Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Analysis of the Bolt Inclination Angle Using Digital Image Correlation (New Optical Method)

Faci Youcef[1], Djillali Allou[1], Mebtouche Ahmed[2]

[1]*Research Center in Industrial Technologies (CRTI), BP 64, Route Dely Brahim, Cheraga, Algiers, Algeria*
[2]*Research Center in Industrial Technologies (CRTI), BP 64, Route Dely Brahim, Cheraga, Algiers*
Email: 1y.faci@crti.dz

The inclination of the bolt during a tensile test in a fastened joint of composite material can be influenced by several parameters, including bolt dimensions, preload, type of composite material and its properties, design, joint configuration, and testing conditions. This work focuses on the impact of specimen geometry and the stacking sequence on the inclination angle of the bolt under load. Three types of specimens were used in the experimental tests. Digital image correlation (DIC) was employed to identify damage and measure displacement strain in the fastened joint. The inclination of the bolt during the tensile testing of the specimens was measured using DIC across the three types of composite joints. Consequently, a new optical method allows for the evaluating the bolt's inclination throughout the experimental test. In conclusion, the correlation between bolt inclination under load and damage mechanisms was established experimentally. The results demonstrate the influence of stacking sequence and specimen geometry on the evolution of bolt inclination under stress.

1. Introduction

When using composites, strength and joint efficiency are much lower than, those obtained in metallic materials, thereby hindering the widespread utilization of composites [1-3]. Digital image correlation for measuring displacement on solid surfaces was introduced in the 1980s by researchers at South Carolina University. In modern years, many researchers have improved and optimized this technique [4-5]. They have been applied to surface deformation measurement using images from Atomic Force (AFM), Scanning Electron Microscopy (SEM), X-ray microtomography, and Microscopy [6]. Quite recently, digital image correlation (DIC) has been used to experimentally study of composite fastened joints using digital image correlation. Caminero et al [7] employed DIC for online damage monitoring in composite laminates with an open hole and adhesively bonded patch repairs. They found that the location and extent of damage identified by DIC correlate well with X-ray results. The inclination of the bolt can affect the distribution of load and stress within the joint, which can influence the damage mechanism. An increased inclination of the bolt can lead to higher shear and bearing forces during the contact of the approach points between the bolt and the composite material. This can result in localized damage such as matrix cracking delamination, or fibre breakage. The inclination of the bolt can also lead to stress concentration at specific points within the joint. It is important to consider the effects of bolt inclination when analysing the performance and mode of failure in joints of composite materials [8]. The inclination of bolt during loading can influence the damage type that occurs in composite materials, including shear, tensile, compression, and fatigue damage. Consequently, some potential relationships between bolt inclination and the type of damage can be the object of analysis. Shear damage was obtained by the misaligned bolt that can create shear stress concentrations at the contact points, leading to potential delamination or fibre damage in the composite material. This can occur when the load is applied and the misaligned bolt cause a shearing force on the material. By analysing the strain data, the relative displacement and deformation of the joint can be determined, which can be used to calculate the angle of bolt inclination overall, non-destructive application testing techniques such as digital image correlation and strain gauges can provide valuable experimental data to determine the angle of bolt inclination in a composite bolted joint during a tensile test [9]. This work has two main objectives: to develop and validate an optical method for measuring the inclination angle of a bolt in a composite joint during loading, and to investigate the relationship between bolt inclination and structural damage in composite joints.

2. EXPERIMENTAL PROCEDURE

Three different bolted joints were investigated. This specific material is the composite carbon/epoxy as shown in Fig. 1. This two-part epoxy is a thermoset polymer.

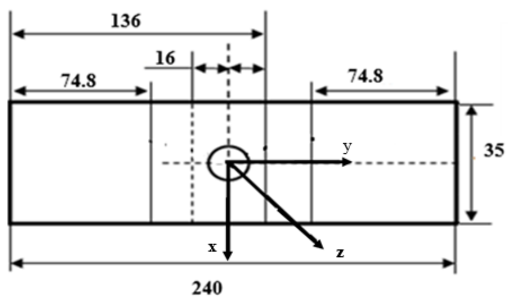

Fig. 1 Single lap joint of top-view with a coordinate system in mm

TABLE I Group of Specimens used

Specimen	Thickness (mm)	Number of plies	Stacking sequences
S1	1.38	4	(90°,90°, -45°,0°)

S2	3.5	10	$(0°,90°, -45°,0° ,90°)_S$
S3	4.2	12	$(0°,90°, -45°,0° ,90°,0°)_S$

The same type of bolt is used in all objects. Table II lists all joints with their object number. The names in the quotation mark refer to the names used in the text. Several plies and thicknesses are listed. In all objects, the torque refers around 1.3-1.5 Nm. The lay-up of fibers is quasi-isotropic $[\pm45^o,0^o,90^o,0°]_{ns}$ for all joints.

