

Finite Element Analysis of the Tensile Performance of Single-Lap GFRP Plate Joints Connected by One-Sided Bolts

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Abstract:

To improve the design reliability of mechanical joints in pultruded GFRP plates, this study investigates single-lap joints fastened by one-sided Hollo-bolts through finite element analysis and experimental comparison. A three-dimensional numerical model was established in ABAQUS, and the Hashin failure criterion was adopted to describe the in-plane damage and stiffness degradation of the GFRP plate. A standard specimen with a 14 mm hole diameter, a 5 mm plate thickness, and a preload of approximately 6.3 kN was used for model validation by comparing the load-displacement response and final failure mode. After validation, the effects of preload, plate thickness, and bolt-hole diameter on the ultimate bearing capacity and failure mode were analyzed. The results show that an appropriate increase in preload enhances the mechanical interlocking between the sleeve and the hole wall as well as the friction between plates; however, excessive preload induces initial damage around the hole and reduces the subsequent bearing capacity. Increasing the plate thickness significantly improves the bearing area and anchorage depth of the hole wall, making it the key factor that increases ultimate capacity and promotes the transition from shear-out failure to bearing failure. The influence of bolt-hole diameter is relatively limited, but either an excessively small or excessively large hole is unfavorable for the full and uniform transfer of radial pressure from the expanded sleeve. The findings provide a reference for parameter selection and engineering application of one-sided bolted connections in GFRP plates.

Keywords:

One-sided Bolt, Finite Element Analysis, Tensile Performance, GFRP, Single-lap Joint

1. Introduction

Glass fiber-reinforced polymer (GFRP) composites have attracted increasing attention in civil engineering, aerospace engineering, and transportation infrastructure because of their light weight, high specific strength, corrosion resistance, and design flexibility [1,2,3]. In practical engineering applications, reliable connections are essential for ensuring the overall performance and safety of composite structures. Compared with bonded joints, mechanical connections, especially bolted joints, offer clear load-transfer paths, controllable construction quality, and convenient

disassembly and maintenance. However, the anisotropic and brittle nature of GFRP materials makes bolted connections particularly vulnerable. In inevitable single-lap configurations, load eccentricity generates additional bending moments, intensifies stress concentration around the hole, and may lead to brittle bearing failure, shear-out failure, or net-section failure. Consequently, connection efficiency and ductility are often limited [4]. Therefore, developing new connection forms capable of improving stress distribution and enhancing the ductility and load-transfer efficiency of GFRP joints is of practical engineering significance.

A one-sided bolt is a type of blind fastener that can be installed and tightened from only one side, making it suitable for construction scenarios where access from both sides is difficult. Unlike conventional bolts that mainly transfer load through shank-hole bearing and clamping, Holo-bolts transfer load through the mechanical interlocking formed by the radial expansion of an internal sleeve against the hole wall, providing a promising approach for improving the connection performance of GFRP plates. Wu et al. [5] conducted static tests on pultruded GFRP double-lap joints using ordinary bolts and blind bolts, and subsequently performed constant-amplitude fatigue tests on double-bolt double-lap joints. Their results indicated that the static failure load of blind-bolted joints was up to 21% lower than that of ordinary bolted joints, while bolt type had little effect on fatigue performance. Gopalan and Narayanan [6] investigated tensile-loaded staggered double-lap GFRP joints fastened with Holo-bolts and combined with flexible epoxy adhesives, demonstrating effective load transfer in hybrid joints; the interaction was expected to become more effective with increasing lap length, adherend thickness, and fastener diameter.

Previous studies have also examined the effects of material and geometric parameters on composite bolted joints. Hu et al. [7] focused on the mechanism of bolt pretightening and preload relaxation in composite interference-fit joints under thermal effects and established instantaneous and delayed preload response models based on elastic and viscoelastic theories; the preload increased linearly with tightening torque, while interference-fit size controlled the friction level. Tajeura et al. [8] further demonstrated that increasing plate thickness can significantly improve joint capacity and change the failure mode. Li et al. [9] showed that hole geometry errors, including perpendicularity errors and clearance fit, have significant effects on the dynamic tensile performance of hybrid bonded-bolted GFRP/Al joints, and that excessive clearance can change the failure mode from tensile failure to shear failure. Nevertheless, most of these studies focused on conventional bolted connections or carbon-fiber composites and were mainly based on single-factor analysis. The relative importance and statistical significance of preload, hole diameter, and plate thickness in one-sided bolted single-lap joints of pultruded GFRP plates have not been systematically revealed, and optimized parameter combinations for this connection type remain insufficiently studied.

At present, systematic investigations of one-sided bolted single-lap connections in pultruded GFRP plates remain limited, especially with respect to key design parameters such as preload, bolt-hole diameter, and plate thickness. The dominant effects and coupling mechanisms of these parameters are still not fully understood. Therefore, this study uses finite element simulation to analyze the individual effects of preload, hole diameter, and plate thickness on joint capacity and failure mode. The results provide an optimized design basis and theoretical reference for engineering applications of this new connection form.

