Bearing Strength and Failure Behavior of Bolted GLARE Joints

Mohammed Y. Abdellah[1,3*], Mohamad K. Hassan[2,3], T. Mandourah[3], Ahmad F. Mohamed[3,4]
[1]Mechanical Engineering Department, Faculty of Engineering, South Valley University, Qena, Egypt, 83521
[2]Production Engineering and Design Department, Faculty of Engineering, Minia Universities, Minia, Egypt, 61111
3Mechanical Engineering Department, Collage of Engineering and Islamic Architecture, Umm Al-Qura University, Makkah, KSA
[4]Mechanical Engineering Department, Faculty of Engineering, Sohag University, Sohag, Egypt
*mohammed_yahya42@yahoo.com

***Abstract*--** **Glass fiber reinforced aluminum laminates (GLARE) are main important types of fibre metal laminates composite material. The composite sandwich is manufactured by inserting glass fibre composite laminate between two chemically treated aluminium thin sheet. GLARE material is manufactured with three stacking sequences using random mate layered glass fibre of 1, 2, and 4 layers. The strength and failure of mechanically fastened glass fiber aluminum reinforced epoxy (GLARE) joints are experimentally investigated. The results indicate that bearing strength of GLARE increases with increasing number of glass fiber reinforced laminates but with limitation of that thickness not largely increasing to avoid delamination. Modes of failure for the bolted joint are enhanced to bearing modes for all types of specimens.**

***Index Term*--** **GLARE, Bolted Joint, Aluminum, Reinforced Glass Fiber, X-FEA**

INTRODUCTION

Fiber-metal laminates (FMLs) are considered hybrid structure which are composed of glass fiber and aluminum alloy. These materials are widely used in A380 Airbus aircraft industry [1]. Joints of composite material in aircraft industry are facing a lot of problems especially for mechanical fixation such that hole elongation and bolt bending under compressive loading due to low bearing stiffness of composites [2]. Many researchers studied and examined the behavior of fastener joints and their effect on specimen geometry and fiber orientation [3, 4].

Xiao and Ishikawa [2] studied strength and failure of the mechanical fastened composite joint. They studied the effect of polymer matrix properties on bearing strength response of joint. They concluded that bearing failure was due to compressive damage accumulation and it had four stages; damage initiation; damage growth and structural fracture. Established failure modes are; fiber microbuckling; matrix cracking; delamination and out of plane shear cracks.

Xiao and Ishikawa [5] proved and extracted an analytical model for simulation the bearing failure and response characteristics of bolted composite joints. The mode was based on progressive damage finite element method. The numerical simulation results were in good agreement with the experimental results, but the model needs a lot of experience in numerical knowledge.

Hung and Chang [6] studied the effect of clamping pressure and lateral constraint on the bolted joint. They developed a two-dimension damage accumulation model, but the delamination due to bearing damage was not completely described.

Camanho et al. [7] experimentally investigated the damage mechanisms of double lap joint with finger tight washer. It was summarized that failure modes were fiber fracture, delamination at loaded hole, matrix cracks and fiber microbuckling.

Mohammed et al. [8] used X-FEM procedures to simulate the nominal strength of size effect glass fiber composite laminates, their results were in a good agreement with the experimental results.

Hasan et al. [9, 10] experimentally studied the mechanical and fracture properties of GLARE. The results were conducted that the GLARE material had increasing strengths and ductility and young's modulus.

The novelty of the present study is to study analytically and experimentally bearing strength of double lab joint GLARE material. In addition, it is to build a simple extended-finite element method based on cohesive traction separation laws. Moreover, it is to stop on the failure modes of such new material.

The paper methodology is constructed as follows; in the first paragraph manufacturing technique of GLARE are highlight. The next paragraph the bolted joint test is outlined, then X-FEA is explained and is built. Finally, the validation of the numerical analysis is discussed.

Manufacture of GLARE material

The material used in the manufacturing GLARE are random E-glass fiber, epoxy resin and aluminum alloys sheet having 0.5 mm thickness. The components mechanical properties are listed in Table 1. The GLARE composites are fabricated using hand lay-up technique according to reference [11]. Mainly, the treatment of aluminum surface needs special care because it is a dominant factor to increase debonding between aluminum plates and glass fiber composite laminates. There are 7 steps for aluminum surface treatment to increase debonding in GLARE consists of, it is completely described in reference [9]. GLARE specimens which contain 1, 2, and 4 layers of

IJENS

composite laminates are inserted between the two aluminum sheets (see Fig. 1). The obtained thicknesses are nearly equally 1.2 mm.

Table I
Mechanical and physical properties of E-glass fiber and epoxy resin, [12, 13, 14]

Properties	E-glass	Kemapoxy(150RGL)
Density(kg/m2)	2540	1.07 ±0.02 kg/liters
Tensile strength (MPa)	2000	50-100
Tensile modulus (GPa)	76	1.2-4.5
Passion ratio	0.25	0.35
In plane shear modulus	30.8	1.24
Failure strain		1.7