2.1 Digital Image Correlation Techniques (D.I.C)

The D.I.C technique has obtained and approval in both materials and structural testing due to the non-contact and full field value compared to the standard point-wise measurement techniques. It is based on tracking and image registration techniques for accurate 2D and 3D measurements of changes in images. This technique allows us to obtain finer details related to the deformation scheduled to the faculty to offer both local and mean data. A fluorescent tube illuminated the surface of the sample and digitally photographed. Fig. 2 shows an optical compound and the specimen was mounted on the experimental tensile tests machine. The technique is based on capturing an image of an object that has undergone deformation, using a high-resolution charge-coupled device camera (C.C.D). This image is digitized and compared with the reference image (the original unreformed state). A mathematical correlation function will be employed to perform this comparison. The integral method was used to compare the deformed images with the reference image. The image resolution is set at 28 μm. All images are captured at a rate of five frames per second. A window size of 32 x 32 pixels is used for analysis. Characteristic points will be selected to analyse these images and determine the displacements and strain fields within the studied region. Digital image correlation (D.I.C) can effectively be used to monitor the inclination or movement of a bolt during a tensile test of composite bolted joints. The charge-coupled device (C.C.D) camera on the side of the specimen permits measurement of the bolt angle's inclination during the tensile test until failure. The inclination of the bolt during a tensile test of a composite bolted joint can significantly impact the performance and integrity of the joint, affecting factors such as load distribution, joint integrity, failure modes, strain distribution, fatigue life, torque requirements, and structural performance. Controlling and understanding the inclination of the bolt during experimental tests is crucial to ensure the reliability and safety of bolted joints in composite materials.

3. RESULTS

Typical bearing load versus time curves for the single-lap fastened joints S1, S2, and S3 are presented in Figs. 3, 4, and 5, respectively. A Charge-Coupled Device (CCD) camera monitored the progressive damage until failure.

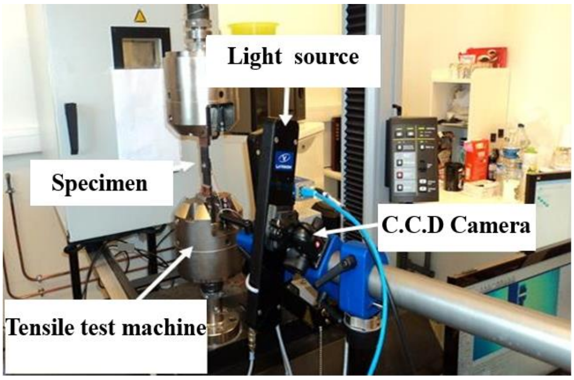

Fig. 2 Experimental set up.

The variations of the different types of forces and stresses are observed. Digital photographs corresponded to the characteristic points of the load versus time curve. For all specimens, the bearing failure mode of composite bolted joints results primarily from the fiber's compression and shear failures. All curves related to groups S1, S2, and S3 begin with an elastic and linear zone. The onset of non-linearity coincides with damage at the hole edge of the substrate. It is about cracked matrices in the plies and fiber micro-buckling. Bearing failure causes a slight drop in load. Despite this small decrease, all tested joints can still support additional loads, increasing until the ultimate load is reached at the subsequent characteristic point. However, bearing failure occurred at the beginning of failure for the entire joint. For all joints, the final rupture was due to bolt failure. Bolt inclination is connected to bearing failure, for the bolt to rotate it has to crush the hole edge which is a bearing failure. The test curves of the five specimens with the stratifications [0°, 45°, 0°, 45°], [0°, 90°, -45°, 0°, 90°]$_s$, and [0°, 90°, -45°, 0°, 90°, 0°]$_s$ is shown in Fig. 6, 7, and 8, respectively. The curves illustrate the mechanical performance of the specimens under tensile testing, highlighting differences in load-bearing capacity and structural integrity as the displacement increases. Overall, all graphs emphasize how different specimens respond to applied loads, with important implications for understanding their mechanical properties and behaviours during testing.