2. Finite Element Model Development and Validation

2.1. Specimen and Material Parameters

As shown in Figure 1, the one-sided bolted joint consists of pultruded GFRP plates and Holo-bolts. The GFRP plate was a pultruded composite plate with a thickness of 5 mm, a width of 50 mm, and a length of 150 mm. The matrix was unsaturated polyester resin, and the reinforcement was E-glass fiber with a fiber content of approximately 60%. The tensile strength of the plate in the pultrusion direction was 578 MPa. The pultruded GFRP plate consisted of longitudinal continuous fibers in the 0 degree direction, accounting for approximately 70% of the total fibers, as well as ± 45 degree bidirectional fabrics and chopped strand mats. This layup provided high longitudinal tensile strength and elastic modulus, while the ± 45 degree layers and chopped strand mats supplied the necessary transverse and shear capacity. The standard bolt-hole diameter was 14 mm, and the material properties of the GFRP plate are listed in Table 1.

The fastener was an M8 Holo-bolt expansion bolt developed by Lindapter. For the M8 Holo-bolt, the nominal inner diameter is 8 mm and the sleeve outer diameter is approximately 13.75 mm. During tightening, the sleeve expands radially, so sufficient clearance must be provided to ensure reliable mechanical interlocking between the sleeve and the hole wall. According to the product manual, the recommended hole diameter range for an M8 one-sided bolt is 13-15 mm; therefore, a 14 mm hole diameter was adopted in this study. The material properties of the M8 Holo-bolt are listed in Table 2 [10].

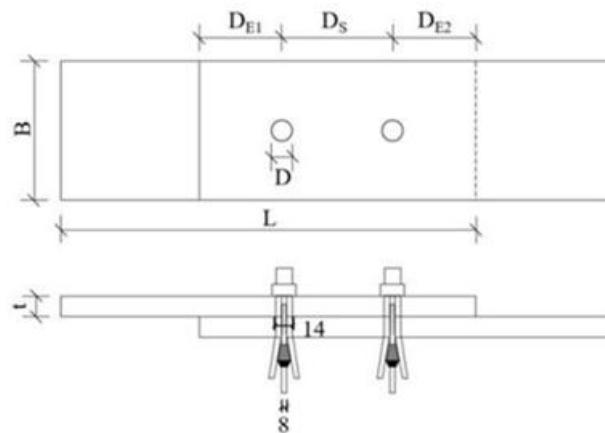


Figure 1. Schematic diagram of specimen dimensions.

Table 1. Material properties of the GFRP plate.

Property	Value	Property	Value
E_{11} /GPa	28.1	X_T /MPa	578
$E_{22}=E_{33}$ /GPa	1.2[11]	X_C /MPa	412
$G_{12}=G_{13}$ /GPa	2.96[11]	$Y_C=Z_C$ /MPa	106
G_{23} /GPa	2.60[11]	$Y_T=Z_T$ /MPa	100 ^[12]
$\nu_{12}=\nu_{13}$	0.33	$S_{12}=S_{13}$ /MPa	50 ^[12]
ν_{23}	0.41[11]	S_{23} /MPa	50 ^[12]

Table 2. Material properties of the M8 Holo-bolt.

Material	Density (kg/m ³)	Elastic modulus (GPa)	Poisson ratio	Yield strength (MPa)	Ultimate strength (MPa)
Grade 8.8 M8 one-sided bolt	7850	210	0.3	640	880

2.2. Experimental Method

The standard specimen shown in Figure 2, with a 14 mm hole diameter, a 6.3 kN preload, and a 5 mm plate thickness, was selected for three repeated tensile tests to validate the finite element model. According to the Holo-bolt design manual, the standard tightening torque for an M8 bolt is 23 N·m, corresponding to a bolt preload of 6.3 kN. The preload was estimated using Eq. (1):

$$T = KDP \quad (1)$$

where T is the bolt tightening torque, D is the bolt diameter, P is the bolt preload, and K is the torque coefficient, taken as 0.45 in this study.

The bolts were installed on the GFRP plates using a torque wrench. Tensile tests were performed using a WAW-EY600C microcomputer-controlled electro-hydraulic servo universal testing machine. The test procedure followed ASTM D3039 [13], as shown in Figure 3. During the tensile tests, both ends of each prepared lap-joint specimen were clamped in the testing machine. The upper end was fixed, while the lower end was loaded under displacement control at an approximate loading rate of 1 mm/min until failure. Three repeated tests were carried out, the failure modes were recorded, and the load-displacement curves were obtained.



Figure 2. One-sided bolted GFRP joint.



Figure 3. Schematic of the specimen loading setup.

2.3. Damage and Evolution of GFRP Plates

The in-plane damage of the composite material was predicted using the Hashin criterion. The corresponding failure initiation criteria are expressed as follows:

Fiber tensile failure ($\sigma_1 \geq 0$):

$$F^{ft} = \left(\frac{\sigma_1}{X_t} \right)^2 + \left(\frac{\tau_{12}}{S_1} \right)^2 = 1 \# \quad (2)$$

Fiber compressive failure ($\sigma_1 < 0$):

$$F^{fc} = \left(\frac{\sigma_1}{X_c} \right)^2 = 1 \# \quad (3)$$

Matrix tensile failure ($\sigma_2 \geq 0$):

$$F^{mt} = \left(\frac{\sigma_2}{Y_t} \right)^2 + \left(\frac{\tau_{12}}{S_1} \right)^2 = 1 \# \quad (4)$$

Matrix compressive failure ($\sigma_2 < 0$):

$$F^{mc} = \left(\frac{\sigma_2}{2S_2} \right)^2 + \left[\left(\frac{Y_t}{2S_2} \right)^2 - 1 \right] \frac{\sigma_2}{Y_c} + \left(\frac{\tau_{12}}{S_1} \right)^2 = 1 \quad \# \quad (5)$$

where σ_i denotes the normal stress and τ_{ij} denotes the shear stress. X_t and X_c are the longitudinal tensile and compressive strengths, respectively; Y_t and Y_c are the transverse tensile and compressive strengths, respectively; and S_1 and S_2 denote the longitudinal and transverse shear strengths. When the failure index of any damage mode reaches 1, the corresponding type of damage is initiated.

