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COMPARATIVE STUDY BETWEEN NUMERICAL ANALYSIS AND EXPERIMENTAL STUDY OF THE LOCATION OF STIFFENERS IN PLATES WITH A SET OF CIRCULAR NOTCHES

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Abstract

In this study the finite element method is used to analyse the distribution of failure stresses in circular aperture wire plates with different type of stiffener location. The stress distribution in the adhesive layer will be analysed to estimate the durability of the repair technique by varying the different stiffener parameter, this analysis allows the designers to optimise the location of the stiffener used for the repair of the structures, the results obtained showed the best locations of the stiffener used for the repair of the structures. This study provides a novel approach to optimizing stiffener locations in repair techniques, enhancing the durability and efficiency of structural repairs through detailed finite element analysis.

Index Terms: The Finite Element Method, Stiffener, the Durability, the Stress Distribution, the Adhesive Layer, Optimizing Stiffener, Failure Stresses.

1. INTRODUCTION

In aircraft structures, a stiffener is a component that helps to strengthen and reinforce the structure. It is usually a thin, lightweight material that is attached to a skin panel to provide additional support and prevent buckling. Stiffeners can be made from various materials, such as aluminum, titanium, or composite materials, and can be designed in different shapes and sizes depending on the specific requirements of the aircraft. They are commonly used in areas such as fuselage frames, wing spars, and bulkheads to improve the structural integrity and ensure the safety of the aircraft. Stiffeners are an essential component of aircraft structures, providing structural support to the skin and increasing the carrying capacity of the structure Zain et al., 2010 [1]. They help to distribute loads evenly, preventing buckling and deformation of the skin. Recently, an extended topology optimization method has been proposed for designing stiffener layouts in aircraft structures Yallese et al., 2005 [2]. This approach takes into consideration joint loads and manufacturing constraints simultaneously, resulting in improved stiffener layouts and better control of joint loads. They are thin, lightweight materials attached to skin panels to prevent buckling and improve structural integrity. Stiffeners can be made from various materials such as aluminum or titanium and designed in different shapes and sizes depending on the aircraft's requirements. Recently, a paper proposed an extended topology optimization method for designing stiffener layouts while considering joint loads and manufacturing constraints. This method can optimize the placement, size, and shape of stiffeners to reduce weight while maintaining structural integrity, which is crucial for aircraft performance and safety.

They are designed in different shapes and sizes to prevent buckling and improve structural integrity. Stiffeners can be made from various materials and play a crucial role in maintaining the aircraft's performance and safety. An extended topology optimization method has been proposed for designing stiffener layouts while considering joint loads and manufacturing constraints Meddour et al., 2018 [3]. This method can optimize the placement, size, and shape of stiffeners to reduce weight while maintaining structural integrity. Recent research also shows the effectiveness of topology optimization techniques in designing aeroelastic wingbox models with run-out blade stiffeners Suresh et al., 2021 [4]. The use of a continuous uniform circumferential stiffener can significantly reduce stress singularities and maximum load concentration in such structures Paturi et al., 2018 [5]. An approach for designing the stiffener curves based on the first buckling mode of the unstiffened panel has been presented in a research paper Meknassi, 2019 [6]. The axial tensile damage is considered to be the damage mode of T-piece bolts Kumar, 2018 [7] used in stiffening ribs of structures. A study on the force analysis of bolts with stiffening ribs has been conducted Kumar, 2018 [7]. The Marguerre complex stress function is used for a numerical analysis of the effect of the stiffener, and the article provides equations and calculations for the integral representation of the stress function and correction factors Paturi et al., 2018 [5]. Based on the research Paturi et al., 2018 [5], a study was conducted to analyze the effect of a circumferential stiffener on the stress singularities and maximum load concentration in a cylindrical shell with a longitudinal crack. The study used an integral representation of the Marguerre complex stress function to calculate and display the results graphically. The stiffness of the stiffener was defined in terms of several abbreviations, and an IBM 7094 computer was used to solve the equations. The study also examined the strain and displacement in the stiffener. Another study Meknassi., 2019[6]. Presented a new approach to designing the stiffener curves based purely upon the first buckling mode of the unstiffened panel.

In order to counteract these effects, stiffening techniques are used, and numerical modeling is a useful tool for assessing and forecasting how well these kinds of constructions will fracture. The most often utilized numerical method in this field is the Somme works in Finite Element Method (FEM). With complex geometries, such as circular holes and stiffeners, it enables precise stress analysis and fracture prediction in the plate. Different FEM models have been created by researchers to examine how stiffening affects fracture behavior. FEM has been used by researchers such as Lee et al. (2017) [8] to forecast the start and spread of cracks by analyzing the stress distribution surrounding circular apertures in plates. Their research shows that in order to get correct findings, mesh refinement and suitable material models are crucial.Stiffeners were included into FEM models by Nguyen et al., 2019 [9] in order to assess their effect on lowering stress concentrations and enhancing fracture resistance. Their findings showed that the structural integrity of plates with circular apertures might be greatly improved by placing stiffeners in the ideal location. The Extended Finite Element Method (XFEM) allows for the modeling of fracture formation without the requirement for remeshing, therefore expanding the possibilities of classical FEM. Studying fracture behavior in plates with pre-existing cracks is a particularly good use for this approach. Researchers such as Zhang et al 2018 [10] have utilized finite element modeling (XFEM) to model the onset and spread of cracks in stiffened plates including circular apertures.