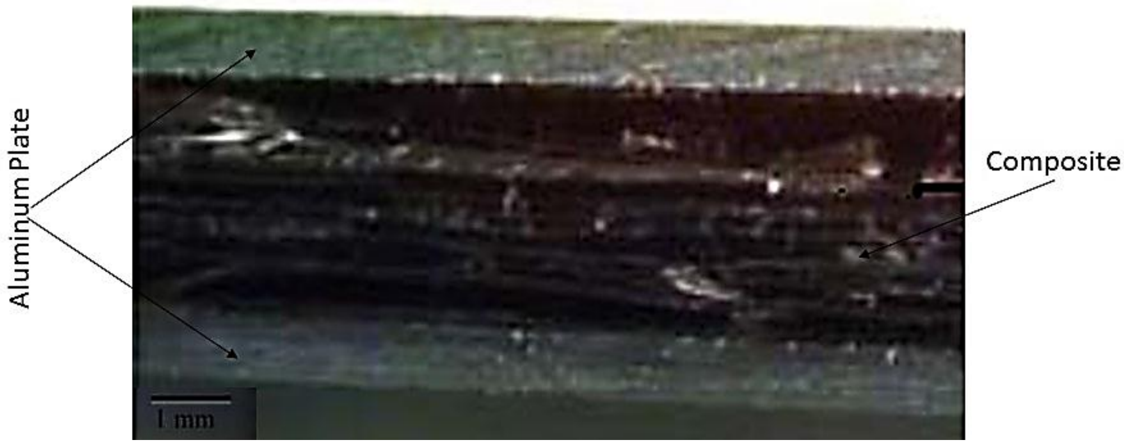

Fig. 1. GLARE specimen cross section [10]

The volume fraction of GLARE material is determined using ignition removal technique according to ASTM D3171-99 standard [15]. It is found for glass fiber composite laminate sandwiched between the two aluminum plates as 45% and 55% for epoxy resin.

Exprimental work

The joint is more complicated problem in designing of composite structures, this can be attributed to that the joint passes through geometry of structure and material discontinuity. Testing setup of the double lap joint specimens are shown in Fig.2. The test set up is consists of three metal plates of steel; two of them for holding specimen with bolt and anther is work as loading plate. The GLARE specimens have rectangular cross section of 40 mm width and 80 mm length with hole of 5 mm located at 20 mm from plate end.

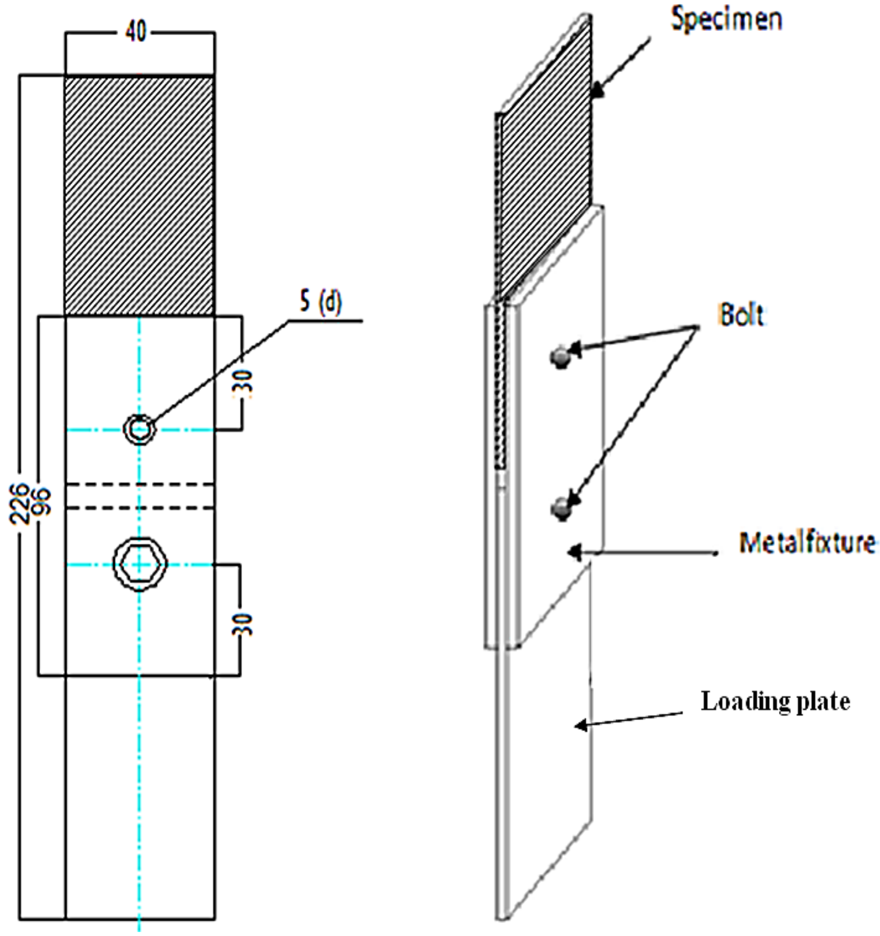

Fig. 2. Testing setup of bolted joint specimens with dimensions in mm.

The specimen and loading plate are prepared for gripping into the jaws of the testing machine vertically. The tests are carried out using computerized universal testing machine (model WDW-100) of load capacity (200kN), at controlled speed of 2mm/min.

Bearing strength is defined as the bearing load when pin relative displacement is deformed to (4%) of the pin diameter. The average bearing strength, is expressed as [2]:

$$S_b^{4\%} = \frac{P_{4\%d}}{d.t} \quad (1)$$

Whereas, ultimate bearing strength is expressed as:

$$S_b^{Ult} = \frac{P_{max}}{d.t} \quad (2)$$

Where (P_{max}) is the maximum load, N, ($P_{4\%}$) is the bearing load, N, (d) is the pin diameter, mm, and (t) is thickness of specimen, mm.