The failure process of a GFRP lamina is governed by multiple interacting factors. The Hashin criterion provides a systematic failure framework that accounts for composite failure modes such as fiber fracture and matrix cracking, and it is therefore well suited for the analysis of composite connection regions. In addition, this criterion is implemented as a standard material damage model in ABAQUS, which facilitates the subsequent numerical simulation. Accordingly, the Hashin criterion was adopted in this study as the failure initiation criterion for the GFRP plate.

Damage evolution in composite materials refers to the process in which damage initiates once the stress state satisfies the Hashin failure criterion. With continued loading, the material stiffness gradually degrades and the load-carrying capacity decreases. This stage is defined as the damage evolution process. The stiffness degradation can be described by a damage state variable d ; accordingly, the constitutive model of the GFRP plate can be written as:

$$\sigma = C(d)\varepsilon \quad (6)$$

where σ and ε denote the stress and strain, respectively, and the stiffness matrix is expressed as a function of the damage state. Its specific form is given as follows:

$$C(d) = \frac{1}{D} \begin{bmatrix} (1-d_f)E_1 & (1-d_f)(1-d_m)v_{21}E_1 & 0 \\ (1-d_f)(1-d_m)v_{12}E_2 & (1-d_m)E_2 & 0 \\ 0 & 0 & D(1-d_s)G_{12} \end{bmatrix} \quad \# \quad (7)$$

where $D = 1 - (1-d_f)(1-d_m)v_{12}v_{21}$; E_1 and E_2 denote the Young's moduli; G_{12} is the shear modulus; v_{12} and v_{21} are Poisson's ratios; and d_f , d_m and d_s are the damage state variables associated with fiber damage, matrix damage and shear damage, respectively. These variables correspond to the four failure modes described above. The damage variable d_i characterizes the degree of fiber or matrix damage: $d_i = 0$ indicates an undamaged material, whereas $d_i = 1$ indicates complete material failure. The expression is as follows:

$$\begin{aligned} d_f &= \begin{cases} d_{fi} & \text{当 } \sigma_1 \geq 0 \\ d_{fc} & \text{当 } \sigma_1 < 0 \end{cases} \\ d_m &= \begin{cases} d_{mt} & \text{当 } \sigma_2 \leq 0 \\ d_{mc} & \text{当 } \sigma_2 < 0 \end{cases} \quad \# \\ d_s &= 1 - (1-d_{fi})(1-d_{fc})(1-d_{mt})(1-d_{mc}) \end{aligned} \quad (8)$$

The evolution law of each damage variable is related to the equivalent displacement and equivalent stress. Table 3 gives the expressions of the equivalent displacement and stress for the four failure modes.

Table 3. Equivalent displacement and stress expressions for different failure modes.

Failure mode	δ_{eq}	σ_{eq}
Fiber tension ($\sigma_1 \geq 0$)	$L_c \sqrt{(\varepsilon_{11}) + \alpha \varepsilon_{12}^2}$	$\frac{L_c(\sigma_{11})(\varepsilon_{11} + \alpha \sigma_{12} \varepsilon_{12})}{\delta_{eq}^{ft}}$
Fiber compression ($\sigma_1 < 0$)	$L_c(-\varepsilon_{11})$	$\frac{L_c(-\sigma_{11})(-\varepsilon_{11})}{\delta_{eq}^{fc}}$
Matrix tension ($\sigma_2 \geq 0$)	$L_c \sqrt{(\varepsilon_{22})^2 + \varepsilon_{12}^2}$	$\frac{L_c((\sigma_{22})(\varepsilon_{22}) + \sigma_{12} \varepsilon_{12})}{\delta_{eq}^{mt}}$
Matrix compression ($\sigma_2 < 0$)	$L_c \sqrt{(-\varepsilon_{22})^2 + \varepsilon_{12}^2}$	$\frac{L_c((- \sigma_{22})(- \varepsilon_{22}) + \sigma_{22} \varepsilon_{22})}{\delta_{eq}^{mc}}$

In Table 3, L_c denotes the characteristic element length. For the four independent failure modes of a lamina in a laminated plate, the damage state variable can be expressed as:

$$d_{ij} = G(d) = \begin{cases} 0 & \delta_{eq} \leq \delta_{eq}^0 \\ \delta_{eq}^f (\delta_{eq} - \delta_{eq}^0) & \delta_{eq}^0 < \delta_{eq} \leq \delta_{eq}^f \end{cases} \quad \# \quad (9)$$

where the damage variable ranges from 0 to 1. A value of 0 indicates that no damage has occurred, whereas a value of 1 indicates complete failure. The initial equivalent displacement at damage initiation is related to the product of the characteristic element length and the strain at damage onset; the equivalent displacement corresponds to a specific damage mode; and the ultimate equivalent displacement represents complete failure. Assuming that the fracture energy of the composite plate is G_c , it can be calculated as follows:

$$\delta_{eq}^f = \frac{2G_c}{\delta_{eq}^0} \quad \# \quad (10)$$

2.4. ABAQUS Finite Element Model

A three-dimensional finite element model of the standard specimen was established in ABAQUS, as shown in Figure 4. A coupling constraint was created between the end face of the GFRP plate and a reference point. The end of the upper plate was fully fixed, while an axial displacement U_1 was applied to the lower plate using a tabular amplitude. The reaction force at the moving loading reference point was extracted as the load response.

