrid joints is greater than the sum of the impact strengths of rivet and adhesive joints. The effect of the clamping force on the fatigue life of riveted connections was experimentally and numerically analyzed by Unterweger and Derler [18] and Leonetti [19]. The authors considered that the clamping force caused by the rivet was affected the fatigue life of riveted connections. To estimate fatigue strength of hot riveted double covered joints Maljaars [20] developed a theoretical fatigue strength prediction model. The results showed that the plate width and rivet diameter ratio have obviously important on the strength but the tensile strength of the plate material has small influence. To estimate the probabilistic fatigue life and the fatigue behavior of riveted joints Leonetti [21] and Correia [22] developed a FE model. Comparison of obtained results with the fatigue experimental results, showed a good agreement. The influence of the ply angle and sheet thickness of the CFRP on the mechanical properties and failure mechanisms of riveted-bonded hybrid joints with CFRP/Aluminium have studied by Liu and Zhuang [23]. The results show that the increasing the CFRP thickness significantly improved the strength and the energy absorption of the joints. da Silva [24] proposed both experimental and numerical study to assess the fatigue behavior of a beam-to-column riveted joint using specialized commercial codes. More recently, Presse [25] developed a numerical model to estimate the fatigue life of hybrid joined connections based on material SN curves for adhesively bonded and self-piercing riveting. A validation of the fatigue life estimation shows a good agreement with test data.

Thus far, the most important research has focused on the static analysis of hybrid lap joints; however, there are few published works on the fatigue behavior, and even more on the numerical models simulating the fatigue life and the evolution of stresses concentration near the connection. For this, the present study has been proposed to further improve the knowledge of the fatigue behavior performance of hybrid (bonded-riveted) double shear lap joints. Using ANSYS software [26] a numerical model was developed to investigate both the static and the fatigue behavior of hybrid double shear lap joints made by S235 steel. Using the ANSYS/explicit dynamic software, finite element model was developed and calibrated to analyze stresses field near the connexion. Results obtained numerically in terms of normal and shear stresses, load-displacement, and stress-strain curves were compared to those given by the literature. In static analysis, effect of the substrates thickness, the rivet diameter, the load ratio, size of the lap joint on the stresses was predicted for the riveted and riveted-bonded joints. In the fatigue model, hysterical normal stress-strains response is evaluated at the Rivet, upper, Middle and lower of the substrate. Finally, the fatigue life was compared between purely riveted joint and a hybrid joint (bonded-riveted).

2. Materials and Methods

2.1 Geometry and Material

From Figure 1, the three-dimensional models were created and meshed to replicate the tensile test of riveted, bonded, and hybrid double-shear joints. The joints were produced using a plate (250×54×8) mm^3 in S235 base steel and connections are composed of rivet in S355 base steel with a diameter of D = 18 mm. The distance between the middle of the hole and the end of the overlap area equals 2D = 36 mm. At the covering region, a bonded joint is made using epoxy resin used as an adhesive to join the three plates. The adhesive bond was made by a thin film (54x54x0.2) mm^3 thick along the overlap area. It was assumed that the adhesive and the adherents remained in linear elastic conditions during the analysis. The value of tensile load used in static test equal to 43 kN. Mechanical properties of the adhesive, riveted and hybrid shear connections are given in Table 1.

Table 1: Mechanical properties of the riveted joints used in finite element simulations

	Steel adherents	Rivet	Adhesive
Young's modulus [GPa]	190	210	0.354
Tensile strength [MPa]	290	386	3.28
Poisson's ratio	0.3		0.27