Finite element simulation

the Extended Finite Element Method (X-FEM) has been Recently developed by Belytschko and Black [16]. Mainly, X-FEM uses the concept of partition of finite element unity and enrichment function [17]. The X-FEM is distinguished that the mesh does not need to conform to the geometry of the problem anymore. Therefore, failure analysis of cracks is established without remeshing and with increasing numerical accuracy around the crack tip. More descriptions of the method are found in reference [18].

Finite element constitutive model

The mechanical behavior of GLARE is employed for simplicity by isotropic elasticity and isotropic plasticity. The simplest form of linear elasticity is the isotropic case, and the stress-strain relationship is calculated using the following strain tensor [19, 20];

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \varepsilon_{12} \\ \varepsilon_{13} \\ \varepsilon_{23} \end{Bmatrix} = \begin{bmatrix} 1/E & -v/E & -v/E & 0 & 0 & 0 \\ -v/E & 1/E & -v/E & 0 & 0 & 0 \\ -v/E & -v/E & 1/E & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G \end{bmatrix} \begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix} \quad 3$$

Where $(E, G\ and\ v)$ are elastic constants and $(\sigma, and\ \varepsilon)$ are components of stress and strain. The material stress strain curves for different layers are shown in Fig.3. The evaluated damage is maximal at crack opening and is calculated using the following equation [18, 19]:

$$\delta_n = \sqrt{\langle \delta_n \rangle^2 + \delta_s^2 + \delta_t^2} \quad 4$$

Where (δ_n) critical crack opening, and (δ_s, δ_t) are shear and traction separation displacement. The maximum flow principal stress is the value of the un-notched nominal strength which is measured using simple tension test. The flow curves for these material are shown in Fig. 4. In addition, the damage evaluation criterion is maximum traction displacement (maximum crack opening is assumed to be 0.3 mm). The elastic young's modulus is measured from stress strain curves which are shown in Fig. 3.

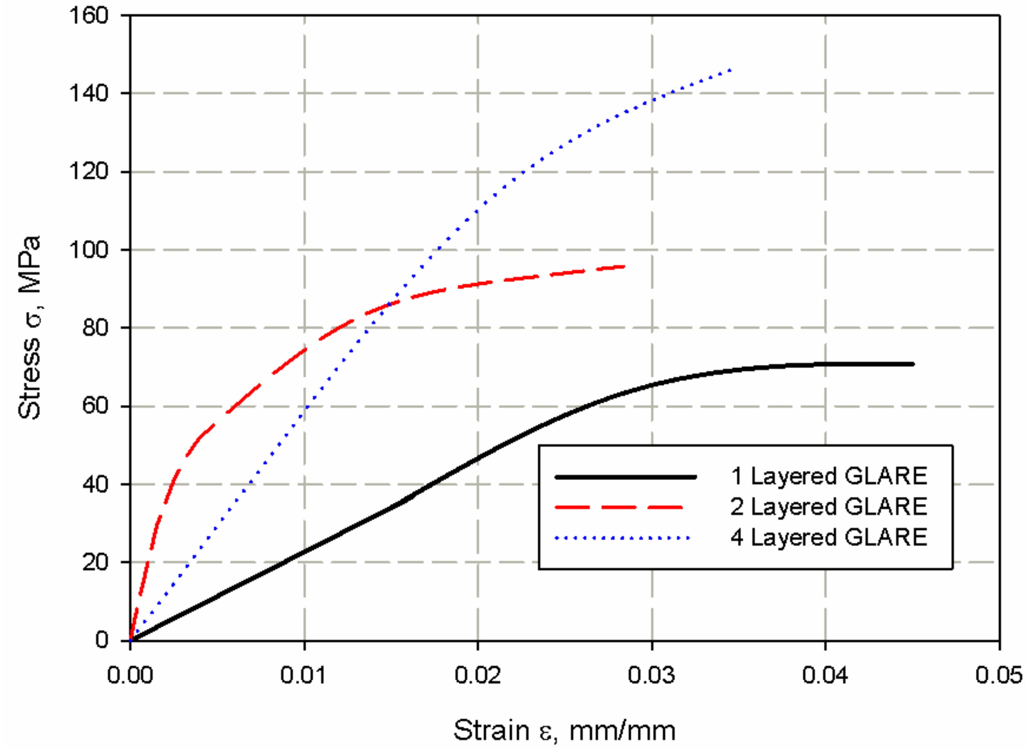

Fig. 3. Stress strain curve for GLARE Material with different glass fiber reinforced epoxy layered laminates