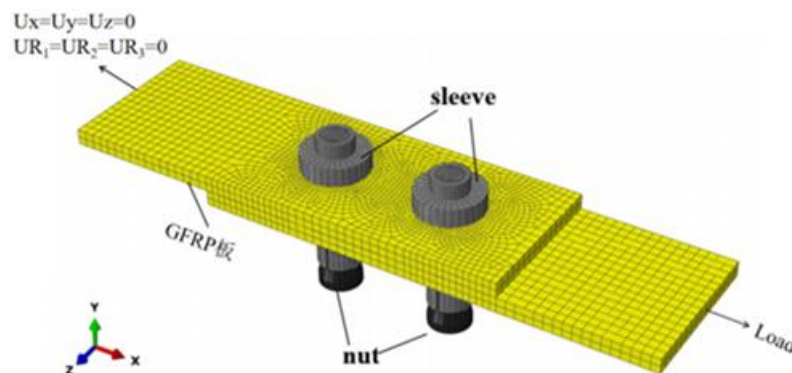


Figure 4. Finite element model of the one-sided bolted connection.

The GFRP plate was modeled using eight-node reduced-integration continuum shell elements (SC8R). To improve convergence and computational efficiency, the bolt

shank, washer, and sleeve were modeled as an integral component, and the secondary influence of thread geometry on contact behavior was neglected. The bolt assembly was discretized using eight-node linear reduced-integration solid elements (C3D8R), which provide adequate accuracy while avoiding shear locking. Because contact occurs between the bolt and the composite plate, finite-sliding contact was used at the bolt-GFRP interfaces. Tangential friction was defined using a penalty formulation with a friction coefficient of 0.30, and the normal contact was modeled as hard contact to transmit contact forces. Local mesh refinement was applied around the hole wall and other critical regions to capture stress variations more sensitively, and high-quality hexahedral meshes were generated using the sweep meshing method.

The analysis was divided into three steps. In the first step, the components were brought into sufficient contact. In the second step, the bolt expanded inside the hole and the preload was applied by coupling the lower surface of the nut to a reference point and applying a concentrated force upward to complete the expansion. In the third step, the two ends of the specimen were coupled to two reference points. The displacement of the left reference point was fixed, while an x-direction displacement was applied to the right reference point at an approximate loading rate of 1 mm/min. Unlike conventional bolts that transfer load mainly through direct bearing between the shank and the hole wall, the one-sided bolt exhibits a two-stage load-transfer mechanism: during installation, the tightening torque first drives the sleeve to expand radially and form mechanical interlocking with the hole wall; subsequently, continued tightening is transformed into axial preload on the connected plates. This special mechanism indicates that the bearing performance of a one-sided bolt depends not only on the final preload, but also on the interaction between the expanding sleeve and the hole wall during installation.

2.5. Finite Element Model Validation

The load-displacement response of the standard specimen was obtained from the finite element model and compared with the experimental results, as summarized in Table 4. The relative error between the finite element ultimate load and the average experimental ultimate load was less than 10%. In addition, Figure 5 shows that both the simulation and the experimental specimen exhibited shear-out failure, indicating good agreement between the model and the test results.

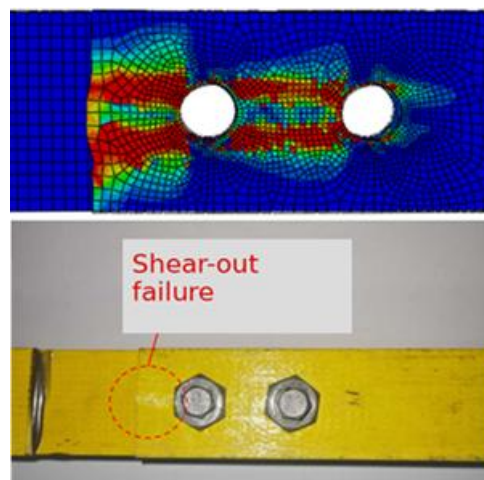


Figure 5. Comparison of failure modes between the finite element model and the experimental specimen.

Table 4. Load-displacement results from experimental testing and finite element simulation.

Specimen	Plate thickness (mm)	Preload (kN)	Hole diameter (mm)	Mesh size (mm)	Ultimate capacity (kN)	Error relative to test average
EXP-1	5	6.3	14	-	19.50	-0.27%
EXP-2	5	6.3	14	-	18.97	-2.95%
EXP-3	5	6.3	14	-	20.17	3.17%
FEM-1	5	6.3	14	5	20.65	5.63%
FEM-2	5	6.3	14	4	19.59	0.22%
FEM-3	5	6.3	14	3	19.56	0.05%

3. Parametric Finite Element Analysis of the One-Sided Bolted Joint

3.1. Parameter Design

To reveal the individual influence of each design parameter on connection performance, three key parameters were considered: preload (P), plate thickness (T), and bolt-hole diameter (D). Under the baseline condition of $P = 6.4$ kN, $T = 5$ mm, and $D = 14$ mm, one parameter was varied at a time while the other two parameters were kept constant. Five engineering-relevant levels were selected for each factor, and the ultimate bearing capacity was extracted as the key evaluation index. The parameter combinations are listed in Table 5.