According to their findings, XFEM outperforms classical FEM in providing a more realistic description of fracture patterns and crack courses. Another numerical method that has been used in this subject is the Boundary Element Method (BEM). For situations requiring infinite or semi-infinite domains, like plates with openings, BEM is useful. Kim & Lee 2016 [11] computed stress intensity factors and assessed how stiffening elements affected these variables for plates with circular holes. Their research demonstrated that complex boundary condition problems might be effectively handled by BEM. Studies comparing FEM and XFEM show that although FEM is very good at stress analysis in general, XFEM is better at simulating crack formation without requiring remeshing. The accuracy and computational efficiency of FEM and XFEM were compared in the studies conducted by Park et al., 2020 [12]. They came to the conclusion that, at a computational cost comparable to FEM, XFEM offers forecasts of crack formation that are more accurate. It has been determined which stiffening strategies—like adding ribs, patches, or composite materials—work best for increasing fracture resistance. Li and Wang's 2018 [13] study examined the relative merits of patch reinforcements and rib stiffeners in terms of lowering stress concentrations near circular apertures. According to their findings, rib stiffeners worked better in specific arrangements, although, patches offered superior overall stress dispersion. Research by Chen et al., 2019 [14] looked on stiffening plates with circular apertures using composite materials. When compared to conventional metal stiffeners, they discovered that composite stiffeners may greatly increase fracture toughness and postpone the onset of cracks.

The optimisation of aeronautical structures is a crucial area of research for improving aircraft performance and efficiency. Among the key structural elements, stiffener-reinforced plates play an essential role in the design of fuselages and wings. This study focuses on the analysis of the optimum orientation of a stiffener in a plate with an aperture wire, a common configuration in aeronautical structures. The main objective of this research is to assess the impact of the stiffener orientation angle on the stress distribution and overall stiffness of the plate. Using a combination of analytical and numerical methods, we examine how different orientations of the stiffener affect the ability of the structure to support the applied loads, while minimizing the stress concentration around the opening wire Aerospatiale. The aim of this study is to provide guidelines for the optimal design of stiffened plates with aperture wire, thereby contributing to the improvement of the structural performance of aeronautical components. The results of this research have significant implications for reducing weight, increasing fatigue life and optimizing manufacturing costs in the aerospace industry.

The rest of this paper is organized as follows. The study's theoretical background and computational methodology are explained in depth in Section 2, which also presents the Finite Element Model. We go over the Materials' attributes and qualities that are pertinent to our examination in Section 3. The numerical simulation is covered in Section 4, where the setup, settings, and operation of the simulation procedures are explained. Section 5 presents the results and discussion, where we examine and explain the numerical simulations' results. In-depth discussion of the adhesive shear stress analysis is covered in Section 6, along with how the stress distribution affects structural integrity. The Tensile Experiment is described in Section 7, along with the methods and outcomes. Lastly, the Conclusion highlights the most important discoveries and makes recommendations for further research.

2. FINITE ELEMENT MODEL

ABAQUS is structured in several models. The complete realisation of a simulation project simulation project under ABAQUS, is carried out after a successive passage in these modules. We try to present the main models of ABAQUS. Let us consider a plate with holes, Let us consider an aluminium plate 2024 with a rectangular section S=50x100 mm² and thickness e=5mm, with three identical holes of diameter d=12mm and the distance between its centres 30 mm, the plate is embedded at one end and free at the other. A tensile field is applied to the top of the plate of 70 MPA is applied to its top surface (Fig 1). The plate is assumed to be elastic, with Young's modulus. The plate is assumed to be elastic, with Young's modulus E = 73 100 MPA and Poisson's ratio =0.3.

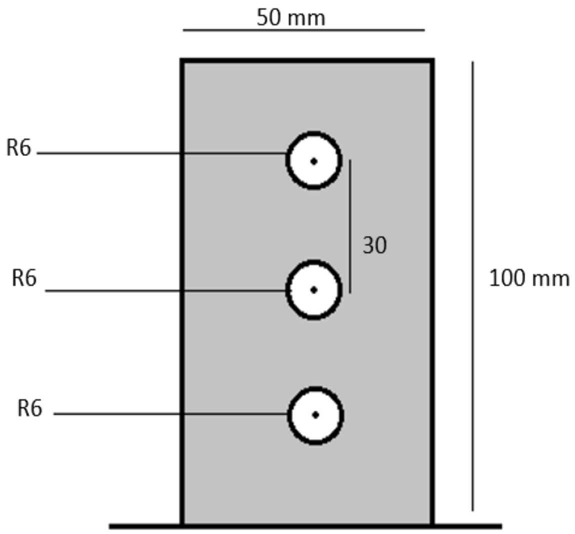

Figure 1: Realised Plate

3. MATERIALS

There are two key materials involved in the strengthening process; the aluminium alloys that make up the strengthened and unreinforced specimens and the Araldite 2015 adhesive that bonds the aluminium to the strengthened structure. The 2024T3 aluminium is heat treated at a temperature of 351°C and cold rolled. It is relatively soft and more ductile and has good tensile-stress fatigue resistance. The chemical compositions of 2024T3 aluminium alloy given by the supplier are presented in Table 1.