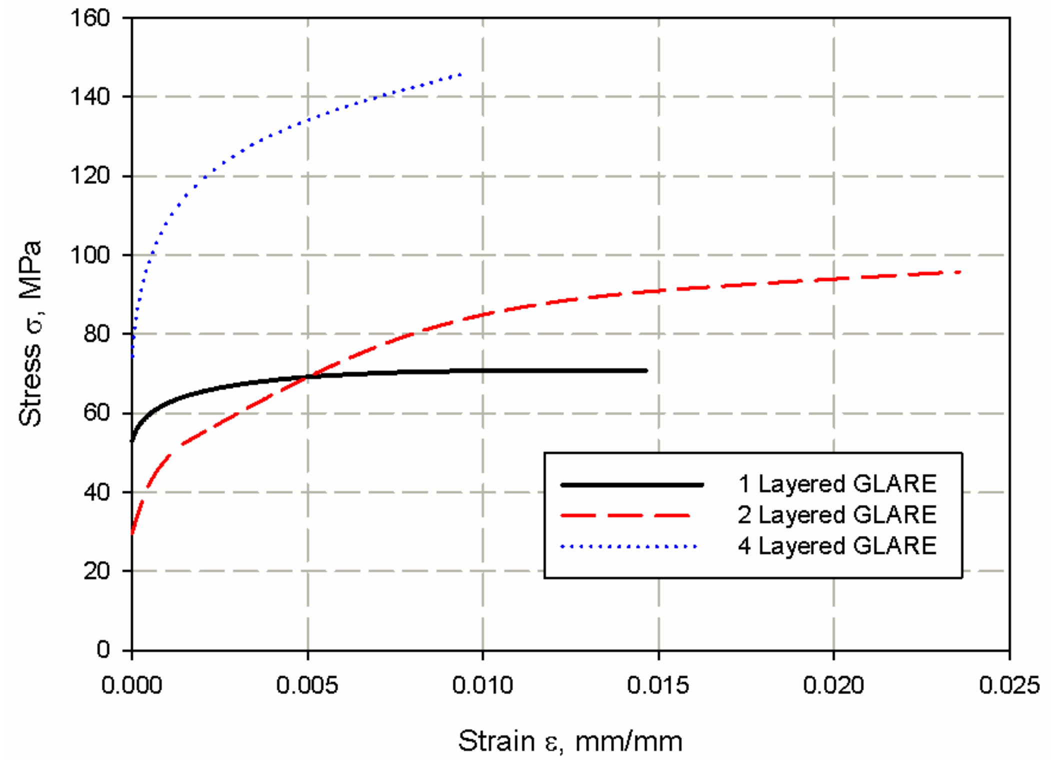

Fig. 4. Stress strain curve for GLARE Material with different glass fiber reinforced epoxy layered laminates

Finite element domain, mesh and boundary condition

The swept meshing technique is used to generate a domain of 1638 elements of (C3D8R) type as it is shown in Fig. (5-a). The specimen domain is attached to the testing set up where load is applied to the end of specimen and at the steel plate vertically. The displacement control boundary conditions technique is applied as it is shown in Fig. (5- b). The interaction between the steel bolts and the holding steel plate is assumed to be constrained as (tie) Fig. (6-a), while the interaction between bolts and specimen domain is applied as penalty of fraction coefficient 0.3. The domain with interaction is shown in Fig. (6-b).

