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Full Length Research Paper

Effects of geometric parameters on failure behavior in joined-rivet and single lap laminated composite plate under bending moment

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In this study, failure behavior of single lap composite plate fixed by means of both rivets and adhesive bonding was investigated using three-point bending test. Rivet connections were made on specimens at different geometrical intervals. Force-displacement graph were drawn. The composites used were made of glass epoxy materials with four plies and 0° layer angle. An FM73 film layered binder was used for binding process, whereas riveting was done with a 5 mm diameter dome shaped rivets. The bending test model was performed using Abaqus 6.9.1, finite element analysis software. After the three-point bending tests, the failure behavior obtained experimentally was compared with that obtained with numerical analysis. The failure behavior obtained experimentally was compared with that obtained with numerical analysis. In addition, two different failure criteria (Tsai-Wu and Tsai-Hill) were used for the composite test specimens and the failures that occurred in each layer were determined.

Key words: Glass-epoxy material, rivet connection, three-point bending test, rivet geometry.

INTRODUCTION

Glass-epoxy reinforced composites materials with high elastic modules and strengths have diverse applications in spacecraft structures, aircraft sector and other important sectors. Generally, it is necessary to connect composite materials with other composites or metal components depending on application field of the materials. Riveting, one of the mechanic joining methods is simple, quick and most importantly an economic way of joining components which renders it being widely used for mending activities. The increase of importance of composite materials has boosted researches on the methods of joining composite materials. Some researchers in this field have shown that glass-epoxy reinforced composite materials can be used in various applications including marine applications due to the fact that they can easily and economically be obtained (Dharmawan et al., 2006). On the other hand, researchers who investigated mechanical properties of glass-epoxy reinforced composites have found that the decrease in load carrying capacity on mechanic rivet connection around rivet holes is related to material properties, number of layers and layer orientations (Scalea et al., 1998). Karakaya and Soykasap (2008) have investigated failure behaviors of single-joined composites both experimentally and numerically. In their study, they determined a radius of curvature formed on specimen during the three-point bending test and investigated its correlation with the critical radius of curvature on failure. Several researchers have studied the effects of geometry, the number of layers and layer orientation on connection methods (Okutan et al., 2001; Okutan and Karakuzu, 2003; Xu et al., 1996; Ashcroft et al., 2001). Some researchers have conducted studies on failure behaviors of mechanical joints on composite materials (Chang et al., 1984; Chang and Chang, 1987; Chang, 1986). Avila and Bueno (2004) compared the advantages and disadvantages of single joint connections with those

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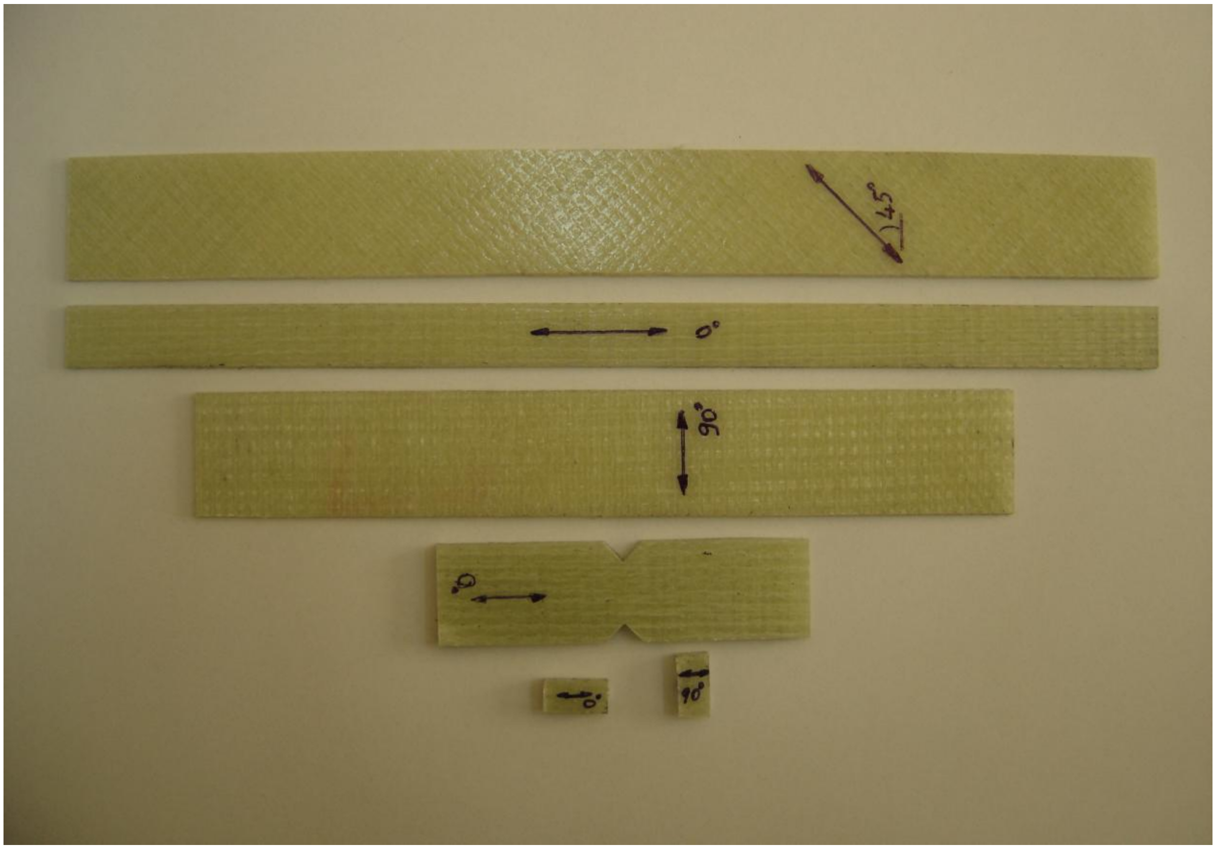

Figure 1. Coordinate system of the composite plates (for mechanical properties).

of wavy connections. In their study, they found that a wavy single connection is better by 41% under tensile effects. Quaresimin and Ricotta (2006) conducted study on determination of fatigue life of single overlay connections. Other researchers estimated failure and fatigue lives of composite plates (hybrid) joined with different joining methods (Kelly, 2006). New solutions are produced consistently on laminated composite materials.