Table 1: Chemical Compositions of: Al2024T3

	%									
	Al	**Cr**	**Cu**	**Fe**	**Mg**	**Mn**	**Si**	**Ti**	**Zn**	**autre**
2024T3	90.7-94.7	Max 0.1	3.8-4.9	Max 0.5	1.2-1.8	0.3-0.9	Max 0.5	Max 0.15	Max 0.25	Max 0.15

These properties are consistent with those given by the supplier, shown in Table 2

Table 2: Mechanical Characteristics of the Materials Used

Propriétés	Al 2024T3	Araldite
Longitudinal Young's modulus (GPa)	73.1	2.52
Transversal Young's modulus (GPa)	73.1	2.52
Longitudinal Poisson's ratio	0.33	0.36
Transversal Poisson's ratio	0.33	0.36
Hardness	29.5	-
Expansion to failure	18	-
Shear modulus	26.9	0.954
Elastic limit	370	-

4. NUMERICAL SIMULATION

In this context, our study focuses on a numerical analysis using the three-dimensional finite element method of reinforcement with stiffeners made of the same material. The structure being modelled by eight-node iso-parametric brick elements using the Abaqus finite element code. The mesh of the specimen used in the 3D finite element model is shown in Fig 2. A regular mesh is made for the whole structure. This mesh remains the same throughout the calculation to avoid any influence of the mesh on the results. The perfect bond is created between the plate and the stiffener by merging the nodes of the elements. Merging the nodes results in the same mesh for structure and the stiffener.

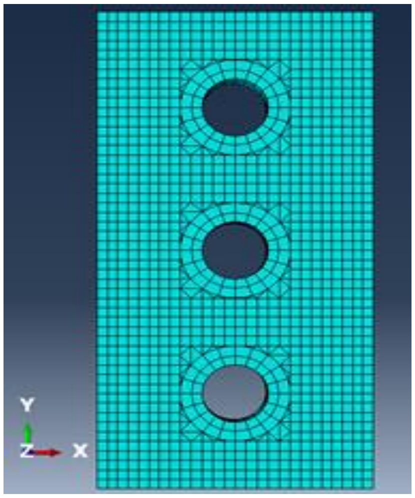

Figure 2: Typical Mesh of the Reinforced Structure

5. RESULTS AND DISCUSSION

- The figure (Fig3) shows the variation of the maximum stress recorded as a function of loading for different locations of the stiffener. From the graphs it can be seen that the relationship between the maximum stress and loading is linear, the same remark for the stresses (Fig4) while noting that the ratio of stress variation to loading is different for the three locations of the stiffener, for a loading of 70Mpa, the stress concentration factor (Kt) decreases by about 27.3% for the 0° location, 26.74% for the 45° location 25.45% for the 90° location in relation to the plate that is not strengthened.
- It is also noted that the location of the stiffener has an effect on the maximum stress recorded in the reinforced plate, with each increase in the applied stress, the results obtained are higher.
- This behaviour can be explained by the fact that the more surface area the stiffener occupies in the intermediate zone between the notches, the greater the stress transfer through the adhesive layer.

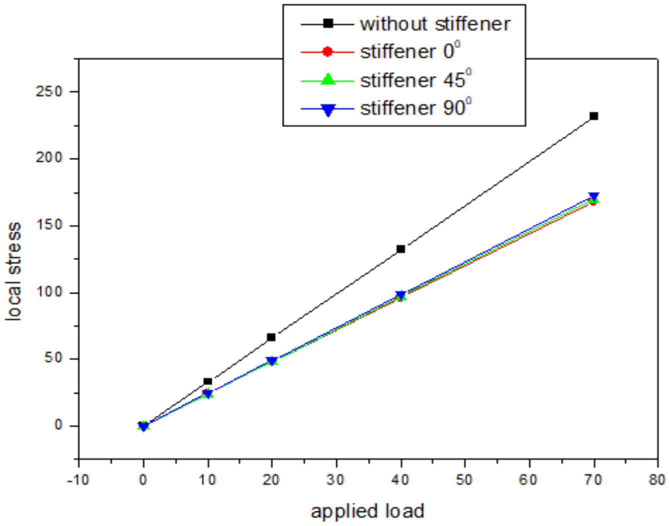

Figure 3: Shear stress for different load values of the reinforced plates (depending on the location of the stiffener) and not reinforced loading in vertical direction