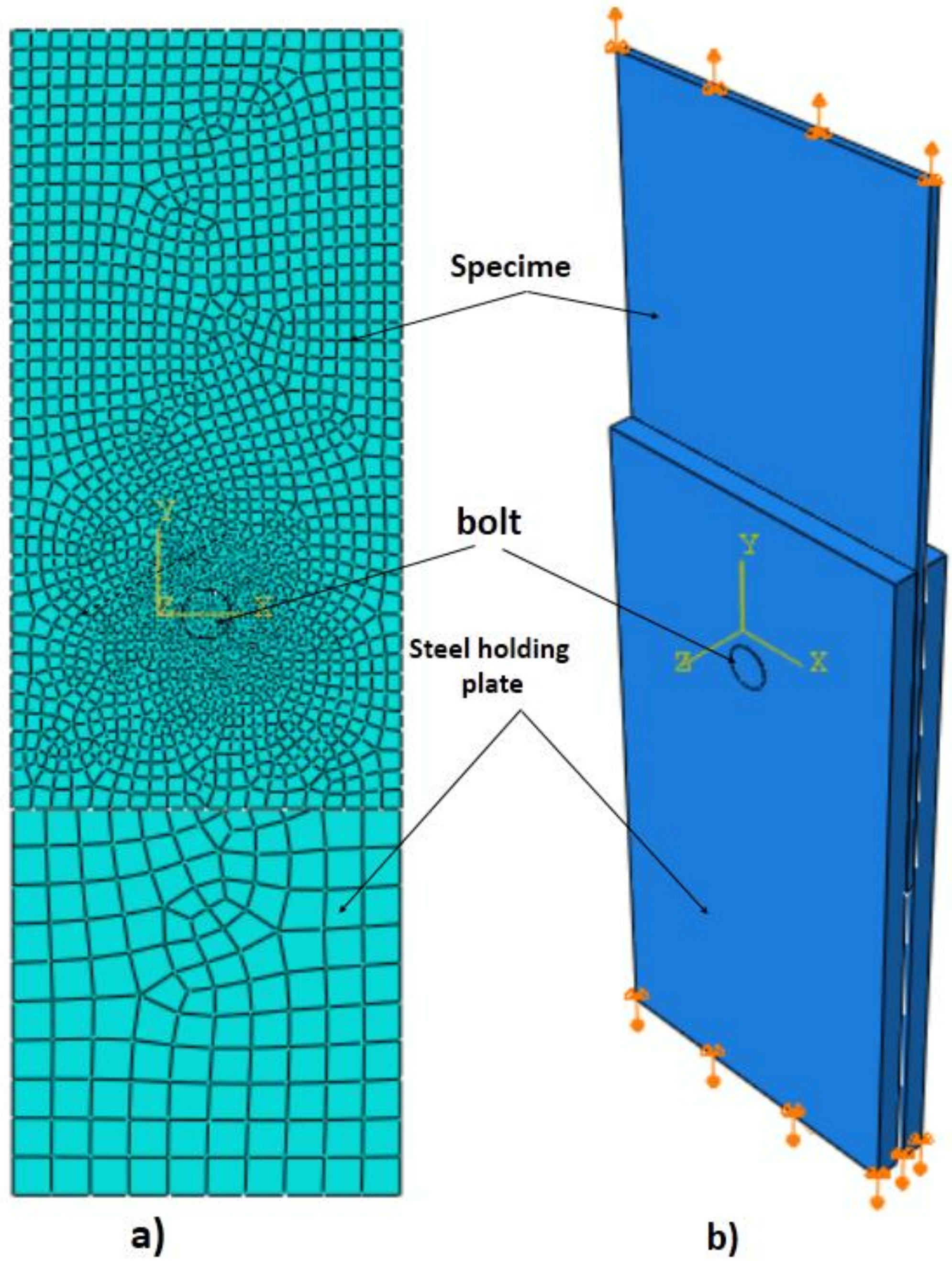

Fig. 5. Finite element domain a) Mesh domain b) Boundary condition

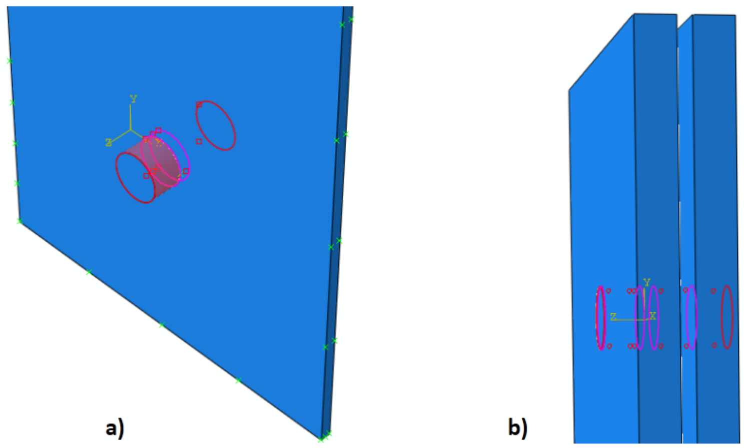

Fig. 6. Interaction domain a) Tie interaction between bolts and GLARE b) penalty between bolts and holding steel plate

RESULTS AND DISCUSSION

Bolted Joint Test:

An experimental study on the effects of bolt joints on GLARE material panel specimens is performed. Fig. 7 illustrates load-displacement curves of GLARE material panel specimens of the double lap joint with 1, 2 and 4 glass reinforced composite laminates respectively. It is observed that the maximum bearing strength of bolt joint can be measured using Eqn. 2 at maximum load point. These values are 89.5, 119.6 and 169.5 MPa for 1, 2 and 4 glass reinforced composite laminates repetitively. While, average bearing strength can be measured according to Eqn. 1 respect to Fig. 7 at (4% d) loaded pin deformation. The values of bearing strength are measured as 60.8, 90 and 108.3 MPa for 1, 2 and 4 glass reinforced composite laminates repetitively. Failure modes are shown in Fig. 9, it is enhanced to be bearing failure modes for all specimen whereas delamination observed through the aluminum and glass fiber interfaces. The bearing mode is confirmed due to the increasing ductility of aluminum, whereas, wake debonding strength led to delamination through the interface between glass fiber and the aluminum sheet.