Civalek and Baltacioglu (2010) are development new numerical solution of laminated composite materials. In this study, failure behavior of composite materials joined with a single and rivet binding at three different geometry during a three-point bending tests was investigated both experimentally and numerically. Abaqus 6.9.1 finite element software was used for the numerical method and two different failure criteria are used.

MATERIALS AND METHODS

The composite materials used in the experiment are made of four-ply glass fiber reinforced epoxy matrix materials. The fiber-reinforced composite plates were manufactured from unidirectional E-glass fabric having weight of 270 g/m^2 and epoxy resin by hand lay-up method. The composite material consists of 59 % fibers and 41% epoxies (Ergun, 2010). The density of the laminated plates was 2.026 g/cm^3 (Figure 1). Mechanical properties of the composite materials were measured using tensile specimens manufactured according to ASTM-D3039 standard. The specimens were singly bonded and riveted, then, FM73 film adhesive was used to bond them. Elastic modulus and Poisson ratio of the adhesive are 1830 MPa and 0.33 respectively. Bending test specimens were bonded to one another as a single overlay at temperature of 120°C and pressure of 6 bars with a press. The bending tests were conducted on Instron 8801 brand test device. Bending tests speed was adjusted at 5 mm/min. Mechanical properties of the composites were determined from same test device according to ASTM D3039 standards and their values are given in Table 1. In Table 1, X_t refer to the longitudinal tensile failure stress, Y_t refer to the transverse tensile failure stress, X_c refer to the longitudinal compressive failure stress, Y_c refer to the transverse compressive failure stress. Schematic view of the specimen used in the tests is shown in Figure 2. In this figure, L_T is the total length of the specimen, s refer to the distance between supports, u refer to the interval between rivets, w refer to specimen width, whereas a and b refer to rivet bonding distances from bonding edges.

Experimental study

All the mechanical tests were performed by using servo-hydraulic INSTRON 8801 tensile testing machine of 50 kN load capacity. The specimens used in the three-point bending tests are given in Figure 3. Specimen A was bonded only, whereas specimens B, C and D were bonded and riveted. They have different connection cases. Rivet diameter is 5 mm. The results obtained from the tests are given in Table 2. For every experimental case, five specimens were

Table 1. Mechanical properties of composite materials.

E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	ν_{12}	X_t (MPa)	Y_t (MPa)	Xc (MPa)	Yc (MPa)	Extension (%)
44150	12300	4096	0.20	775	130	305	80	2.2

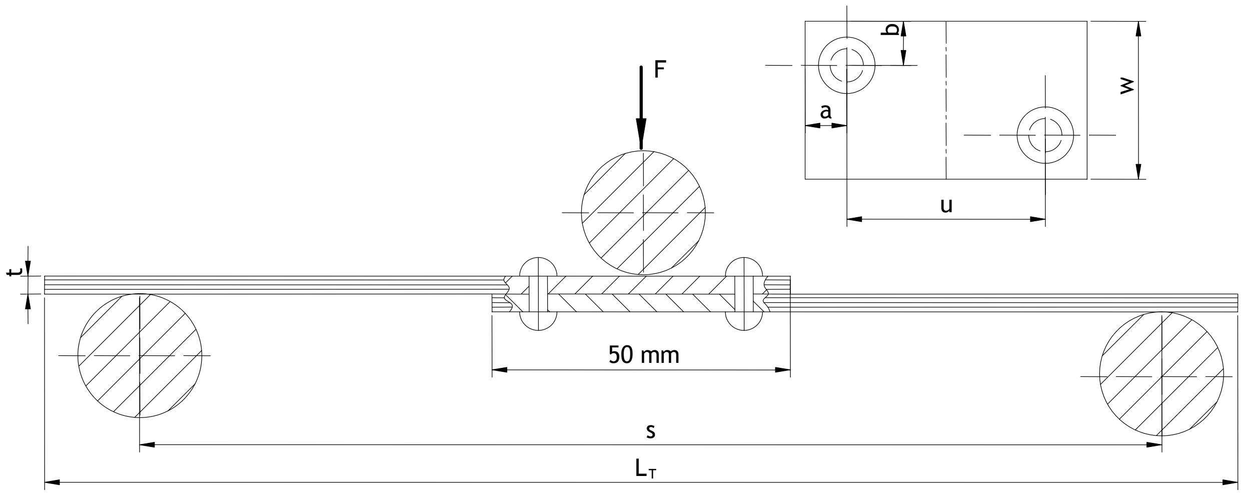

Figure 2. Schematic view of the three-point bending test specimens.

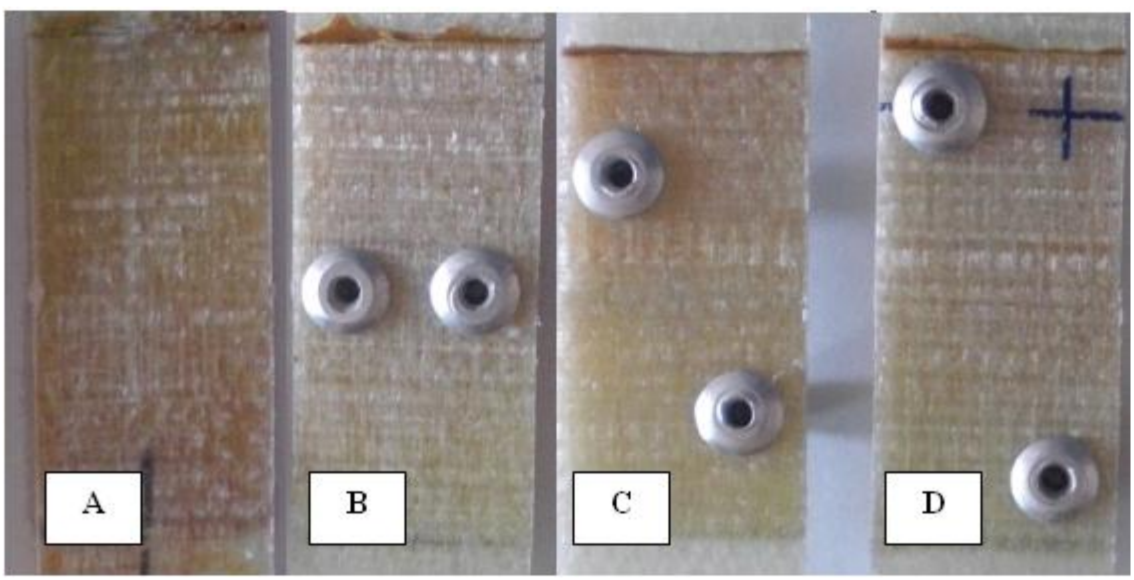

Figure 3. Test specimens.