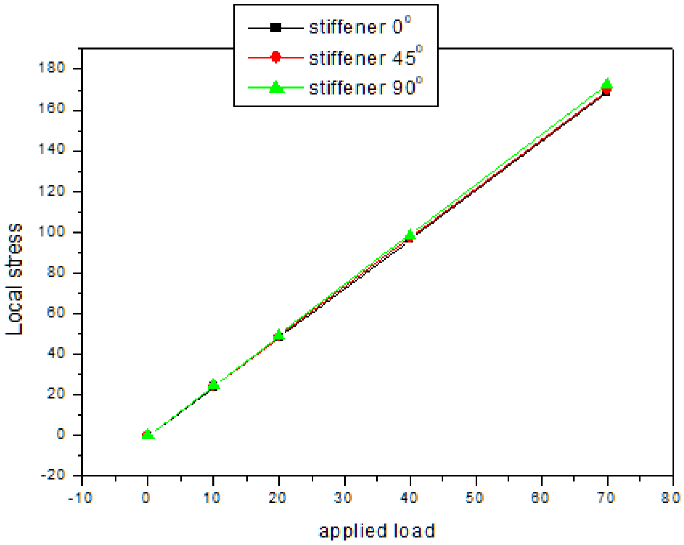

Figure 4: Shear stress for different load values of the reinforced plates (Depending on the location of the stiffener) loading in vertical direction

Fig 5. Shows the stress distribution for different values of plate loading in the vertical direction. It can be clearly seen from these figures that the stress concentration follows the loading line and has a large value in the vicinity of the notch.

The values of the stress concentration factor are:

- Kt=3.31 for plates that are not reinforced with a stiffener
- Kt=2.4 for plates reinforced with a stiffener oriented at an angle of 0°.
- Kt=2.42 for plates reinforced with a 45° oriented stiffener
- Kt=2.46 for plates reinforced with a 90° angle stiffener
- The best location for the stiffeners is the 0° orientation because the area where the stresses are concentrated is the area between the notches.

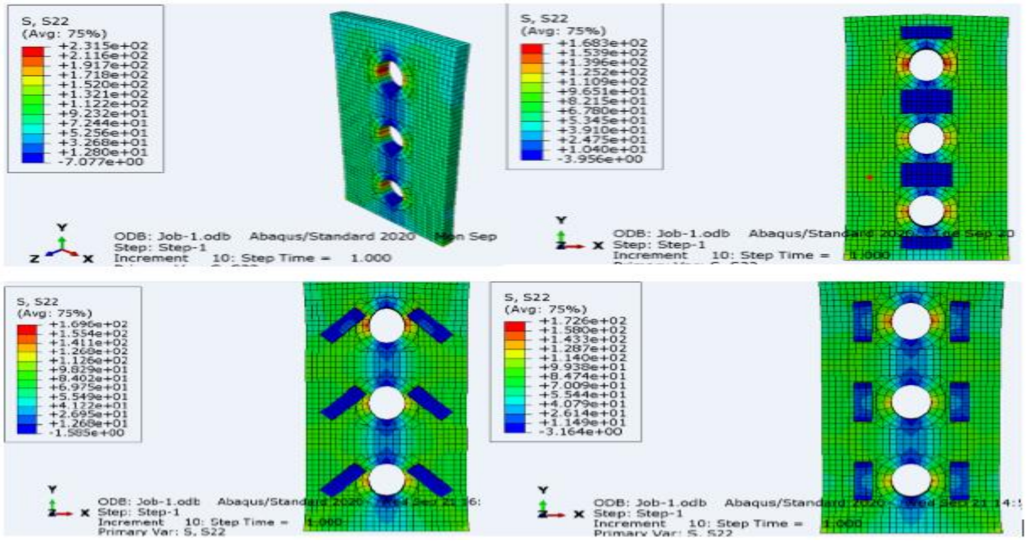

Figure 5: Stress Distribution for different load values of the reinforced plates (depending on the location of the stiffener) and not reinforced loading in vertical direction

- Fig 6 and 7 show the variation of the recorded maximum stress as a function of loading for different locations of the stiffener under loading in the horizontal direction. It can be seen that the recorded maximum stress increases with increasing applied loading.
- For a loading of 70Mpa, the stress concentration factor (Kt) decreases by about 52.8% for the 0° location, 52.7% for the 45° location and 52.4% for the 90° location compared to the unreinforced plate.
- It is also noted that the location of the stiffener has an effect on the maximum stress recorded in the reinforced plate, with each increase in the applied stress, the results obtained are higher.
- It can be seen that the different locations of the stiffener have almost identical max stress values for different values of applied load, this equality is valid for loading values below 20Mpa where it appears that there is a clear difference in max stress on the reinforced plate.