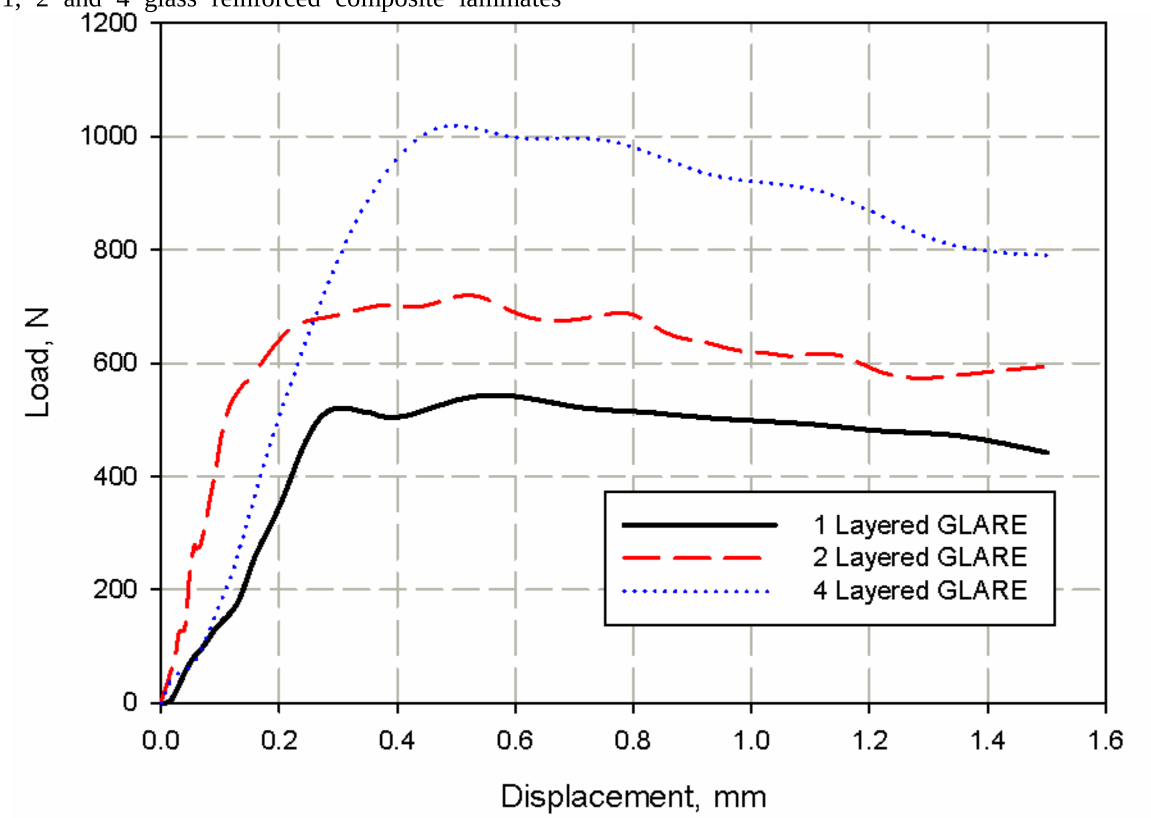

Fig. 7. Typical load–displacement curves for bolted GLARE joint

Finite element results validated with the experimental

Based on the experimental observation described in the previous sections, bearing failure is mainly related by matrix and fiber compression damage. Therefore, a cohesive damage zone model is developed to predict the matrix compression and fiber compression-shear failure of a laminate layer though X-FEM. Figure 8 illustrates the X-FEA prediction for the double lap joint bearing strength. The simulation is in good agreement and it is observed that for one layered GLARE sandwich X-FEM prediction is higher than experimental results, this may due to that effect of glass fiber is wake respect to the aluminum behavior in the GLARE material. The failure mode is predicted in good agreement with the experimental bearing mode as shown in Fig. 9, comparing Von-Mises failure with the experimental failure modes. STATUS XFEM for all simulated specimens are shown in Fig. 10.

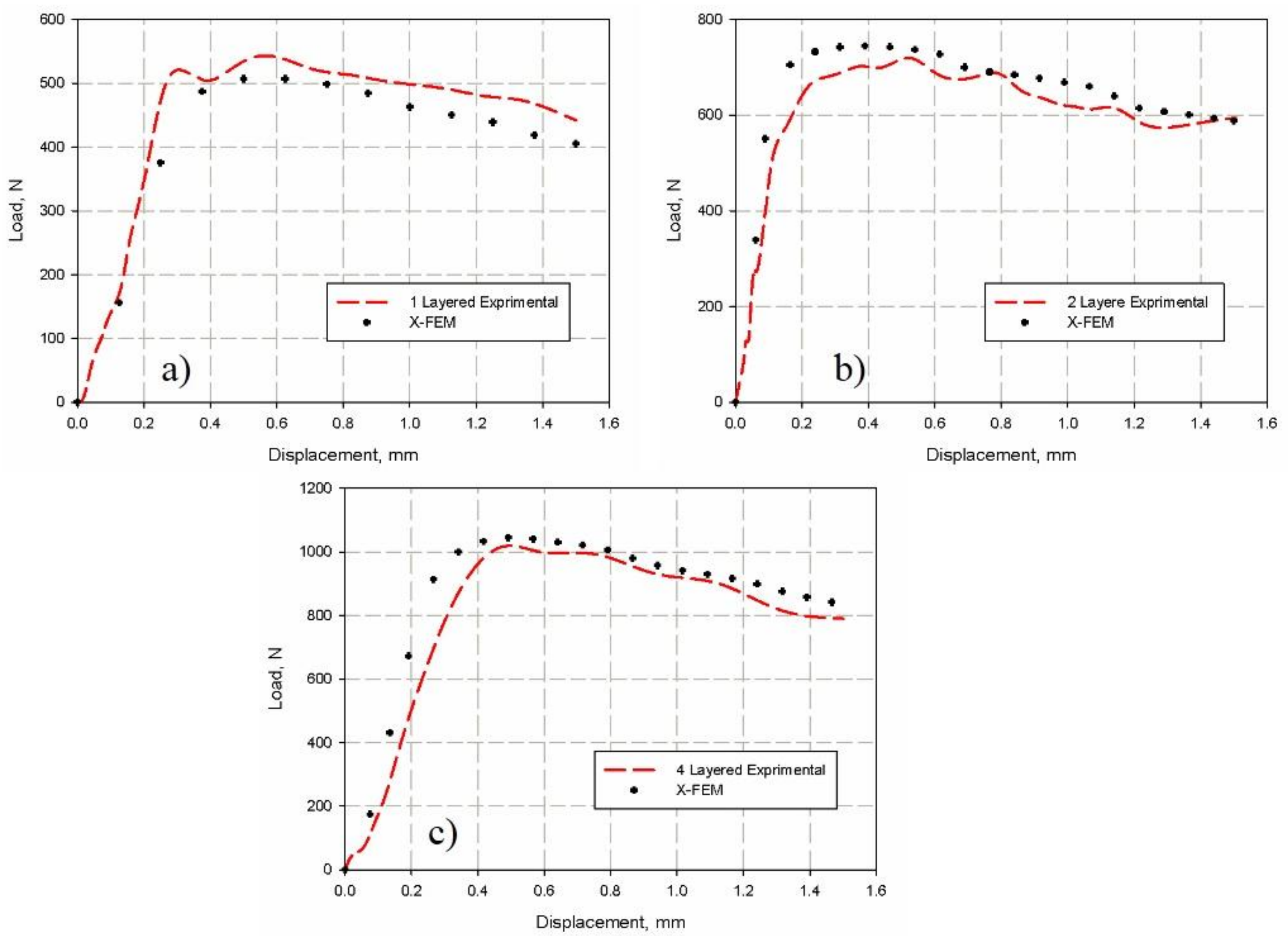

Fig. 8. Bearing load respect to X-FEM for a) one layered b) Two layered c) Four Layered reinforced laminates at GLARE