used and average value was taken. Ultimate force, $F_{ultimate}$ was measured force value after head of rivet strips from layers. Force - displacement curve is divided in three regions as seen in Figure 4. These divided regions are effect of adhesive linear area, effect of adhesive and rivet low slope nonlinear area and effect of rivet head high slope nonlinear area. While the non-riveted specimen A shows a linear curve, the riveted specimens exhibit some sort of straining in the second step. When the riveted B, C and D specimens were compared among themselves, it is seen that specimen D which has its rivet joint at the far most edge exhibits the highest endurance strength. Then, the endurance value drops progressively at C and B. It was also found that all the riveted specimens have almost same displacement value and approximately four times larger than that of the bonded specimen A. In Figure 5, state of failure for the bonded specimen A is seen along the bonding line. The failure has happened at a lower displacement value as compared to the other

Table 2. Results of a three-point bending test.

Specimen No.	Width (w) mm	Thickness (t) mm	Length (L_t)	A (mm)	B (mm)	S (mm)	$F_{Ultimate}$ (N)
A1	25.35	1.48	200	…	…	100	305.6
A2	25.40	1.45	200	…	…	100	278.6
A3	25.30	1.44	200	…	…	100	301.7
A4	25.20	1.42	200	…	…	100	304.2
						Mean	297.54
B1	25.05	1.45	200	25	6	100	275.0
B2	24.96	1.43	200	25	6	100	234.0
B3	24.90	1.40	200	25	6	100	241.0
B4	25.00	1.40	200	25	6	100	242.5
						Mean	218.35
C1	25.05	1.45	200	13	6	100	330.7
C2	24.96	1.44	200	13	6	100	258.4
C3	25.10	1.45	200	13	6	100	276.0
C4	25.10	1.44	200	13	6	100	328.5
						Mean	298.4
D1	25.05	1.48	200	6	6	100	411.0
D2	24.96	1.43	200	6	6	100	446.0
D3	24.85	1.42	200	6	6	100	452.0
D4	25.00	1.45	200	6	6	100	458.5
						Mean	441.87

specimens. The bonding material (adhesive) accumulated at the edges (shown with arrows) provides an additional strength to the gluing area; it is also clear that the rupture was not a gradual one instead, an instantaneous separation taken place. Failure states of riveted specimens are shown in Figure 6.

Areas with serious damages are shown with dashed lines. These are the areas around riveted joints. This case can be seen in both experimental and numerical results. It is also seen that both results are compatible with each other. Generally, the failure on composite layers initiates with the entry to nonlinear area. The study of the failure on composite layer was performed using finite element method.

Numerical study

In the numeric study, three-point bending test was performed for B, C and D test specimens using Abaqus 6.9.1 software programmer. Rivet and adhesive test specimens was modeled parallel to the experimental case. Finite element model of specimens D was shown in Figure 7. Model consists of four main parts which are one direction glass-epoxy composite plates, supports, adhesive face and rivet connections. Composite and adhesive plates are modeled as a compact then separating to parts, plates and adhesive region are constituted. In the rivet modeling, rivet diameter is as 5 mm, rivet head diameter is 8.5 mm and rivet end diameter is 6.5 mm. The supports were modeled as cylinders with diameter of 25 mm and then parts assembly is constructed as seen in Figure 7. Every ply thickness is 0.36 mm and adhesive thickness is 0.2 mm. Properties of composite materials are given in Table 1 and properties of rivet, supports and adhesive materials are given in Table 3. Each ply was identified as composite materials and the type of element was determined as continuum shell. This analysis is a non-linear static analysis. Automatic stabilization value is set as 1e-6 and mesh size is set as 10800 elements totally. For the element type of composite layer and adhesive materials is SC8R quad literal, C3D8R brick elements are used for rivet and supporters. Mesh structure of adhesive zone and rivet contour were generated in such a way that the elements are more intense. Interaction between supporters and composite plate are defined as surface to surface and friction contact between faces is accepted. The same situation also between rivet top and bottom contact face and composite plate is valid. Friction coefficient is taken as 0.24. The boundary conditions for numerical analysis are the same as experimental conditions. The degrees of freedom of supports are fixed in all direction and top support is fixed in all direction (u_x, u_y, u_{Rx}, u_{Ry} and u_{Rz}), except displacement in z direction. 10 mm displacement is given in the $-u_z$ direction. To determine whether the failure will be after three-point bending test analysis of rivet joint of D specimen, Tsai-Hill failure criteria is used.

According to Tsai-Hill failure criteria, failure condition on composite was investigated using Equation 1:

$$F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + F_1\sigma_1 + F_2\sigma_2 + 2F_{12}\sigma_1\sigma_2 \geq 1 \quad (1)$$

In which:

$$F_{11} = 1/(S_L^+ S_L^-), F_{22} = 1/(S_T^+ S_T^-), F_1 = 1/S_L^+ - 1/S_L^-, F_2 = 1/S_T^+ - 1/S_T^-$$

$$F_{66} = 1/S_{LT}^2 \; ve \; F_{12} = -(F_{11}F_{22})^{0.5}/2, \;\; \sigma_6 = \tau_{12}$$