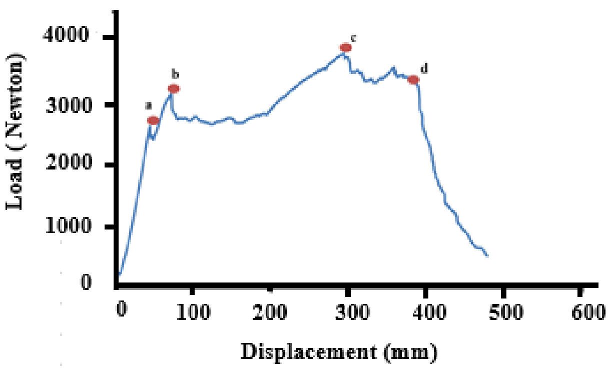

Fig. 3 Typical curve of load versus time of group S1 accompanied with C.C.D camera.

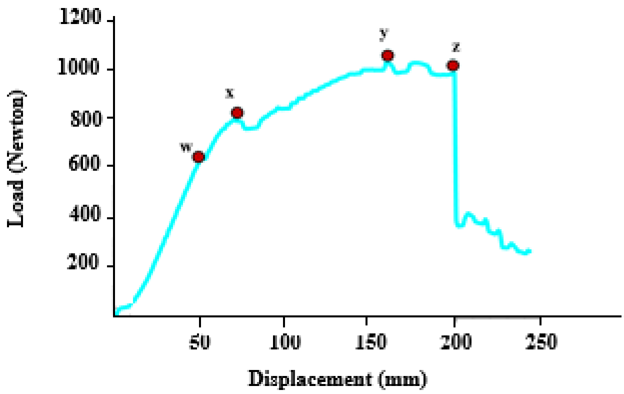

Fig.4 Typical curve of load versus time of group S2 accompanied with C.C.D camera.

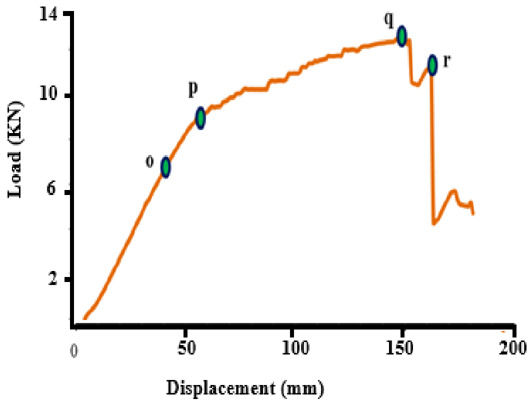

Fig. 5 Typical curve of load versus time of group S3 accompanied with CCD camera.

3.1 Analysis Of Displacement And Strain Field

Displacement and strain field analysis of joints represent a critical aspect of understanding their mechanical behavior, failure mechanisms, and overall performance under different loading conditions. Our objective is based on the detection of characteristic points to the load as function as time curve. For this propose, a specimen belonging to group S3 is chosen Fig. 5. Characteristics points of the curve are presented respectively as the axial displacement field v_y in Fig. 9 and strain field in Fig. 10. The representation of axial displacement and strain field provides valuable insights into the mechanical behavior of the specimen, allowing for a better understanding of how load is transmitted through the composite structure. As load levels increase, the observed strain concentration indicates localized deformation. It represents a precursor to damage initiation. Higher strain concentrations can lead to failure mechanisms, such as matrix cracking at point “o”, decohesion of fiber matrix at point “p”, delamination at point “q”, and the failure of fiber at point “r”.