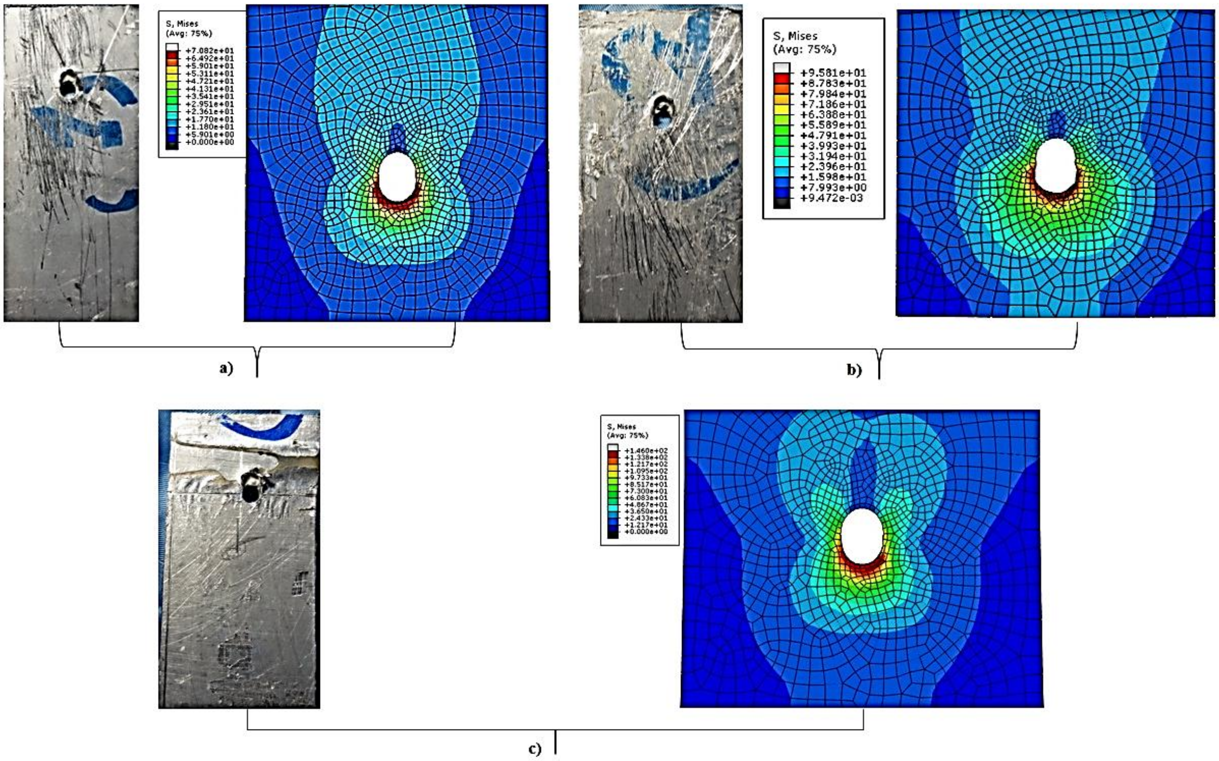

Fig. 9. Predicted failure modes of GLARE material having a) one layered b) Two layered c) Four Layered reinforced laminates at GLARE

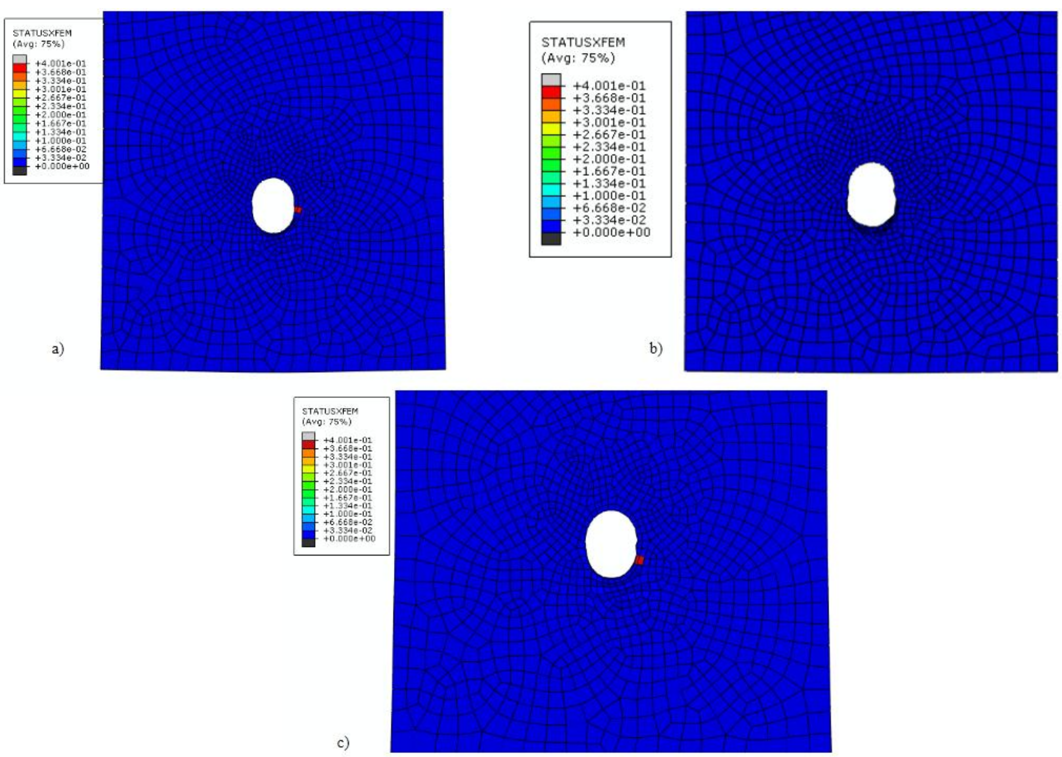

Fig. 10. STATUS XFEM of GLARE material prediction a) one layered b) Two layered c) Four Layered reinforced laminates at GLARE