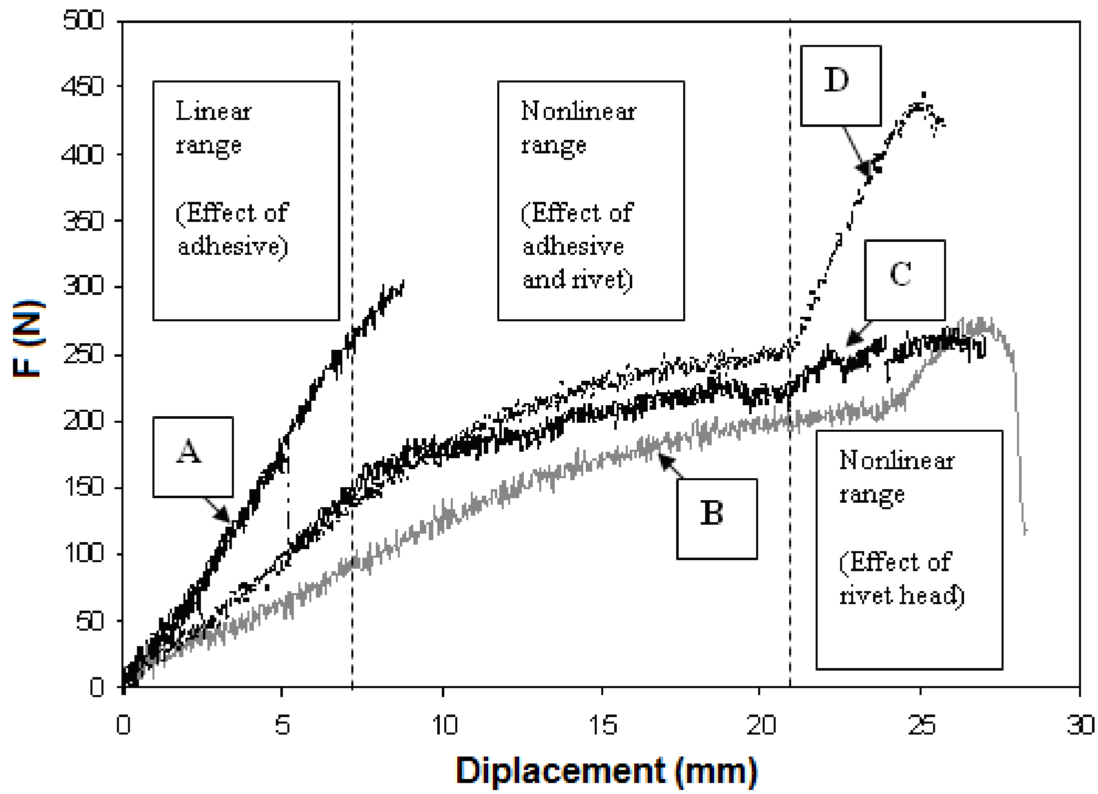

Figure 4. Curves of force-displacement for the test specimens.

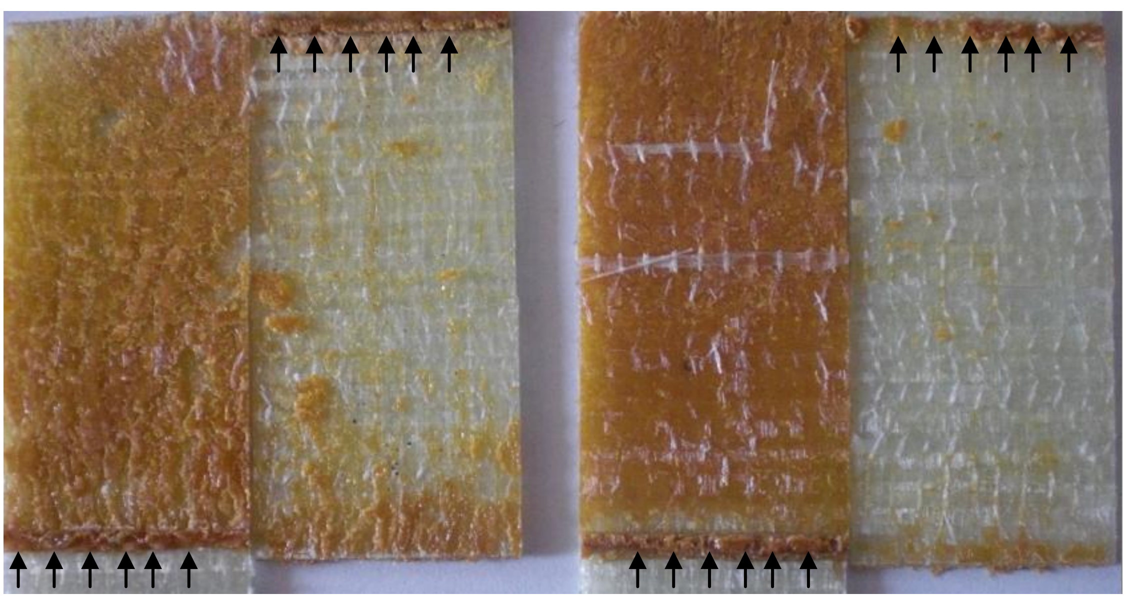

Figure 5. Failure condition of bonded (for specimen A).

Where S_L^+ and S_L^- are strength of longitudinal tensile and compression. S_T^+ and S_T^- are also strength of transverse tensile and compression. Longitudinal and transverse strength are accepted positively. Strength values for glass-epoxy are given in Table 1. Shear strength is obtained as S_{LT} = 60 MPa (Gdoutos et al., 2000).