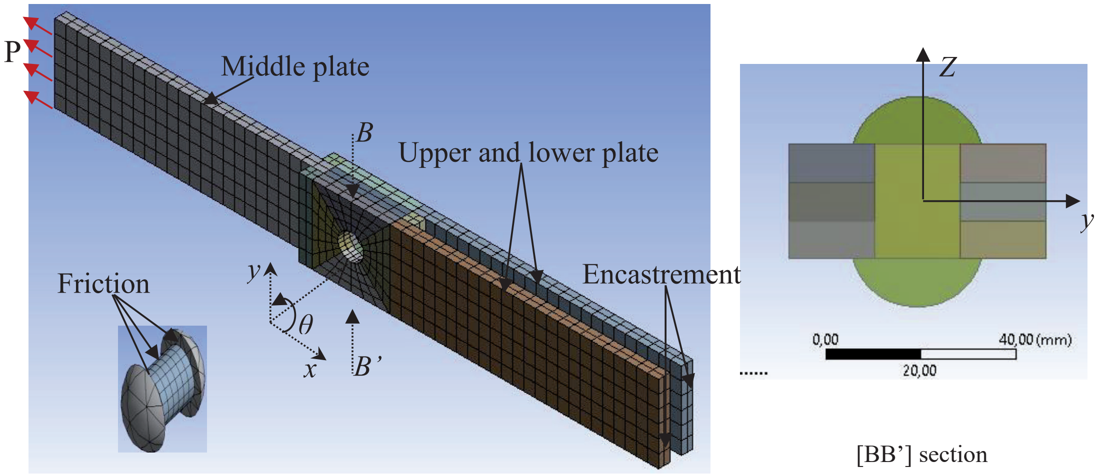


Figure 1: Modeled geometry for the FEM analysis and used boundary conditions.

2.2 Meshing

The FE analysis was carried out with the ANSYS WORKBENCH software [26]. The rivet, plates and its friction coefficient are taken into consideration in this model. To describe the tangential load-transferring mechanism, the friction coefficients (Contact elements) of different steel surfaces defined between different components of plates and rivet, is taken 0.2.

The external loading is applied in the end of the plates with an adequate boundary conditions. In the overlap area, the substrates are divided into several volumes by using the ANSYS WORKBENCH in order to control the creation of a regulated mesh. The mesh sizes have been reduced in correspondence of the contact and stress concentrators. A coarser mesh was used to model the free parts of the substrates outside the overlap area. In these analyses, an 8-node hexagonal element is used to model the plate and the adhesive in the hybrid joint, while a tetrahedral element is used to model the rivet head. This mesh is subdivided into two regions. At the far region a regular mesh is used. But near the overlap area an adapted (size=2 mm) mesh is considered. This subdivision was adopted to optimize the computed time especially for the fatigue simulation conducting a good convergence. Then, a mesh with 29558 nodes and 6436 elements was considered reliable.

2.3 Validation

In order to assess the behavior of the double shear riveted and hybrid joint, as well to present their advantages (resistance and lifespan) a numerical simulation on the static and fatigue performance of riveted and hybrid joints was performed. The comparison, in term of load-displacement, between the present model and the experimental results [27] is plotted in Figure 2. This comparison which gives the relation of the applied load as a function of the measured displacement at the middle of the plate, demonstrates the very good agreement. The load-displacement curves can be broken into two parts: loading threshold from which assumes a linear relation between the load and the displacement (quasi-linear behavior), followed by a sub-horizontal non-linear trend (elasto-plastic), which defines the beginning of the damage of the riveted assembly.

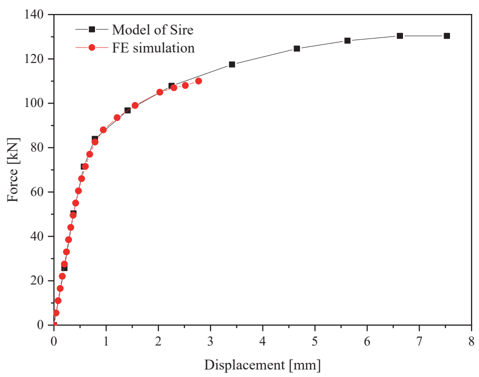


Figure 2: Comparison between experimental and numerical of load-displacement curves.

3. Static Analysis

3.1 Effect of riveting angle

The contour curves plotted in Figure 3, represent the variation of the von Mises stress versus the riveting angle (θ) for both riveted and hybrid joints. In both contours, the riveting angle is divided into 0° to 360° but the direction of the load direction is fixed at 0°. We observe a perfect symmetry of von Mises stress contours at 180°. It is notable that, the maximum values of the stress are observed for a riveting angle of 0°, because it corresponds to the direction of the load.

By comparison between the two joints, it's clear that the hybrid joint presents better stresses relaxation with less significant stress distribution near the hole. For the riveted joint (θ = 0°), the maximum stress near the rivet is about 292MPa, but it's reduced to 181.5 MPa for the hybrid joint. This reduction it's almost 38 %. This reduction is caused by the presence of the adhesive, because the load transmitted by the shank of the rivet remains low by friction and by shear stresses on the adhesive. The load transmitted by friction at this location is therefore very low. Most of the load would therefore be transmitted through the adhesive.