CONCLUSION

In this study, a detailed experimental investigation and numerical model are performed to evaluate the bearing strength and damage behavior of mechanically fastened joints of GLARE material. The relationships between the load–displacement curve, and failure mechanism are examined. The bearing strength is measured at (4% d) of deformation of load pin displacement. The failure modes are enhanced to be all bearing due to increasing ductility of aluminum plates. X-FEM simulates very well the bearing strength and failure modes. The nonlinear isotropic X-FE model presented in the paper based on cohesive law can be established for fast prediction for selection purpose of GLARE material.

REFERENCES

[1] V. A., Chapter 1 in fibre metal laminates; an introduction, Dordrecht: Kluwer Academic Publishers; ., 2001.

[2] Y. Xiao and I. Takashi, "Bearing strength and failure behavior of bolted composite joints (part I: Experimental investigation).," *Composites Science and Technology,* vol. 65, no. 7, pp. 1022-1031, 2005.

[3] L. J. Hart-Smith, "Bolted Joints In Graphite-Epoxy Composites," MCDONNELL DOUGLAS CORP LONG BEACH CA DOUGLAS AIRCRAFT DIV, 1976..

[4] M. FL, Joining fiber-reinforced plastics, New York: Elsevier Applied Science, 1986.

[5] Y. Xiao and T. Ishikawa, "Bearing strength and failure behavior of bolted composite joints (part II: modeling and simulation).," *Composites science and technology,* vol. 65, no. 7, pp. 1032-1043, 2005.

[6] C. Hung and F. Chang, "Bearing failure of bolted composite joints Part II: model and verification," *Journal of composite materials,* vol. 30, no. 12, pp. 1359-1400, 1996.

[7] P. P. Camanho, S. Bowron and a. F. L. Matthews., "Failure mechanisms in bolted CFRP," *Journal of Reinforced Plastics and Composites* , vol. 17, no. 3, pp. 205-233, 1998.

[8] Y. Mohammed, M. K. Hassan and A. M. Hashem, "Finite Element Computational Approach of Fracture Toughness in Composite Compact Tension Specimen," *International Journal of Mechanical & Mechatronics Engineering,* vol. 12, no. 4, pp. 57-61, 2012.

[9] M. K. Hassan, M. Y. Abdellah, S. K. Azabi and W. Marzouk, "Investigation of the Mechanical Behavior of Novel Fiber Metal Laminates," *International Journal of Mechanical & Mechatronics Engineering,* vol. 15, no. 3, pp. 112-118, 2015.

[10] M. K. Hassan, M. Y. Abdellah, S. K. Azabi and W. Marzouk, "Fracture Toughness of a Novel GLARE Composite Material," *International Journal of Engineering & Technology,* vol. 15, no. 6, pp. 36-41, 2015.

[11] M. A. Ardakani, A. A. Khatibi and S. A. Ghazavi, "A study on the manufacturing of Glass-Fiber-Reinforced," in *Proceedings of the XIth International Congress and Exposition*, Orlando, Florida USA, 2008.

[12] M. Y, H. M. A. E.-A. H. and H. A.M, "Size effect analysis of open-hole glass fiber composite laminate using two-parameter cohesive laws.," *Acta Mechanica,* vol. 226, no. 4, pp. 1027-1044, 2014.

[13] J. R.M., Mechanics of Composite Materials, London: Taylor & Francis, 1999.

[14] M. P.K., Fiber-Reinforced Composites, New York: Marcel Dekker Press., 1993.

[15] ASTM., D3171-99 , Stander Test method constituent content of composite materials, American Society of testing and materials, 1999.

[16] B. T. and B. T., "Elastic crack growth in finite elements with minimal remeshing," *Int.J. Numer Meth Engng,* vol. 45, no. 5, p. 601; 620, 1999.

[17] M. J.M. and B. I, "The partition of unity finite element method: Basic theory and applications," *Comput Meth App Mechs Engrg,* pp. 289-314, 1996.

[18] M. Y. Abdellah, M. S. Alsoufi, M. K. Hassan, H. A. Ghulman and A. F. Mohamed, " Extended Finite Element Numerical Analysis of Scale Effect in Notched Glass Fiber Reinforced Epoxy Composite," *Archive of Mechanical Engineering,* vol. 62, no. 2, pp. 217-236, 2015.

[19] ABAQUS, Version ”6.9 Documentation.”, Providence, RI: DassaultSystemesSimulia Corporation, 2009.

[20] N. S. Korim, M. Y. Abdellah, M. Dewidar and A. M. Abdelhaleem, "Crushable Finite Element Modeling of Mechanical Properties of Titanium Foam," *International Journal of Scientific & Engineering Research,* vol. 6, no. 10, pp. 1221-1227, 2015.