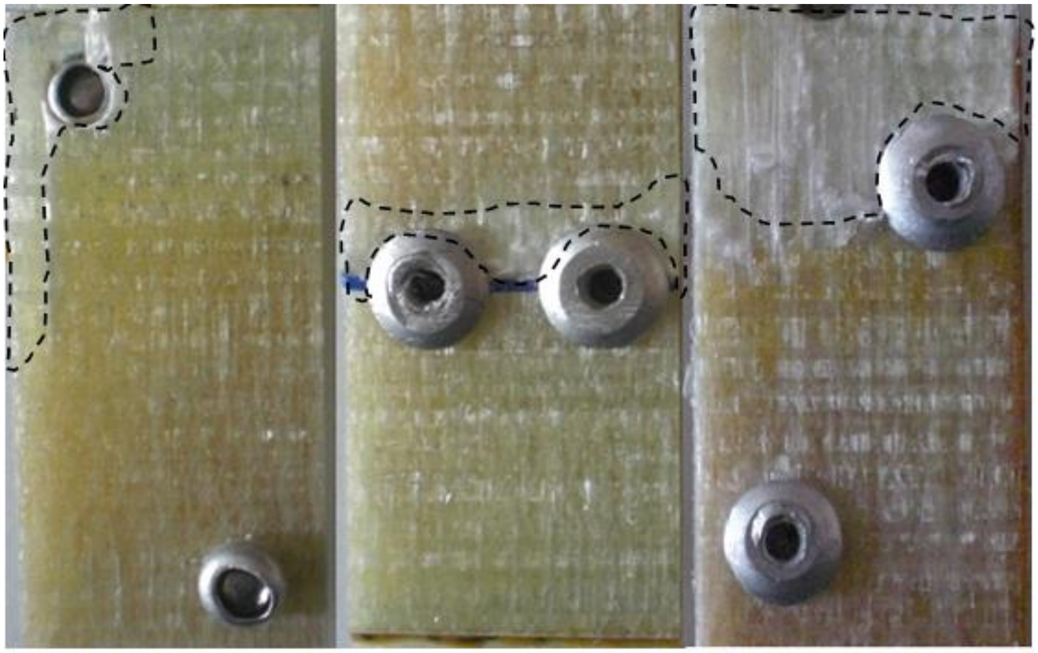

Figure 6. Failure states of riveted specimens.

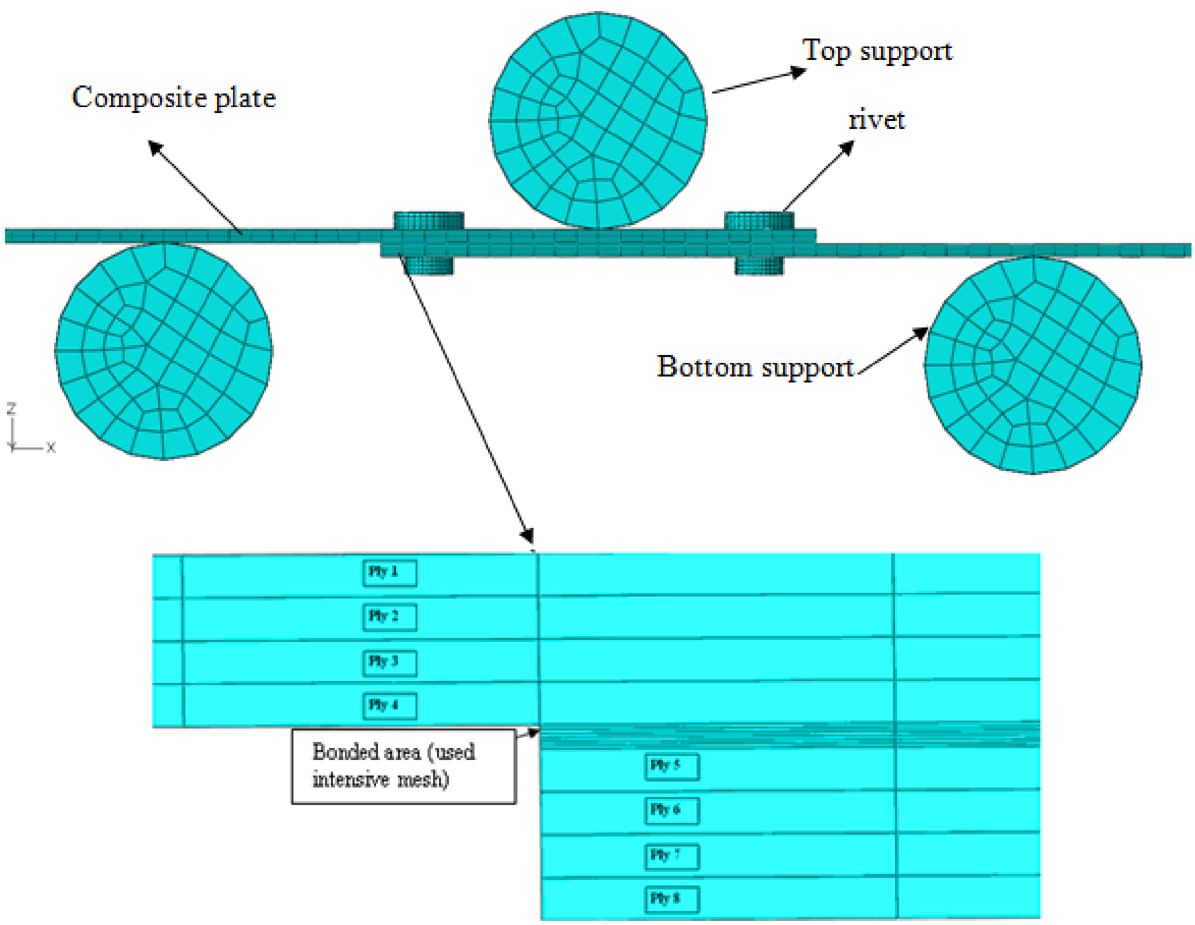

Figure 7. 3D model for three-point bending test.

Table 3. Part properties.

Parts	Elasticity module (E) MPa	Poisson ratio (v)
Rivet (Al alloy)	70000	0.34
Adhesive (FM73)	1830	0.33
Supports (Steel)	210000	0.3