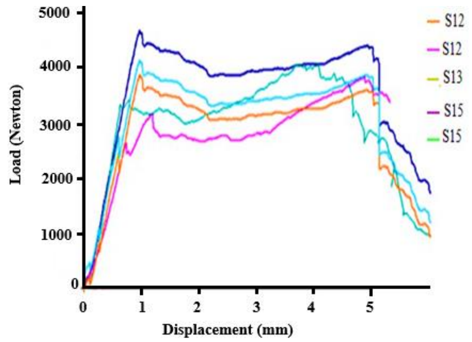

Fig. 6 Bearing load against displacement for single-lap of Specimen S1

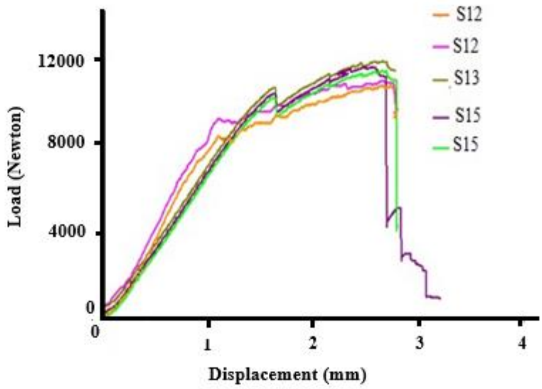

Fig. 7 Bearing load against displacement for single-lap of Specimen S2

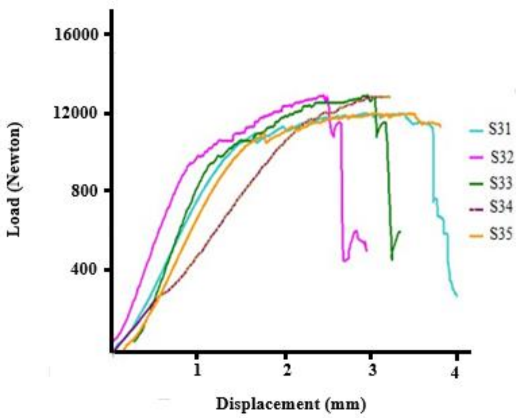

Fig. 8 Bearing load against displacement for single-lap of Specimen S3.

3.2 Analysis Of Displacement And Strain Field

The load drop observed after reaching the ultimate load, associated with excessive strain concentration at point "q", demonstrates the typical behavior of composite materials under tensile loading. This drop indicates that the specimen has exceeded its capacity to carry a load, often leading to the initiation of damage. The observed behavior during tensile testing of composite materials with low inter-laminar shear strength and the dominance of longitudinal fibers in tensile properties highlights critical considerations for material analysis.

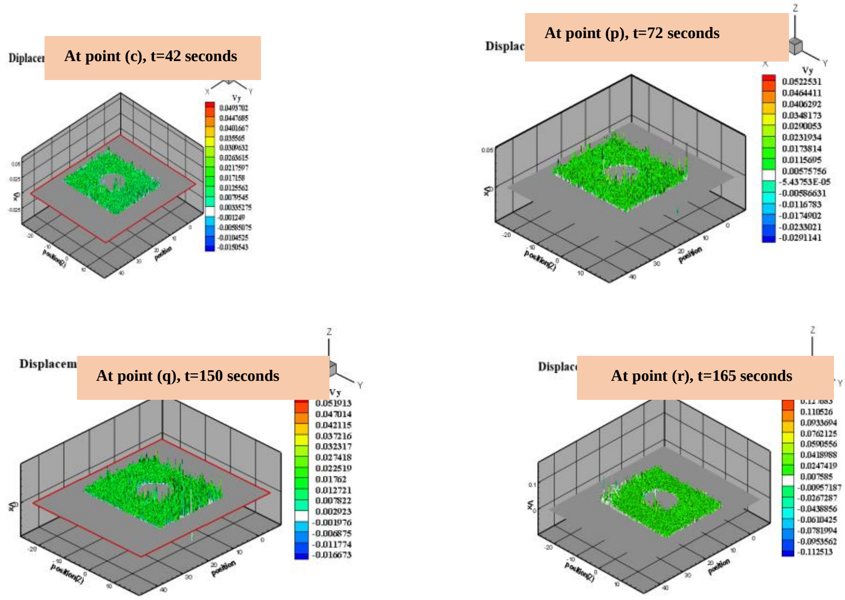

Fig. 9 Axial displacement Vy of the specimen during the tensile test [mm]