Table 5. Parameter combinations for the one-sided bolted GFRP joint.

Group	Specimen ID	Preload (kN)	Plate thickness (mm)	Hole diameter (mm)
Group 1	D1T1P1	6.4	5	14
Group 1	D1T1P2	8.4	5	14
Group 1	D1T1P3	10.4	5	14
Group 1	D1T1P4	12.4	5	14
Group 1	D1T1P5	14.4	5	14
Group 2	D1T1P1	6.4	5	14
Group 2	D1T2P1	6.4	6	14
Group 2	D1T3P1	6.4	7	14
Group 2	D1T4P1	6.4	8	14
Group 2	D1T5P1	6.4	9	14
Group 3	D1T1P1	6.4	5	14
Group 3	D2T1P1	6.4	5	14.25
Group 3	D3T1P1	6.4	5	14.5
Group 3	D4T1P1	6.4	5	14.75
Group 3	D5T1P1	6.4	5	15

3.2. Analysis of Ultimate Bearing Capacity

3.2.1. Effect of Preload on Ultimate Bearing Capacity

In Group 1, the plate thickness and hole diameter were fixed at 5 mm and 14 mm, respectively, while the preload was set to 6.4, 8.4, 10.4, 12.4, and 14.4 kN. The 6.4 kN value corresponds to the standard preload of the M8 Holo-bolt, whereas 14.4 kN corresponds to the preload of a high-strength bolt under a torque of 23 N·m, with a torque coefficient of 0.2. As shown in Figure 6, the ultimate bearing capacity first increased and then decreased with increasing preload. When the preload increased from 6.4 kN to 8.4 kN, the ultimate bearing capacity increased from 19.55 kN to 21.74 kN, corresponding to an improvement of 11.04%. This indicates that this range

represents an effective working region in which sleeve expansion is sufficient and the joint performance is stable.

When the preload is low, the radial expansion of the sleeve is insufficient, and only partial contact is formed between the sleeve and the hole wall. As a result, the mechanical interlocking effect is weak, and load transfer mainly depends on limited contact friction, leading to a lower bearing capacity. With increasing preload, the degree of sleeve expansion increases, the contact area between the sleeve and the hole wall increases significantly, and a more uniform radial contact pressure distribution is formed. At the same time, the axial clamping force increases the frictional resistance between the plates. At this stage, the positive effect of preload dominates, and the bearing capacity increases.

However, when the preload reached 14.4 kN, the ultimate bearing capacity decreased to 15.95 kN, representing a reduction of 18.41% relative to the baseline. When the preload exceeded 10.4 kN, the radial pressure exerted by the sleeve on the hole wall exceeded the local compressive capacity of the GFRP material, causing irreversible microcracks and local crushing during the expansion process. Although this initial damage did not immediately lead to failure, it became a source of stress concentration during subsequent tensile loading and accelerated crack initiation and propagation. Excessive radial pressure may also induce local deformation or delamination around the hole, reducing the effective bearing capacity of the surrounding material. Therefore, although the axial clamping force continues to increase, the degradation caused by initial damage becomes dominant, ultimately resulting in a decrease in bearing capacity.

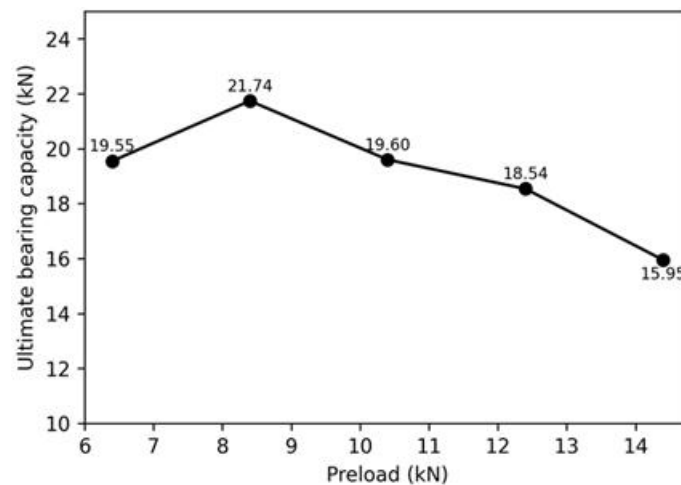


Figure 6. Effect of preload on ultimate bearing capacity.