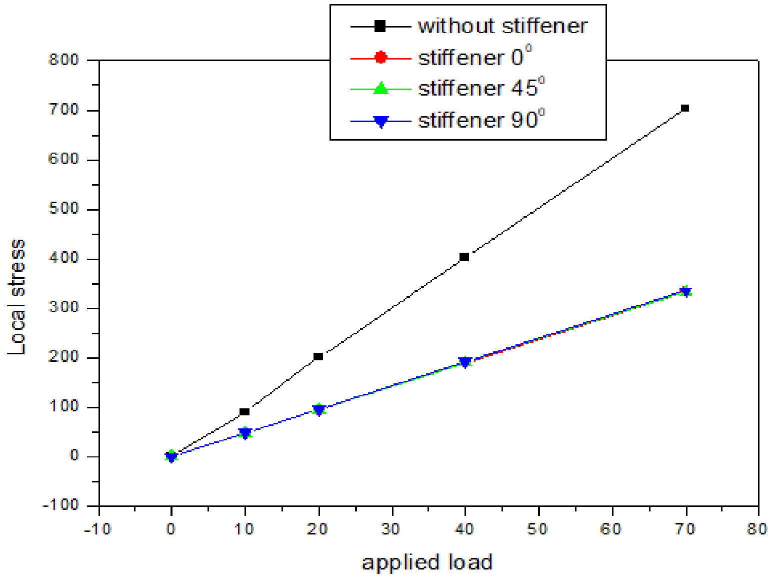

Figure 6: Shear stress for different load values of the reinforced plates (depending on the location of the stiffener) and not reinforced loading in horizontal direction

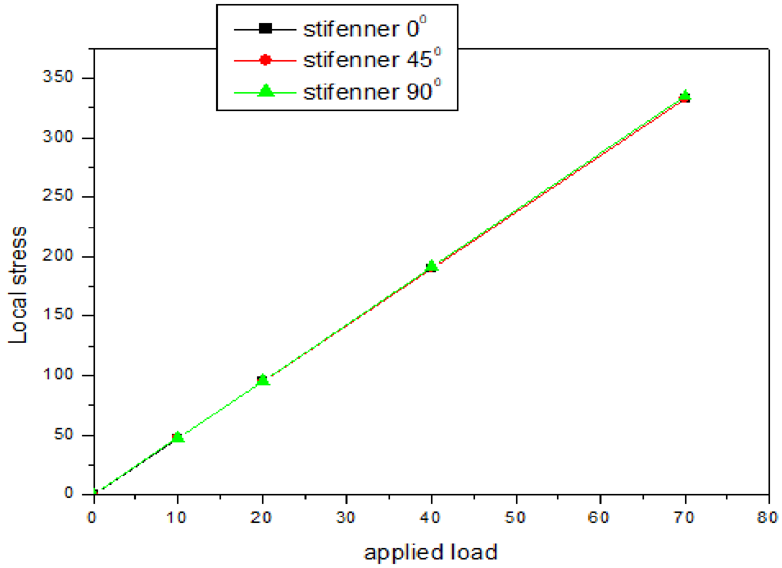

Figure 7: Shear stress for different load values of the reinforced plates (depending on the location of the stiffener) loading in horizontal direction

- Fig 8 shows the stress distribution for different values of plate loading in the horizontal direction. It can be clearly seen from these figures that the stress concentration follows the loading line and has a large value in the vicinity of the notch. The values of the stress concentration factor are:

- Kt=10.04 for plates that are not reinforced with a stiffener
- Kt=4.74 for plates reinforced with a stiffener oriented at an angle of 0°.
- Kt=4.75 for plates reinforced with a 45° oriented stiffener
- Kt=4.79 for plates reinforced with a 90° angle stiffener
- The best location for the stiffeners is the 0° orientation because the area where the stresses are concentrated is the area between the notches and this reinforced the bracket part of the fixed plate.

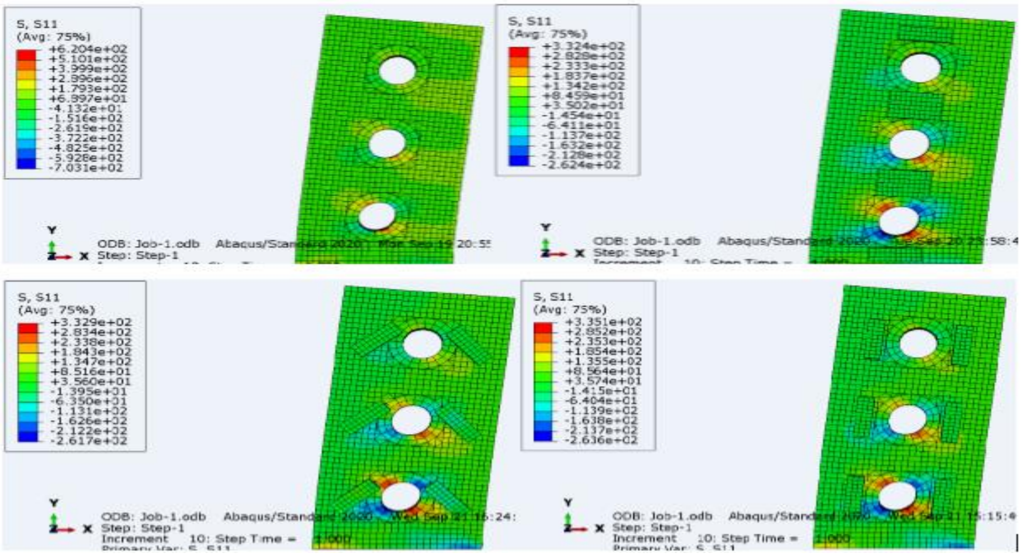

Figure 8: Stress distribution for different load values of the reinforced plates (depending on the location of the stiffener) and not reinforced loading in horizontal direction loading