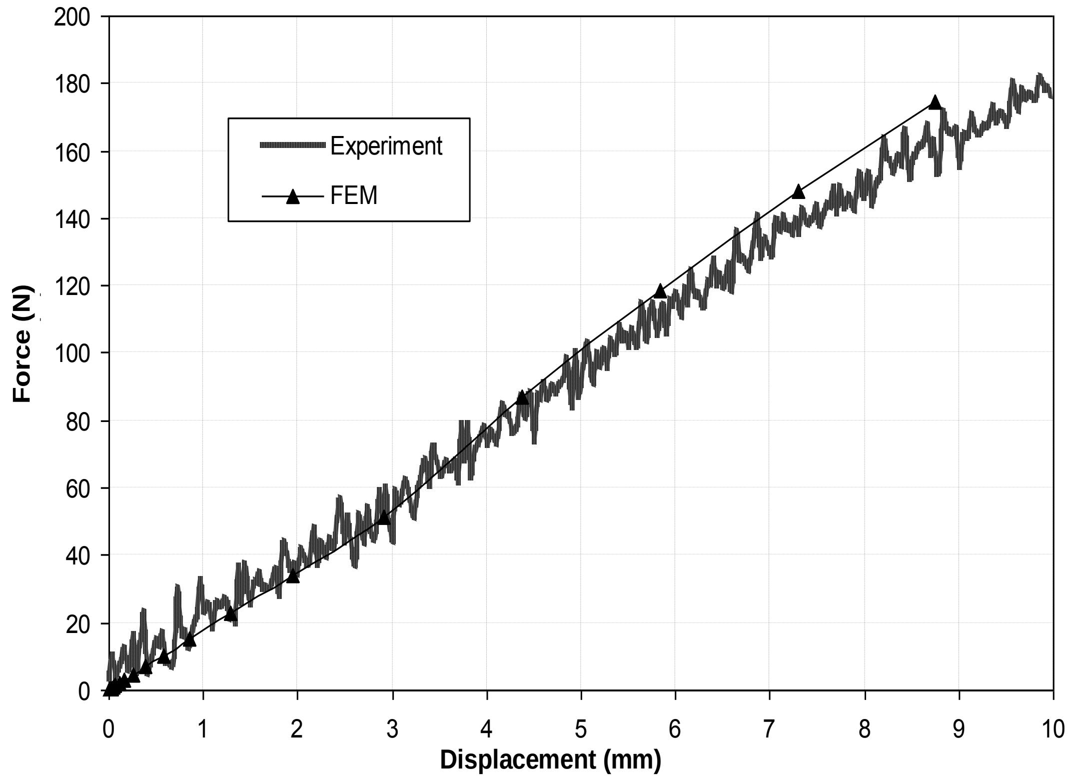

Figure 8. Force-displacement curve for D specimens.

RESULTS AND DISCUSSION

Three-points bending test was applied to both bonded and rivet joints composite materials. Load-displacement diagrams were compared and failure situations were investigated. As seen in Figure 4, load-displacement diagrams were divided into three different zones. Failure formation belong to bending in composite plate was observed out of linear zone (about 7 to 8 mm). It was seen that rivet diameter, head and bottom parts of rivet are directly affected in nonlinear zones (Figure 4). Failure formations generally occurred around the rivet hole and bending zone near bonded area. It was determined that adhesive tip parts supplied positive effect to three-points bending strength in only sample bonded with adhesive. In the numerical analysis, 3D three-points bending test was carried out parallel to the experimental conditions. Force-displacement graph of test specimen D obtained experimentally and numerically is shown in Figure 8. In Figure 9, the failure situation of the layers (D specimen) is determined using Tsai-Hill failure criteria. As seen in Figure 9, extensive damage in the regions are: i) rivet contour, ii) close to adhesive area. In Figure 10, the failure condition of the layers of specimen C is seen. Stress is quite intense around the rivet holes due to the bending moment. In Figure 11, the failure condition on the layers of specimen B is seen. Stress condition is very concentrated around the rivet holes. Bending effect is clearly observed in regions parallel to top support as the same way of particularly specimen C. In Figure 12, damaged D specimen obtained using experimental and FEM studies are compared. In this experiment, the damage is seen to propagate from rivet hole region. Composite plate failure situation obtained by FEM is also seen around the same rivet hole region. As a result of the analysis of three-point bending tests, it is observed that