3.2.2. Effect of Plate Thickness on Ultimate Bearing Capacity

In Group 2, the preload and hole diameter were fixed at 6.4 kN and 14 mm, respectively, while the plate thickness was set to 5, 6, 7, 8, and 9 mm. As shown in Figure 7, the ultimate bearing capacity increased monotonically with plate thickness, rising from approximately 19.55 kN at a thickness of 5 mm to 38.27 kN at a thickness of 9 mm. The failure mode also changed from shear-out failure to bearing failure. This indicates that increasing plate thickness is the most direct and effective measure for improving joint capacity, because it provides a larger bearing area and a greater effective anchorage depth. Although the ultimate bearing capacity increased monotonically with plate thickness, the rate of increase gradually decreased as the

thickness increased. This can be attributed to the transition of the failure mode from shear-out to bearing failure. After bearing failure becomes dominant, additional material far from the high-stress region is less efficiently mobilized, leading to a slower increase in ultimate capacity.

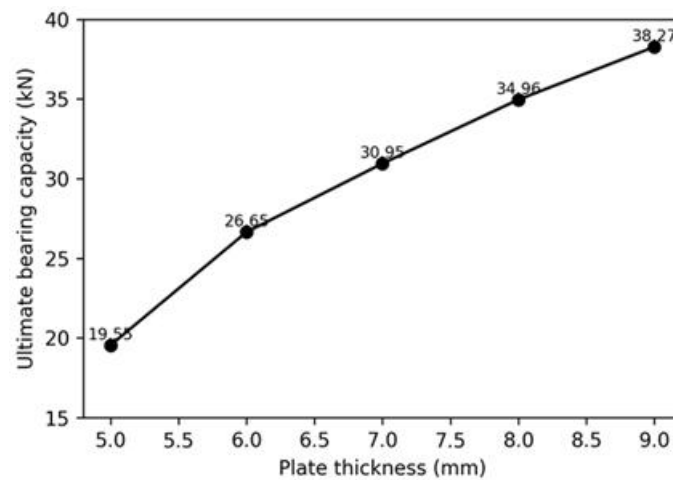


Figure 7. Effect of plate thickness on ultimate bearing capacity.

3.2.3 Effect of Bolt-Hole Diameter on Ultimate Bearing Capacity

In Group 3, the preload and plate thickness were fixed at 6.4 kN and 5 mm, respectively, while the hole diameter was set to 14.00, 14.25, 14.50, 14.75, and 15.00 mm. As shown in Figure 8, the bearing capacity increased slightly at first and then decreased with increasing hole diameter. The peak capacity of 21.17 kN occurred at a hole diameter of 14.25 mm, after which the capacity gradually decreased. Overall, the effect of hole diameter on ultimate bearing capacity was relatively small, and the capacity remained around 20 kN.

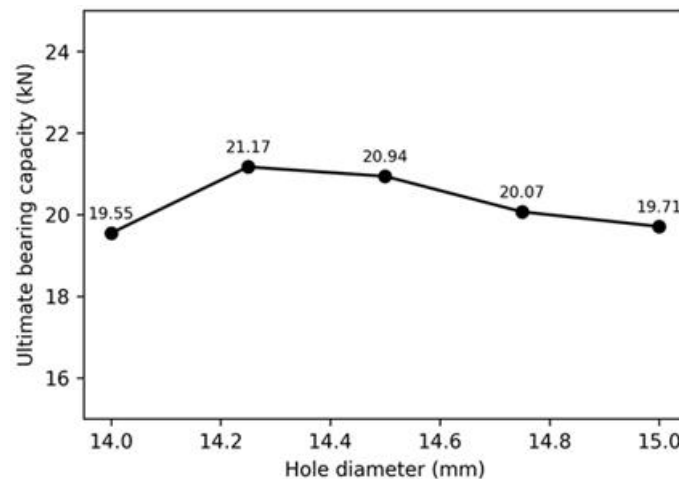


Figure 8. Effect of bolt-hole diameter on ultimate bearing capacity.

The conversion of preload into effective bearing capacity depends on the contact state between the sleeve and the hole wall. When the hole diameter is too small, such as 14.0 mm, the clearance between the sleeve and the hole wall is insufficient, and the sleeve may be constrained during expansion, preventing full deployment. This restricts mechanical interlocking and reduces preload transfer efficiency. When the hole diameter is slightly larger than the standard value, such as 14.25 mm, the sleeve has sufficient space to expand radially and form uniform and adequate contact with

the hole wall, resulting in the highest preload transfer efficiency and peak bearing capacity. When the hole diameter is too large, such as 14.5-15.0 mm, the clearance between the sleeve and the hole wall increases. Even under the same preload, the expanded sleeve exhibits a lower contact area and contact pressure, which weakens the mechanical interlocking effect. In addition, excessive clearance may cause nonuniform sleeve deformation during expansion, nonuniform stress distribution around the hole, and partial consumption of the preload in overcoming the initial clearance rather than generating effective contact pressure, ultimately reducing the bearing capacity.

3.3. Failure Mode Analysis

Based on the damage-stress analysis method for GFRP, the failure modes of 15 specimens were analyzed, and the results are summarized in Table 6. The specimens in Group 1 and Group 3 mainly exhibited shear-out failure, although the preload group showed a nonmonotonic capacity trend with a relatively large variation. Bearing failure occurred in Group 2 when the plate thickness was increased. Therefore, the damage evolution of the preload group and the plate-thickness group was analyzed in detail, as shown in Figure 9 and Figure 10. The damage contours of Groups 1 and 3 showed typical shear-out failure characteristics. The high-damage region, indicated by the red area, originated from the bolt-hole edge and extended toward the plate side or end along an approximately 45 degree direction, corresponding to the maximum shear stress direction, thereby forming a clear shear-slip path. In contrast, for bearing failure cases D1T4P1 and D1T5P1, the high-damage region was mainly concentrated around the bolt-hole wall and developed in a ring-like or radial pattern through the plate thickness, without forming a through crack extending toward the plate edge.