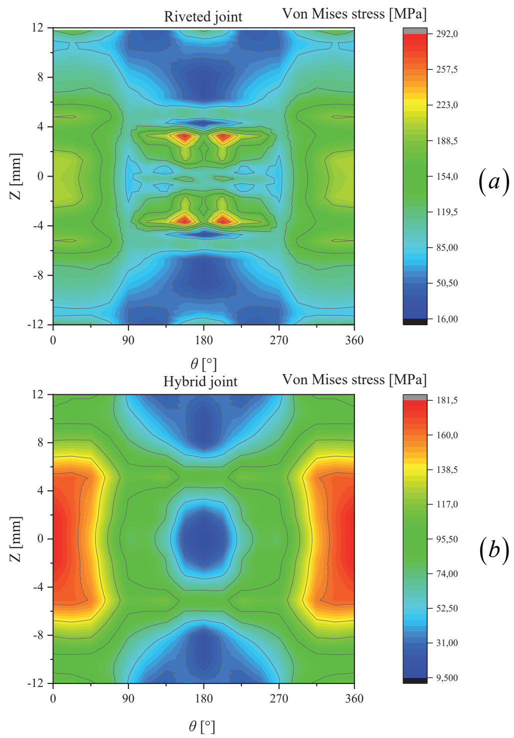
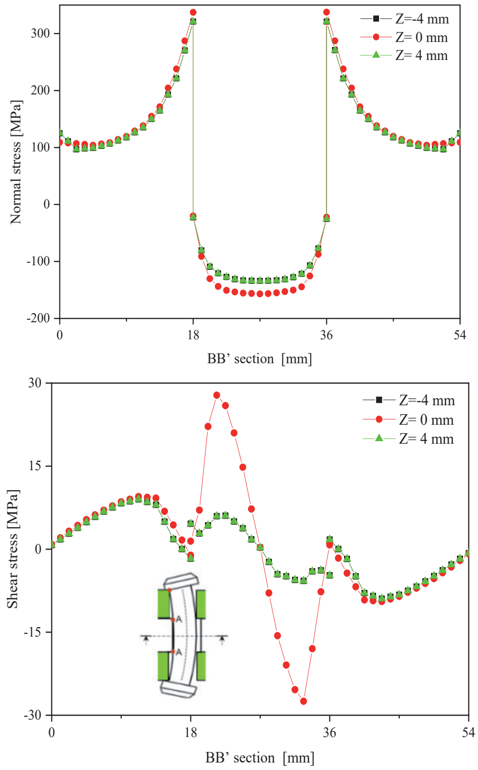


Figure 3: Effect of riveting angle on the stress contours, a) Hybrid joint, b) Riveted joint.

3.2 Riveted joint

Figure 4 show the normal and shear stresses at the [BB'] section for different positions of the middle plate. From this figure, a perfect symmetry of both stresses according to the longitudinal direction is observed. In addition, the variations of the position Z do not affect the normal stress. But, the shear stress is intensively influenced, especially near the rivet area. Maximum values are observed at Z = 0. In this region, a shear failure is most probable because the tensile force transfer is transformed into net shear stress in riveted section with the displacement of the substrates.



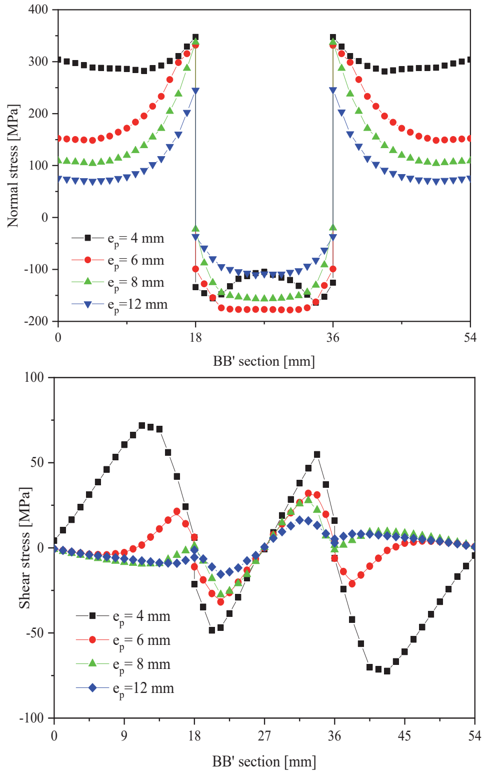
(a)

(b)

Figure 4: Normal and shear stresses distribution at the [BB'] section for different positions Z of the middle plate.