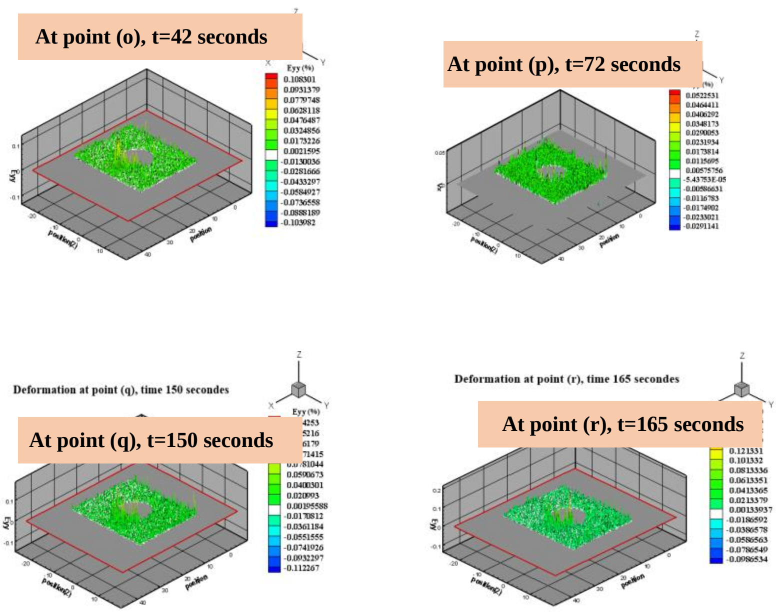

Fig. 10 Axial Strain E_{YY} %) of the specimen during the tensile

3.3 Angle Value Of Bolt Inclination

The evolution of bolt inclination angle in the side view of the bolt throughout the experiment test of composite is shown in Fig. 11 accompanied by the matrix cracking at point “o”, decohesions fiber/matrix at point “p”, delaminate at point “q”, and final failure fiber at point “r”. Load versus angle bolt inclination for typical curves of group S1, S2 and S3 tensile test is presented in Fig. 12. The inclination angle typically changes, reflecting how the specimen responds under stress. Different zones of failure will exhibit varying responses to load, affecting the angle of inclination. At point “o”, Matrix cracking begins at lower loads, with the inclination angle potentially responding more sensitively at this stage due to local stress concentrations. At point “p”, fiber-matrix decohesion involves the interface between fibers and the matrix and may show different inclination angles of as the load approaches higher levels. The inclination angle in the zone of delamination at point “q”, can be significantly influenced by the stacking sequence. Delamination might lead to a pronounced change in torque and load-handling capacity. The final failure at point “r” may present a steep change in the inclination angle, indicative of the fastened joint reaching its load limit [10-12].

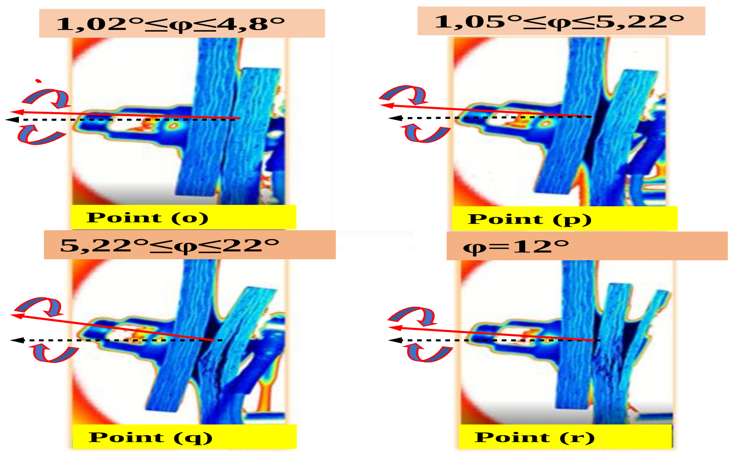

Fig. 11 Evolution of the inclination angle in the side view of the bolt during the experiment

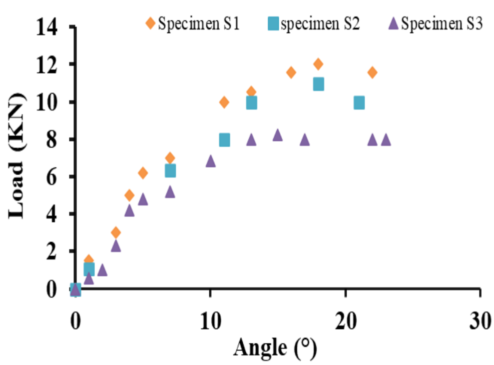

Fig. 12 Load versus angle bolt inclination for a typical specimen S1, S2, and S3 during tensile test.