6. ADHESIVE SHEAR STRESS ANALYSIS

- The durability of the reinforcement can be estimated by the shear stresses of the adhesive. Indeed, the risk of adhesion failure is lower when the shear stresses in the adhesive layer are low. In this part of the work, we analysed the adhesive stress distribution in order to estimate the durability of the reinforcement. The stress distribution was evaluated along the length of the adhesive layer.
- The adhesive is the weakest element in a stiffening system, its shear strength plays an important role in the performance of the stiffener. Therefore, in this study the effect of the load applied to the reinforced plate on the shear stress distribution in the adhesive will be observed. Fig (9 and 10 and 11 and 12) show the variation of the shear stress τxy as a function of the applied load.
- It can be seen that the variation of the stiffener location has a significant effect on the adhesive stress distribution especially for the 0° location.

- The 0° location is considered the best position in all the cases studied.
- The adhesive works well and is not safe from tearing if the applied stress is less than 40 Mpa in the vertical position and 20 in the horizontal position and the positions where the stress is applied in both sides.

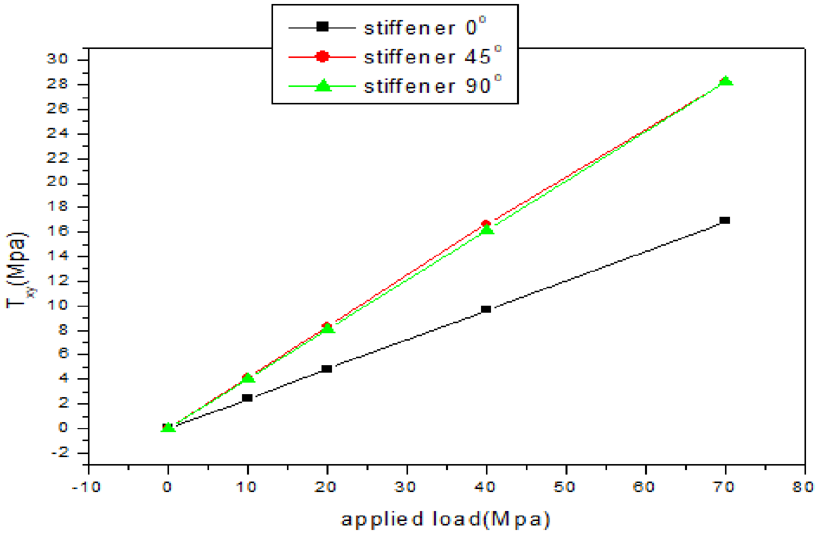

Figure 9: Shear stresses τxy for different applied vertical loads

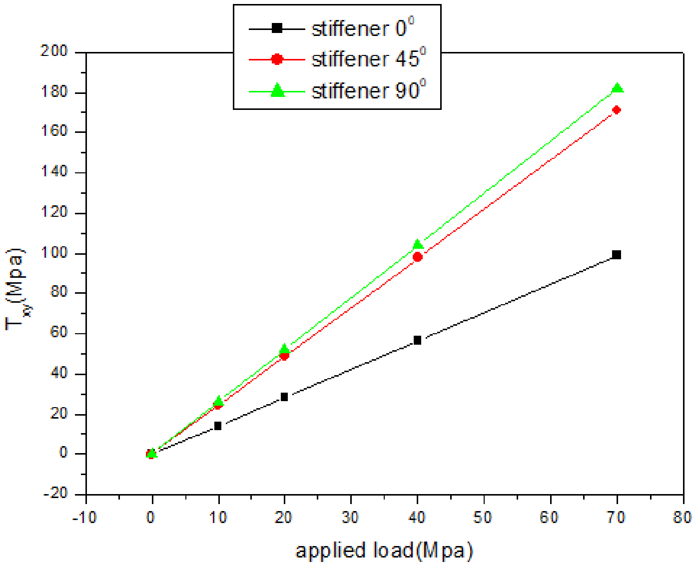

Figure 10: Shear stresses τxy for different applied horizontal loads

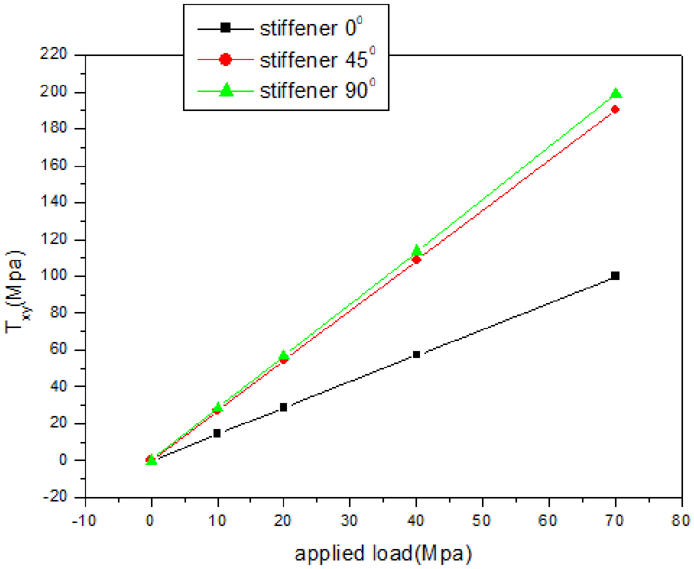

Figure 11: Shear stresses τxy for different loadings in two identical directions applied