3.3 Effect of the substrates thickness

The normal and shear stress distribution at middle plate and at the [BB'] section of rivet for different thickness of the plates are given in figure 5. This figure shows that the normal and shear stress are intensively influenced by the substrates thickness. It is clear the increasing of the adhered thickness decreases load transferred by the rivet. This decrease results the reduction in stresses in the plates and in the shank of the rivet. In addition, an abrupt change in stresses is observed between the assembled plates and the rivet. This change gives us an important relaxation of the stresses by the rivet area.



(a)

(b)

Figure 5: Normal and shear stress distribution at middle plate and the [BB'] section of rivet direction for different thickness of the plate.

3.4 Effect of rivet diameter

Effect of rivet diameter on the normal and shear stresses is evaluated in figure 6. This Figure presents distribution of both stresses at middle plate and at the [BB'] section of the rivet. It has been observed that the increase of the rivet diameter leads to a decrease of normal and shear stresses on the shank of the rivet. In fact, the increase in the diameter from 10mm to 26mm leads to a reduction of about 74% of the normal stress and 65% of the shear stress in the shank of the rivet. We conclude that, the rivet diameter has in important effect on the reduction of stresses.

3.5 Effect of the overlap length

Effect of the overlapping length on the bearing and the normal stress for hybrid joint at the rivet shank at Z = 0 is illustrated in figure 7. For three different positions (0°, 90° and 180°), it can be noted that the increase in the overlap zone induces a beneficial effect on the bearing stress. For the hybrid

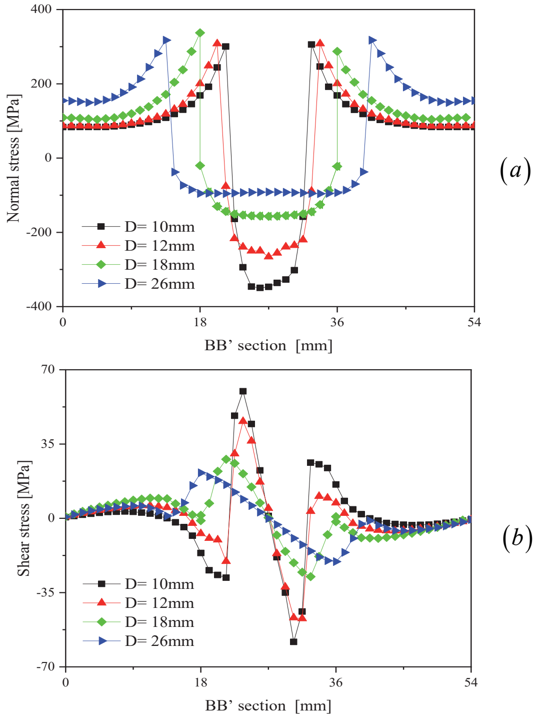


Figure 6: Normal and shear stress distribution at middle plate and at the [BB'] section of the rivet for different rivet diameters.

joint, the low transfer of load by the rivet which means that the normal stresses in the shank rivet are relatively low (θ = 180°). Therefore, the failure of a hybrid joint by bearing is very unlikely. But for θ = 0 and 90°, normal stresses are highly concentrated at the rivet area. The stress concentration around the hole causes early damages, followed by tensile load. We can deduce that 72 mm can be considered as an optimal value of the lap length beyond which the normal stresses do not vary (To have a maximum transfer of the adhesive layer). We concluded that the overlap length plays an important role on the hybrid joint strength compared to the rivet joint.

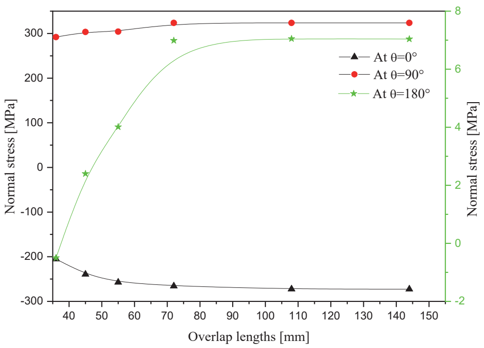


Figure 7: Effect of overlap lengths.