4. CONCLUSIONS

A digital image correlation (D.I.C) technique was utilized to study the evolution damage of composite bolted assembly and the inclination of bolt angle. By employing a charge-coupled device (C.C.D) camera to capture the side-view images, the system can accurately correlate the inclination of bolt angles with the damage mechanisms observed during testing. The DIC technique allows for high-resolution monitoring of the deformation and displacement of composite fastened joints, enabling the assessment of how these joints respond under stress. The study highlights the importance of the bolt angle's inclination, which directly affects the joint's mechanical performance and the onset of damage. The DIC methodology enables the identification of critical points along the load as function as displacement curve that characterizes the mechanical comportment of the bolted assembly. DIC techniques obtained several phases such as elastic phase, plasticization stable and unstable, propagation, and final rupture. The data collected through DIC techniques can reveal how varying the inclination of bolt angles influences the comportment of the mechanical global of the joints. For instance, changes in angle may lead to differences in load distribution, slip behavior, or initiation of damage such as cracks. On conclusion, the stacking sequence and geometry are both critical factors that influence the bolt inclination angle in composite fastened joint. By utilizing numerical models in the future, to simulate various scenarios, leading to a better understanding of these dynamics and informing future design practices for composite bolted assemblies.

References

[1] F. Camano, and PP. Matthews. “Stress analysis and strength prediction of mechanically fastened joints in FRP,”: A review. Composites Part A: Applied Science and Manufacturing., vol. 28, 529-47W.-K. 1997

[2] Chen, Linear Networks and Systems (Book style). Belmont, CA: Wadsworth, pp. 123–135, 1993.

[3] Hart-Smith. L. “Design and analysis of bolted and riveted joints in fibrous composite structures,”. Recent advances structural joints and repairs for composite materials, pp. 211-54, Springer, 2003.

[4] Wor. LC, Rahman MM. “Stress behavior of tailor-welded blanks for dissimilar metals using finite element method,”. International Journal of Automotive and Mechanical Engineering., vol.11, pp. 2541-2554, 2015

[5] V. Sivananth, and Vijayarangan. S, “Fatigue life analysis and optimization of a passenger car steering knuckle under operating conditions,”. International Journal of Automotive and Mechanical Engineering., vol.11, pp. 2417-2429. 2015.

[6] Peters. W, and Ranson. W, “Digital imaging techniques in experimental stress analysis,”. Optical engineering 213427, June 1982.

[7] Schreier. H, Orteu. JJ, and Sutton. M.A, “Image correlation for shape, motion and deformation measurements,”: Basic concepts, Theory and Applications., Springer US, 2009.

[8] Aminero. M, Lopez-Pedrosa, M.Pinna, and C. Soutis, “Damage monitoring and analysis of composite laminates with an open hole and adhesively bonded repairs using digital image correlation,”. Composites Part B: Engineering., vol.53, pp.76-91, 2013.

[9] FACI.Y, and BACCOUCHE.M, “An experimental analysis of fracture mechanisms by acoustic emission of woven composite bolted assembly,” Rev. Sci. Technol., Synthèse, vol. 32, pp. 69 - 85, 2016.

[10] Zhai.Y, Li.D, Li. X, Wang.L, and Lin.Y, “An experimental study on the effect of bolt-hole clearance and bolt torque on single-lap, countersunk composite joints,”. Composite Structures,

vol.127, pp.411-419, 2015.
[11] Y. Faci, A. Mebtouche, and B.Maalem, "Study of Structural Composite Joint Damage by the Digital Image Correlation," Russian Journal of Nondestructive Testing, optical method., vol. 59, pp. 94-105, 2023.
[12] Karolin Karlsson, “An experimental study of rotation in a composite single bolted joint,” Teknisk- naturvetenskaplig fakultet UTH-enhete Hemsida, UPTEC Q12 005, 2012. UPTEC Q12 005, Examensarbete 30 hp, Juni 2012.