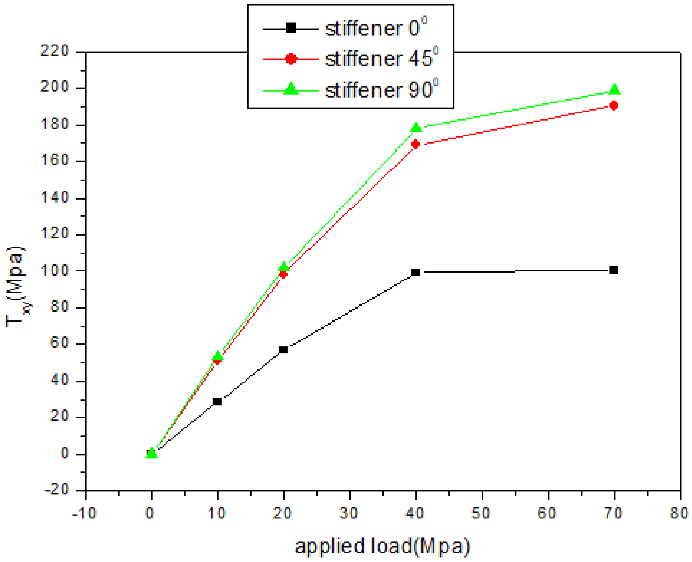

Figure 12: Shear stresses τxy for different loadings in two different directions applied

7. TENSILE EXPERIMENT

The tensile experiment was conducted to validate the numerical simulations by measuring the stress-strain response of the samples. Using a servo hydraulic testing machine (as shown in Fig. 13), the samples were subjected to controlled tensile loading.

The resulting stress-strain curves from the experiment (illustrated in Fig. 14) closely matched the predictions made by the numerical simulations, confirming the accuracy of the numerical models. The agreement between experimental and simulation results highlights the reliability of the numerical approach in predicting the mechanical behavior of the materials under tensile loading. The tensile experiment was carried out to validate the numerical simulations by measuring the stress-strain response of the samples. The results, as shown in the graph, illustrate the relationship between stress and strain for the materials under study.

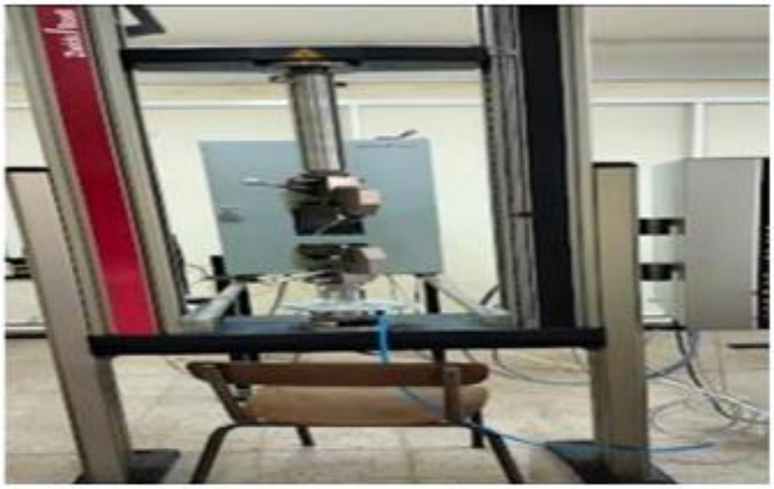

Figure 13: Servo hydraulic testing machine

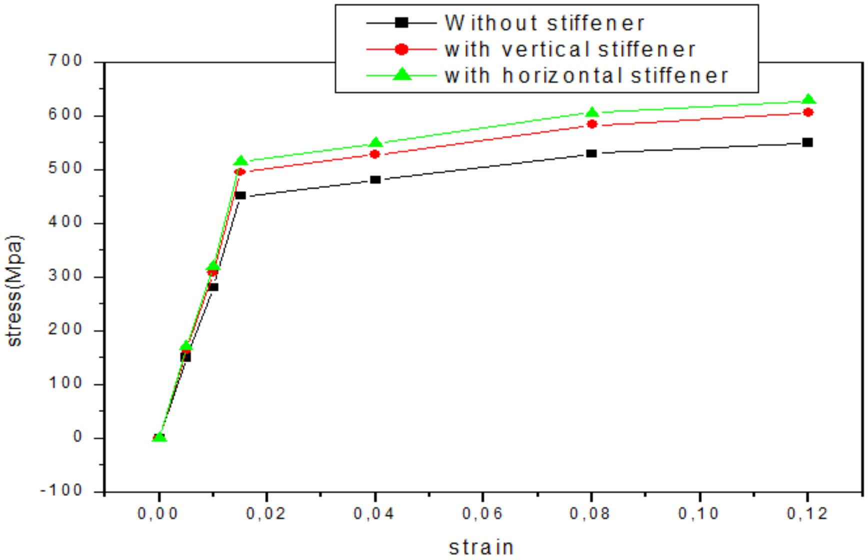

Figure 14: The tensile experiment on the samples studied by numerical simulations