3.6 Comparison between riveted and hybrid joint

For hybrid and riveted joints, the normal and shear stresses are evaluated in Figure 8, at Z = 0 for the middle plate and the [BB'] section of the rivet. It's clear that the presence of the adhesive layer along the overlap area associated with riveted connections will reduce remarkably the normal and the shear stress at the middle plate and the rivet shank. This decrease is directly related to the most important loads transferred by the adhesive layer.

Maximum values of normal stress were particularly observed at the edges of the median plate and at the rivet hole, where important stress concentration is located. On the other hand, for a riveted assembly, the shear stress takes two maximum values in the rivet shank cross-section because the majority of the load is transferred in shear (two sheared sections). But, the shear stress is intensively reduced for the hybrid joint. Therefore, it was concluded that the hybrid joint decreases load transferred by the rivet shank, which causes the reduction in the stress concentrations in the assembly.

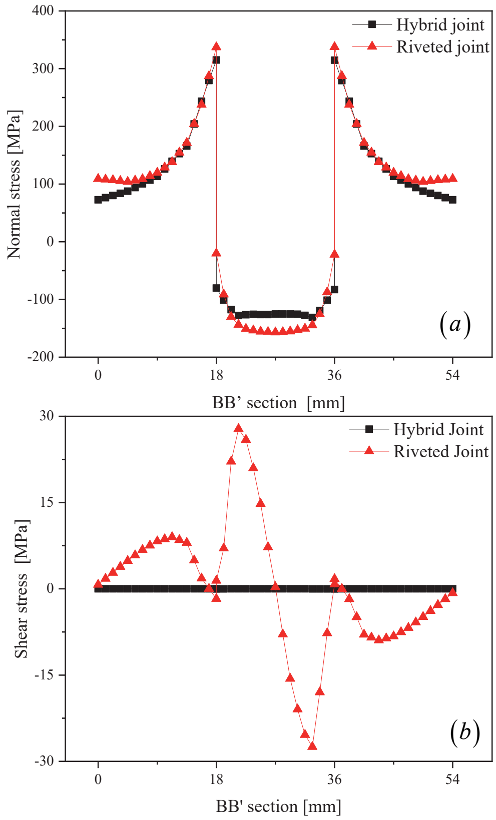


Figure 8: Normal and shear stress distribution at middle plate and at the [BB'] section of riveted and hybrid joint.

The load-displacement curves of the middle plate of the riveted and hybrid joints are shown in Figure 9. For a low load, a linear elastic behavior is observed for both types of assemblies. The elastic limit of the hybrid joint occurs at approximately 135kN while for the riveted joint the elastic limit of the joint is at about 70kN. The elastic limit of the hybrid joint is about 135kN while that of the riveted joint is about 70kN. The resistance of our assembly has been improved by about 48% for the case of a hybrid joint. As the displacement increased, the plasticity at the adhesive is initiated and the total applied load is transferred by the rivet. The results thus far have shown important effect of adhesive in the joint strength behavior in a hybrid joint compared to a riveted joint.

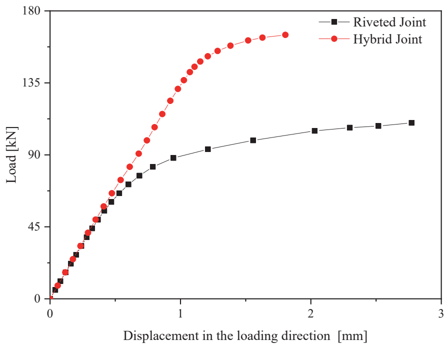


Figure 9: Comparison between load-displacement curves of riveted and hybrid joints.

Figure 10 show a comparison between riveted and hybrid joint, in term of the stress/strain at the middle plate. For small loads, we have a linear behavior for both assemblies. We have a dominance of the load transfer mechanism between the parts by the rivet in a riveted joint or by the adhesive in a hybrid joint. So the totality of the external effort is transferred by friction from the interfaces (phase of adherence).

For the important tensile load, both joints represent two different behavior laws due to the difference in the rigidity of each assembly. The deformation becomes large enough to cause plastic deformations in the adhesive or in the rivet. The hybrid assembly represents an important flow stage with a relatively higher breaking stress (500MPa). By constraint, the riveted joint is less efficient (470MPa), but offers us a more ductile behavior.