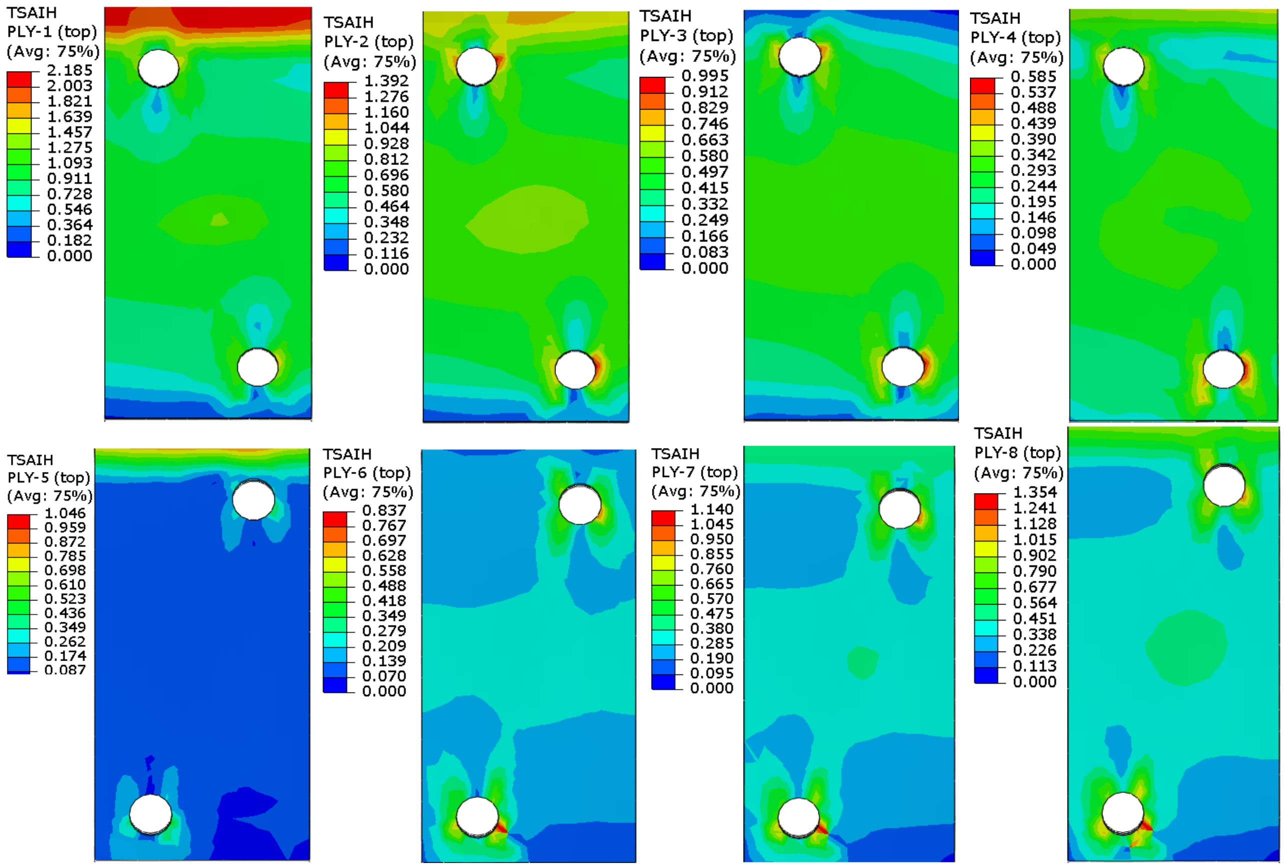

Figure 9. Situation of failures of D specimen (z = 8.5 mm).

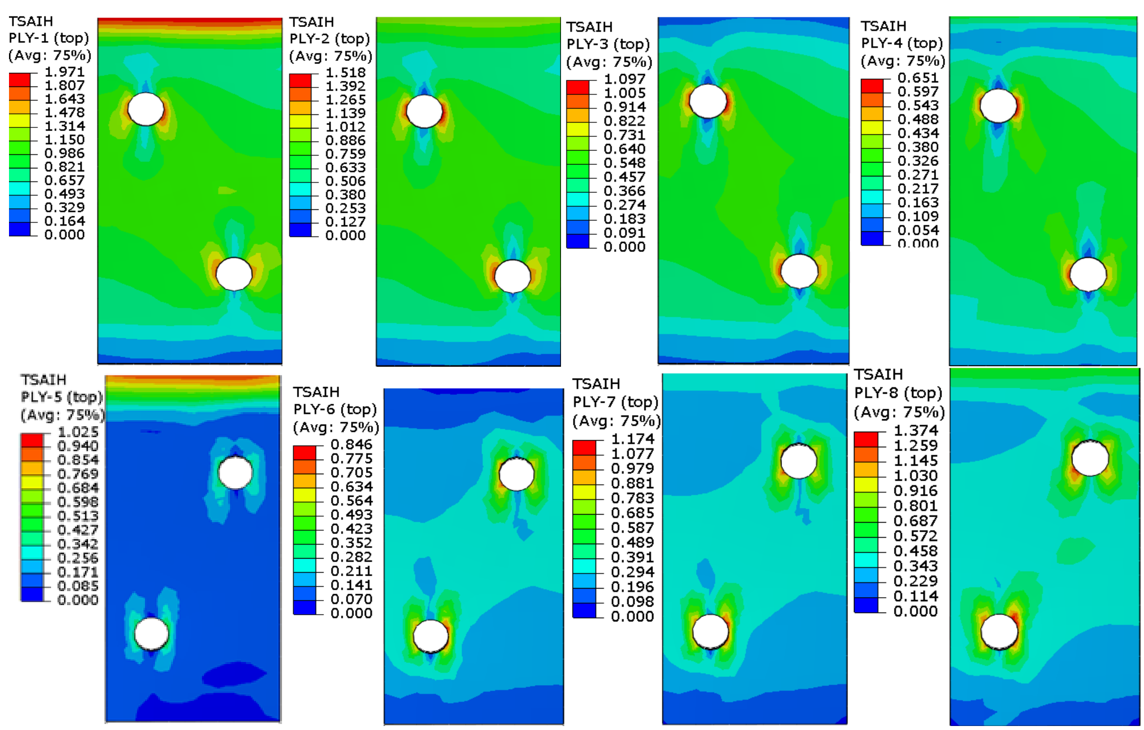

Figure 10. Situation of failures of C specimen (z = 8.5 mm).