8. CONCLUSION

The results obtained allow us to draw the following conclusions:

The finite element analysis has allowed us to learn a new calculation software, in this case the. The finite element analysis allowed us to learn a new calculation software, in this case the ABAQUS code, which is a powerful, useful and very efficient tool. The optimization of the bonded stiffener is obtained by varying the locations, the applied constraints, the loading directions, etc. The lessons to be learnt from the analysis of the stiffener locations are that the loading is the main parameter to be modified to obtain optimal locations, i.e. an increase in the strength of the reinforced plate accompanied by an economical choice. The load applied on the plate is a main factor in the distribution of loads in the patch elements, it is noticed that the relationship between the stress intensity factor and the load applied on the plate is linear, the same for the stress intensity factor. Based on these results, the technique of reinforcement by stiffener was introduced for the purpose of strengthening a damaged structure. This technique is based on the bonding of a stiffener. In the first analysis, a comparison was made between the locations of the stiffener, in which case it was found that the reduction of the stress intensity factor in a location of 0° is much greater than in a location of 45° and 90°. For the shear stress in the adhesive it was noted that the concentration of the shear stress, in the case of a 0° location, is within the boundaries of the adhesive. In order to find out whether the location of a stiffener oriented at an angle of 0° is able to improve the effectiveness of the stiffener compared to all the cases studied.

References

1) Zain, A.M., Haron, H., & Sharif, S. (2010), "Prediction of surface roughness in the end milling machining using Artificial Neural Network", Expert Systems with Applications, Vol. 37 No. 2, pp. 1755-1768.

2) Yallese, M.A., Rigal, J.F., Chaoui, K., & Boulanouar, L. (2005), "The effects of cutting conditions on mixed ceramic and cubic boron nitride tool wear and on surface roughness during machining of X200Cr12 steel (60 HRC)", Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 219 No. 1, pp. 35-55.

3) Meddour, I., Yallese, M.A., Bensouilah, H., Khellaf, A., & Elbah, M. (2018), "Prediction of surface roughness and cutting forces using RSM, ANN, and NSGA-II in finish turning of AISI 4140 hardened steel with mixed ceramic tool", The International Journal of Advanced Manufacturing Technology, Vol. 97 No. 5, pp. 1931-1949.

4) Suresh, R., Joshi, A.G., & Manjaiah, M. (2021), "Experimental Investigation on tool wear in AISI H13 die steel turning using RSM and ANN methods", Arabian Journal for Science and Engineering, Vol. 46 No. 3, pp. 2311-2325.

5) Paturi, U.M.R., Devarasetti, H., & Narala, S.K.R. (2018), "Application of regression and artificial neural network analysis in modelling of surface roughness in hard turning of AISI 52100 steel", Materials Today: Proceedings, Vol. 5 No. 2, pp. 4766-4777.

6) Meknassi, R.F. (2019), "Etude de l’impact des conditions de coupe lors du tournage des polyamides avec renfort en fibre de verre (PA66/GF30) en utilisant les méthodes RSM et ANN".

7) Kumar, R., Sahoo, A.K., Mishra, P.C., Das, R.K., & Roy, S. (2018), "ANN Modeling of Cutting Performances in Spray Cooling Assisted Hard Turning", Materials Today: Proceedings, Vol. 5 No. 9, pp. 18482-18488.

8) Lee, J., Kim, S., & Park, Y. (2017), "Finite element analysis of stress distribution in plates with circular openings", Journal of Mechanical Engineering, Vol. 45 No. 3, pp. 245-256.

9) Nguyen, T., Tran, P., & Le, H. (2019), "Effect of stiffeners on stress concentration in plates with circular openings", International Journal of Structural Engineering, Vol. 23 No. 2, pp. 189-203.

10) Zhang, L., Liu, H., & Chen, Y. (2018), "Crack growth simulation in stiffened plates using XFEM", Engineering Fracture Mechanics, Vol. 200, pp. 120-134.

11) Kim, J., & Lee, D. (2016), "Boundary element method for stress intensity factor calculation in plates with openings", Computational Mechanics, Vol. 58 No. 4, pp. 567-576.

12) Park, S., Lee, H., & Kim, Y. (2020), "Comparative study of FEM and XFEM in crack growth analysis", Journal of Computational Engineering, Vol. 32 No. 1, pp. 50-64.

13) Li, X., & Wang, Z. (2018), "Comparative analysis of rib stiffeners and patch reinforcements in plates with circular openings", Materials and Design, Vol. 145, pp. 111-123.

14) Chen, Q., Yang, J., & Xu, W. (2019), "Composite stiffeners for fracture resistance in plates with openings", Composite Structures, Vol. 208, pp. 546-556.