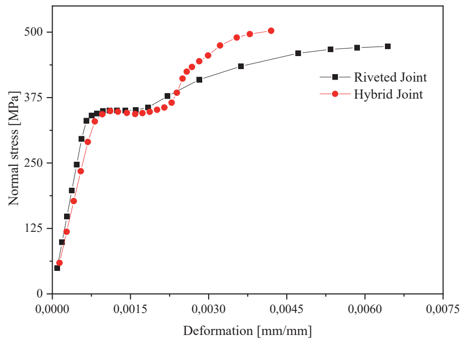


Figure 10: Comparison between stress-strain curves of riveted and hybrid joints.

4. Fatigue Analysis

In this section, the riveted and hybrid joint was subjected to repeated fatigue loading, which was controlled using a form of sinusoidal wave form with constant amplitude and a positive stress ratio (R = 0). By considering a numerical model under ANSYS Workbench "Explicit dynamic", the fatigue analysis enable us to follow the evolution of life span and the damage of riveted and hybrid assemblies. The hysteresis loops and the Wohler curves are the main parameters that allowed us to quantify and value the evolution of the damage during fatigue. For the fatigue analysis, the same mesh and the same computational parameters as in the static analysis were used.

4.1 Comparison between hybrid and riveted joint

To better understand the elastic-plastic local response at the critical location for each element constituting hybrid and riveted joints, hysteresis loop responses and Wohler's curve are shown in Figures 11 and 12. Since the energy absorbed can be calculated by the area bounded by the hysteresis loop, it is the cyclic loading-unloading curve can be applied to determine which element transfers more charge and therefore absorbs more energy.

It is remarkable that in the riveted assembly (Figure 11.a), the hysteresis loop becomes more and more important at the section of the rivet. The rivet joints the rivet transfers and absorb more energy followed by the middle plate. Upper and lower plate does not present a great danger for assembly. We can clearly see, that in the presence of a hybrid assembly (Figure 11.b), the hysteresis loop becomes more flattened which means that we have less damage.

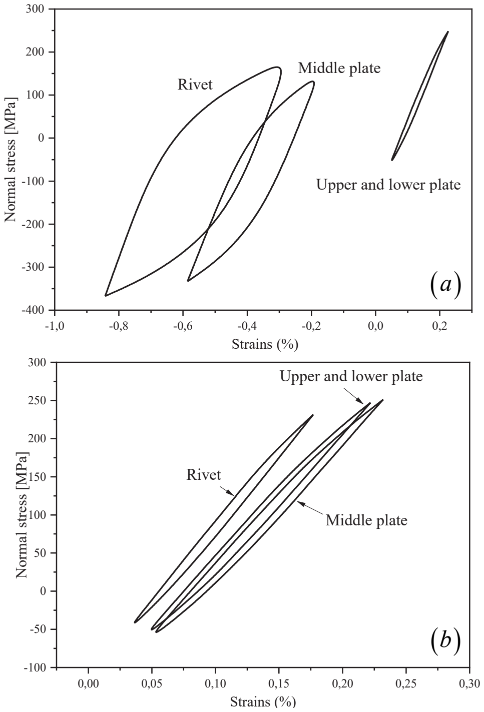


Figure 11: Hysteresis loop response: a) Riveted joint, b) Hybrid joint.

In the case of a riveted assembly (Figure 12.a), it is obvious that the rivet offers a longer life compared to the plate (Lower, upper and middle). By adopting a hybrid assembly (Figure 12.b), the service life becomes longer. In addition, the number of cycles to the rupture of the plate has clearly improved. A quantitative comparison is given in Figure 13.

In addition, the comparison between fatigue life of the component elements constitute these two mechanical connections are shown in Figure 13. The obtained results show that the hybrid joints are structurally more efficient than riveted joints as they perform better in transferring loads problems seen in riveted joints and thus improve the overall joint performance. The addition of adhesive layer in a riveted connection increased the fatigue life of the rivet from 21482 cycles to 2.35 10^7 cycles, and for the middle plate from 94482 cycles to 7.82 10^6 cycles. The increase of the fatigue life is equal to 99% for the rivet and tends to 98% for the middle plate. From the fatigue life of riveted and hybrid joint under fatigue loading the final evaluation of hybrid joint is comparatively efficient. Finally, the addition of the adhesive in a riveted connection plays an important role in improving the life of the assemblies.