Table 6. Ultimate bearing capacity and failure modes from the parametric analysis of one-sided bolted joints.

Specimen ID	Ultimate load (kN)	Failure mode	Variable
D1T1P1	19.55	Shear-out failure	Preload
D1T1P2	21.74	Shear-out failure	Preload
D1T1P3	19.60	Shear-out failure	Preload
D1T1P4	18.54	Shear-out failure	Preload
D1T1P5	15.95	Shear-out failure	Preload
D1T1P1	19.55	Shear-out failure	Plate thickness
D1T2P1	26.65	Shear-out failure	Plate thickness
D1T3P1	30.95	Shear-out failure	Plate thickness
D1T4P1	34.96	Bearing failure	Plate thickness
D1T5P1	38.27	Bearing failure	Plate thickness
D1T1P1	19.55	Shear-out failure	Hole diameter
D2T1P1	21.17	Shear-out failure	Hole diameter
D3T1P1	20.94	Shear-out failure	Hole diameter
D4T1P1	20.07	Shear-out failure	Hole diameter
D5T1P1	19.71	Shear-out failure	Hole diameter

Because D1T1P1, D1T1P2, and D1T1P3 were within the range in which the ultimate capacity first increased and then decreased, the damage contours after one-sided bolt expansion were output for these three specimens. Figure 9 shows that the damage around the hole increased with increasing preload. At relatively low preload levels, D1T1P1 and D1T1P2, the friction between the plate and the sleeve was enhanced, thereby improving joint capacity. At higher preload levels, such as D1T1P3,

D1T1P4, and D1T1P5, the expansion of the one-sided bolt caused initial damage in the GFRP hole wall. During subsequent tensile loading, the accumulated damage around the hole became a source of stress concentration.

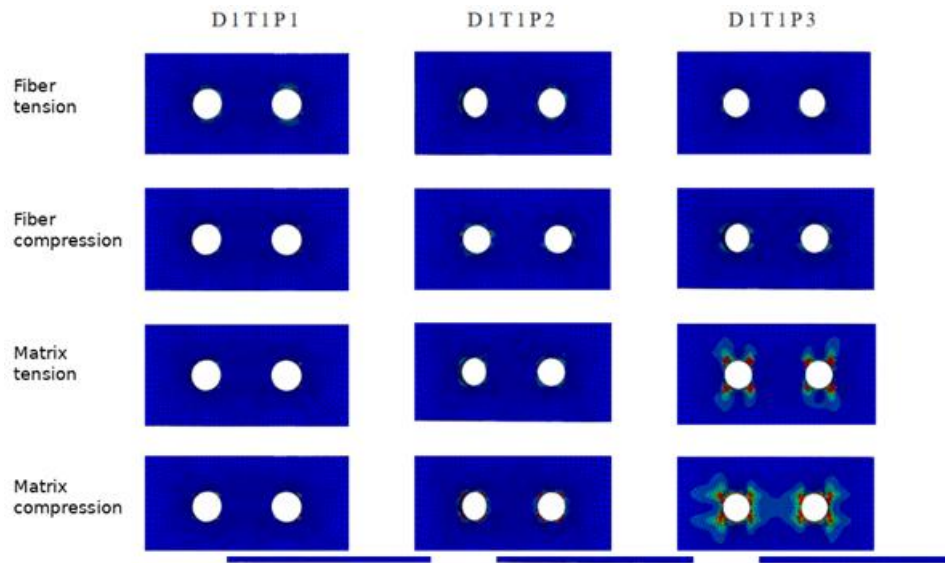


Figure 9. Damage to the GFRP plate induced by expansion of the one-sided bolt.

When the plate thickness changed, the failure mode transformed from shear-out failure to bearing failure. As shown in Figure 10, under thin-plate conditions, namely D1T1P1, D1T2P1, and D1T3P1, shear stress concentration around the hole wall was significant, and shear slip surfaces tended to form along the bolt-hole edge, leading to shear-out failure. As the plate thickness increased, the bearing contact area between the bolt and the hole wall increased. The effective anchorage depth also increased, and the bearing area of the hole wall became significantly larger. Consequently, bearing stress gradually replaced shear stress as the dominant stress component. At the ultimate load, failure manifested as crushing and local damage accumulation of the hole-wall material rather than global shear tearing.