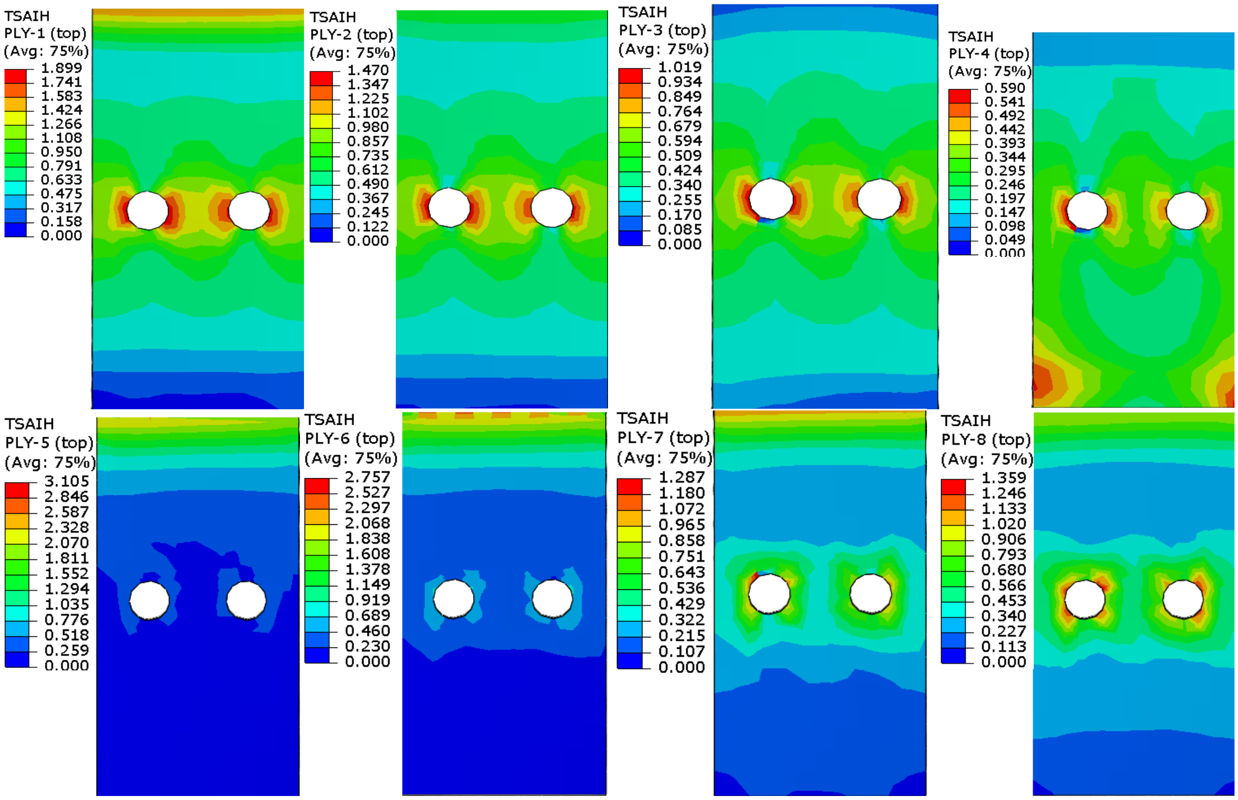

Figure 11. Situation of failures of B specimen (z = 8.5 mm).

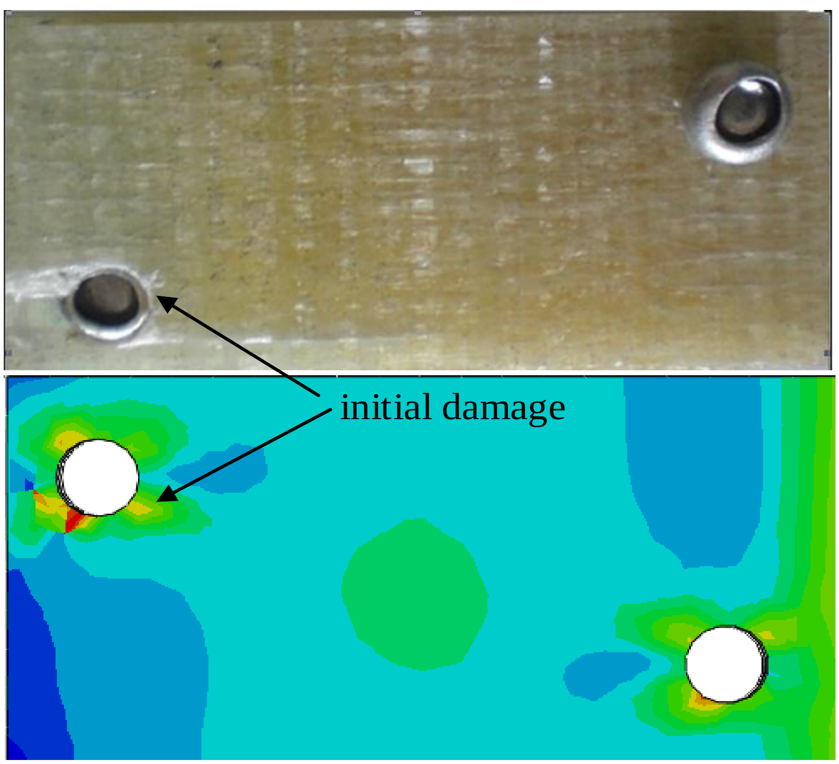

Figure 12. Comparison of experimental and numerical analysis for the region at the bottom of rivet (D specimen and 8 ply).

Table 4. Comparison of strenght ratio from failure theories.

Specimen	Failure criteria	Plies							
		1	2	3	4	5	6	7	8
B	Tsai-H	1.90	1.47	1.02	0.59	3.10	2.75	1.28	1.25
	Tsai-W	2.01	1.55	1.08	0.68	3.41	2.70	1.10	1.15
C	Tsai-H	1.96	1.50	1.09	0.64	1.69	1.88	1.16	1.36
	Tsai-W	2.10	1.63	1.18	0.70	1.79	1.83	0.98	1.18
D	Tsai-H	1.88	1.10	0.84	0.58	2.02	2.36	1.32	1.10
	Tsai-W	1.97	1.19	0.91	0.65	3.20	2.32	1.25	0.95

failure intensity is more in provinces around the rivet for failure specimens B and C, and close the bonded are for specimen D. In Table 4, after the analysis of three-point bending test, failure strength values of B, C and D specimens in each layer are compared using two different failure criteria (Farooq and Gregory, 2010). After 8.5 mm displacement, generally in all the layers except 3th and 4th layers, the failure occurs. This is a positive stress between two layers joined with rivets, so separation does not occur.

Without caring the heads of bottom and top rivet, rivet connection geometry (for 8.5 mm linear section) is not important when the failure condition between the larger is considered. For each three specimens in the first four layers (1, 2, 3 and 4), strength value that accounted according to Tsai-Wu is bigger as averagely 6 to 10%. In other layers (5, 6, 7 and 8) being different from the first four layers, strength rate Tsai-Hill is bigger as 5 to 8% rated according to Tsai-Wu.

Conclusions

In this study, failure behavior of single overlay composite plates joined with both lamination bonding and riveting at three different geometries during three-point bending tests was investigated both experimentally and numerically and the following results were obtained.

1) Joining modes of layered composites plays an important role in different loading types like bending, compressive, tensile and fatigue loading. Among the joining methods, the most widely used is riveting. In order to construct safe structures, it is necessary to optimize the manner of joint and its selection according to the type and magnitude of loading the joint is going to be subjected to.
2) In this study, the rivet joint used was found to be 4 to 5 times stronger than the joint made with lamination only; moreover, the displacement value of the rivet joint was also found to increase.
3) When taking into consideration the bottom and top of rivet; an optimum result of rivet joint with bending loading was obtained on the specimen (specimen D) where the rivet connection’s edge distance was a minimum.
4) After the finite elements solution, when failure condition on composite layer is considered for displacement value after 8.5 mm, the failure occurs in all the layers. Linear part up to 8.5 mm displacement value, it is understood that the rivet connection geometry is not important.
5) Composite specimens with rivet for the bending damage rivet connection condition and rivet geometry is much important (the bottom and top of rivet and rivet diameter).
6) Composite specimens with rivet during three point bending rivet hole that caused geometric discontinuity are identified as failure initial area.

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