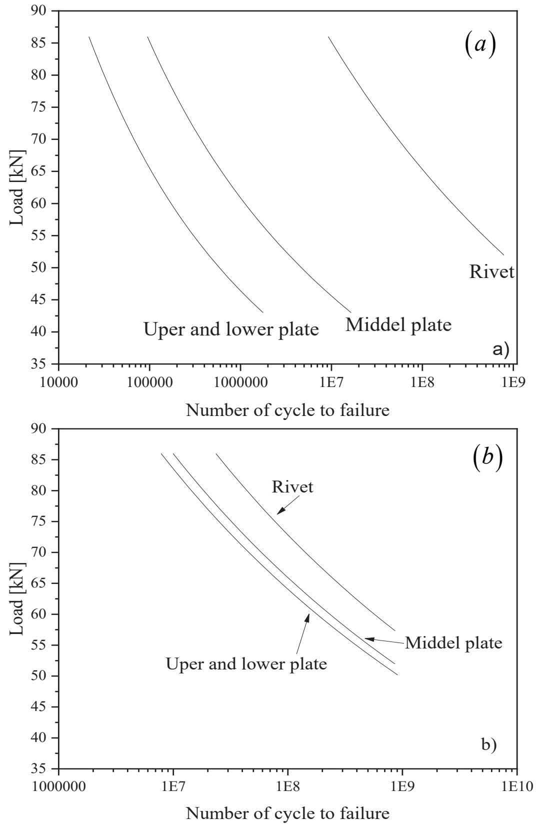


Figure 12: Wohler's curve a) Riveted joint, b) Hybrid joint.

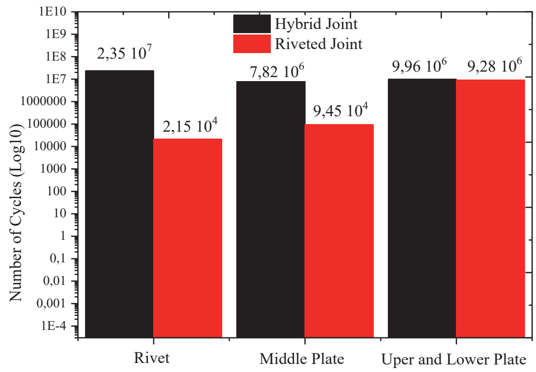


Figure 13: Fatigue life evaluation a) Riveted joint, b) Hybrid joint.

4.2 Effect of the adhesive thickness

The effect of the adhesive thickness on the fatigue life of the hybrid double shear lap joints is shown in Figure 14. This result indicated that the fatigue life decreased with an increase in the adhesive thickness under the fatigue loading. The fatigue life of the riveted joint (thickness of the adhesive ea = 0 mm) is only 21482 cycles, compared to a hybrid joint with an adhesive thickness e_a = 0.1 mm where the service life increases to 4.82 10^6 cycles. This is mainly attributed to the presence of the adhesive layer, so the hybrid joint with e_a = 0.1mm showed a superior initial stiffness compared riveted joint. Finally, the fatigue life decreased with the increase of the adhesive thickness, and the fatigue life of the hybrid joint with e_a = 0.2 mm was longer than other adhesive thickness. Therefore, it is important to control the thickness of the adhesive which can be a source of complete failure of the joint.

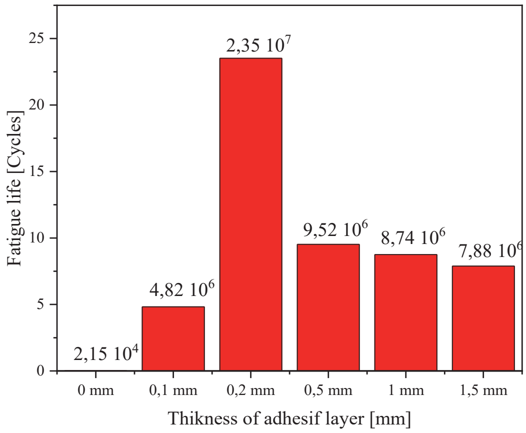


Figure 14: Effect of the adhesive thickness on the fatigue life

4.3 Sensitivity study of a hybrid joint

A sensitivity analysis is performed in order to determine to the relationship between the input parameters and the fatigue life of the hybrid joint. According to these results, the performance of the hybrid joint is greatly influenced by the geometric parameters of the joint. This is reflected by the preponderant influence of the rivet diameter and the plate's thickness.

a) Effect of rivets diameter

The effect of Rivet's diameter (D_r = 18, 16 and 14 mm, respectively) on the fatigue live for each element constituting hybrid joint is represented in Table 2. This table shows that fatigue life of (Middle plate, Rivet, Adhesive) is increased with increasing the rivets diameter. But when the diameter of rivets is increased, the load transfer area becomes larger between the shank of the rivet and upper and lower plate cause the decreased in their life service. This solution has the advantage to increasing the load transfer and also increase the stiffness of the joint by increasing the stiffness of the rivet.