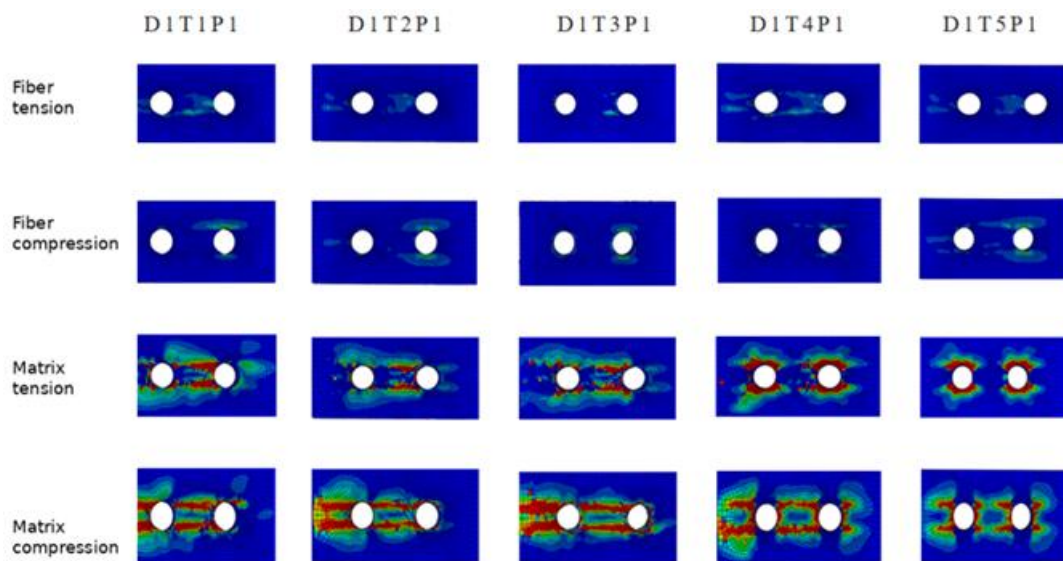


Figure 10. Damage associated with capacity failure governed by plate thickness.

Unlike conventional bolts that transfer load through direct bearing between the bolt shank and the hole wall, one-sided bolts mainly transfer load through radial pressure

between the expanded sleeve and the hole wall. This radial pressure is transformed from the tightening torque during installation and is affected by the preload, hole clearance, and plate stiffness. Although the contact pressure distribution on the hole wall was not directly extracted in this study, the influence of radial pressure on joint performance can be indirectly inferred from the variation of ultimate bearing capacity with preload, hole diameter, and plate thickness. As preload increases, radial pressure also increases. Moderate radial pressure enhances mechanical interlocking and increases capacity in the range of 6.4-10.4 kN. However, excessive radial pressure induces microcracks in the brittle GFRP hole wall, as shown in Fig. 9, thereby reducing the subsequent bearing capacity. Variation in hole diameter changes the initial clearance and contact area between the sleeve and the hole wall, affecting the uniformity of radial pressure. Increasing plate thickness improves the radial stiffness of the hole wall and makes the pressure distribution more uniform, thereby promoting the transition from shear-out failure to bearing failure.

4. Conclusions

This study investigated the tensile performance of single-lap GFRP plate joints connected by one-sided bolts using ABAQUS finite element analysis. The effects of preload, plate thickness, and bolt-hole diameter on ultimate bearing capacity and failure mode were analyzed. The main conclusions are as follows:

(1) The finite element model of the one-sided bolted GFRP plate joint based on the Hashin damage criterion can effectively simulate the tensile response of the joint. The load-displacement curves obtained from the finite element analysis were generally consistent with the experimental curves, the failure modes were all characterized by shear-out failure, and the ultimate capacity error was less than 10%. Therefore, the model is suitable for subsequent parametric analysis.

(2) Preload has a clear effect on the ultimate capacity of the one-sided bolted joint, but a higher preload does not necessarily lead to better bearing performance. When the preload increased from 6.4 kN to 8.4 kN, the ultimate bearing capacity increased from 19.55 kN to 21.74 kN, indicating that appropriate preload strengthens the contact and mechanical interlocking between the sleeve and the hole wall. When the preload further increased to 14.4 kN, the ultimate capacity decreased to 15.95 kN, showing that excessive preload causes initial damage and stress concentration around the hole wall, thereby weakening the subsequent bearing capacity.

(3) Plate thickness is the key parameter affecting joint capacity. As the plate thickness increased from 5 mm to 9 mm, the ultimate capacity increased from 19.55 kN to 38.27 kN. This significant improvement is mainly attributed to the increased effective bearing area and anchorage depth between the bolt and the hole wall, which enables a larger volume of material to participate in load transfer.

(4) Variation in plate thickness also changes the failure mode. When the plate is thin, shear stress concentration near the hole edge is obvious, and damage tends to extend from the bolt-hole edge toward the plate end or side, resulting in shear-out failure. When the thickness increases to 8 mm and 9 mm, damage becomes concentrated around the hole wall, and the failure mode gradually changes to bearing failure. Therefore, increasing plate thickness improves the bearing condition of the hole wall and enhances the stability of the failure process.

(5) The influence of bolt-hole diameter on ultimate bearing capacity is relatively limited, but the hole diameter affects the contact state between the expanded sleeve and the hole wall. A hole diameter of 14.25 mm produced a relatively high capacity in this study. An excessively small hole restricts full sleeve expansion, whereas an excessively large hole reduces the contact area and contact pressure between the sleeve and the hole wall and weakens mechanical interlocking. Therefore, machining tolerance should be reasonably controlled to match the expansion characteristics of the one-sided bolt sleeve.

(6) Overall, the bearing performance of one-sided bolted GFRP plate joints is jointly influenced by preload, hole diameter, and plate thickness. Among these parameters, plate thickness has the most significant effect, followed by preload, while hole diameter has a relatively weaker influence. In practical engineering design, sufficient plate thickness should be prioritized, and preload and hole diameter should be controlled within reasonable ranges to avoid local damage caused by excessive expansion of the GFRP hole wall and to improve connection efficiency and structural safety.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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