Table 2: Effect of rivets diameter

	Life span [cycle]		
	D_r =18mm	*D_r =16mm*	*D_r =14mm*
Middle plate	7.82 10^6	7.27 10^6	6.27 10^6
Rivet	2.35 10^7	2.87 10^6	1.05 10^6
Upper and lower plate	9.96 10^6	1.044 10^7	1.036 10^7

b) Effect of plate thickness

According to the established objectives for the present section, the results of several of plate thickness (ep) are presented, whose main objective was to characterize the fatigue live for each element constituting hybrid joint. Variations of fatigue live of the hybrid joints with different thicknesses of plate are shown in Table 3. Increasing the thickness of plates can significantly affect the fatigue live for each element constituting hybrid joint. So, by changing the thickness of the plates, it is possible to enhance the strength of joint. On the other hand, this increase in thickness causes a reduction in the life of the rivet, so that the majority of the load is transferred by the shank of the rivet.

Table 3: Effect of the thickness of plate

	Life span [cycles]	
	e_p = 8 mm	*e_p =12 mm*
Middle plate	7.82 10^6	9.38 10^6
Rivet	2.35 10^7	2.15 10^6
Upper and lower plate	9.96 10^6	3.01 10^7

c) Effect of upper and lower plate thicknesses

Finally, sensitivity analysis is performed to study the correlation between the geometrical parameters (thickness of upper (e_{pu}) and lower plate (e_{pl}) versus the diameter of the rivet at the same time) and the fatigue life, in order to improve the service life predictions for each element constituting hybrid joint. As clearly confirmed in table 4, the variation of these parameters has an influence on the life of the rivet and the adhesive layer. From *D_r =14 mm* to *D_r =16 mm*, an average variation of the fatigue life of 73% is observed. By analyzing the diameter/ thickness ratio it's possible to say that the ratio variation clearly shows the beneficial effect of the number of cycles to failure.

Table 4: Effect of the thickness of upper, middle and lower plate versus the diameter of the rivet

	Life span [cycle]		
	$e_{pu} = e_{pl}$ =8mm	$e_{pu} = e_{pl}$ =7mm	$e_{pu} = e_{pl}$ =7mm
	D_r =18mm	D_r =16mm	D_r =14mm
Middle plate	7.82 10^6	7.27 10^6	6.27 10^6
Rivet	2.35 10^7	2.87 10^6	1.05 10^6
Upper and lower plate	9.96 10^6	1.044 10^7	1.036 10^7

5. Conclusion

In this research, a numerical model was developed to study the behavior of mechanical joint used in the industry. To compare the static strength and fatigue resistance of the riveted and hybrid joint the FEM was used. Alongside this, work through FE analysis will aid in further understanding how load transfer and stresses vary in hybrid and riveted joints. The prediction model was applied in riveted and hybrid bonded double-lap joint in S355 base steel. A good agreement was obtained between the present model and results issue from the literature. The static and fatigue performances and effect parameters, such as thickness of the substrates, overlap length and rivet diameter, were evaluated and analyzed. Based on the results and the findings of the paper, the following conclusions can be drawn:

– *The results show that the peel stress in the rivet shank of the hybrid joint could be changed using different overlap length. We note that there is an optimal value of the overlap length (72 mm) beyond of which the peel stresses do not vary.*

– *The comparison between the hybrid and riveted joints shown that the hybrid joint has a higher strength than the riveted joint.*

– *Hysterical stress-strains response will provide information on the load transfer for each element constituting hybrid and riveted joints.*

– *For the bonded/riveted joints subjected to fatigue load, the addition of adhesive in the mechanical connection and the increase in the adhesive thickness can increase the fatigue durability of hybrid shear connections.*

– *It is observed that the rivets diameter has considerable effects on the fatigue life of each element constituting hybrid joint. The fatigue life of the hybrid joint is strongly related to the rivets diameter. It has been noted that the number of cycles becomes very large with the increasing of the rivet diameter*

– *The sensitivity analysis confirmed that the ratio between the diameter and the thickness of the plate is the most relevant parameter affecting the variability of the fatigue life of riveted connections.*

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