Research Article

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Experimental research on effect of opening configuration and reinforcement method on buckling and strength analyses of spar web made of composite material

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Abstract: This study experimentally investigates the effect of the opening configuration on the buckling stability and bearing performance of a structural beam web used in a commercial aircraft made of composite materials. The buckling and strength analyses on three opening configurations (circular, oblong, and rhombic) were carried out using test samples with identical web surface size. It is found that the rhombic opening has the minimum effect on the buckling stability and strength of the structure. To compensate for the effect of the opening, two reinforcement methods, using reinforcement rib and thickening the sample, were also investigated in this study. It is concluded that thickening the sample can more effectively improve the buckling stability and strength performance of beam web structure and hence has relatively higher structural reinforcement efficiency.

Keywords: composite structure, buckling, FEM

1 Introduction

Composite materials are commonly used in aircraft structures in the last few decades. The percentage of the composite materials in the aircraft structure of B787 is higher than 50% of its total weight. The amount of composite

material used in aircrafts has become one of the important indexes to measure the advantage of aircraft structures [1].

With the increased usage of the composite material in an aircraft, it is crucial for engineers in the aviation industry to investigate the mechanisms of the composite materials. Due to the anisotropy of the single-layer material, the mechanical properties and other properties of composite laminates are very complex. These composite laminates show different mechanical properties in different directions.

Composite-laminated plate structures are utilized as the shell or plate structure in a commercial aircraft for its advanced properties. In the service process, it bears in-plane load. With the application of in-plane compression or shear load, the plate or shell structure buckles. The buckling of structure and the damage lead to the decrease in structural reliability and could result in the loss of function. In order to meet the functional requirements of composite structure in service, the need for an opening in a subcomponent is commonly required in practice. Openings are provided in structural subcomponents for ventilation and to lighten the weight of the structure. In aircraft subcomponents (such as wing spar and ribs), openings are necessary for access, inspection, and the installation of the electric lines and fuel lines. The stress/strain distribution of the structure with openings under external load is very complex. The stress concentration at the hole is often obvious, and the decrease in the effective area of the structure and its mechanical properties (such as the stability of the structure) significantly changes during the bearing process. The presence of the openings will inevitably lead to the complexity of the stress and strain distribution in the laminate structure. The buckling behavior of composite laminates with openings needs further research and exploration.

In the field of aviation structure design, the opening is a weak structure in the composite structure bearing. Consequently, it is necessary to strengthen the structure around the opening area. Researchers aimed to study the bearing properties of composite laminated plates with openings in order to provide methods for the design opening structure and reinforcement.

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The experimental study on the buckling behavior of composite laminates with circular openings was conducted by Srinivasa et al. [2]. It is found in their study that the existence of openings weaken the buckling capacity of composite's thin-walled structures. To analyze the stress/strain aspect, Wang et al. [3] and Toubal et al. [4] studied the stress concentration phenomenon at the edges of circular holes on composite laminates under tensile load by experiments. Zitoun et al. [5] carried out tests on the tensile properties of quasi isotropic laminates with drilled and molded holes. The test results show that the damage mechanisms of laminates with drilled holes and molded holes are different, and the strength of laminates with molded holes is 20% higher than that of laminates with drilled holes of the same size, indicating that drilling on laminates and cutting fibers have negative influence on the strength of laminates. Caminero et al. [6] used digital image correlation to analyze the damage process of composite laminates with holes under uniaxial tensile load.

Jalaei and Civalek [7] studied the dynamic instability of embedded porous functionally graded (FG) nanobeam with viscoelastic property undergoing a periodic compressive load and found the influences of various significant factors, such as static load factor, foundation type, length to thickness ratio, power-law index, magnetic field, non-local parameter (NP), and porosity volume index, can affect the dynamic instability of porous FG nanobeam. Akgöz et al. [8,9] provided a new nonclassical sinusoidal plate model that was developed on the basis of modified strain gradient theory. It is found that the size dependency of the microplate was more prominent when the thickness of the microplate was close to the material length scale parameter, and the effect of the shear deformation became important for thick microplates with low length-to-thickness ratio. Dastjerdi et al. [10] studied the mechanical response of spherical viscoelastic functionally graded material (FGM) nanostructures with a change in the structure thickness. Moore et al. [11] studied a scaled composite test section, used ply-based modeling to validate the composite of wing attachment hardware, and obtained a good method to evaluate the full-size wing spar bearing. Fraternali et al. [12] studied in-plane and out-of-plane buckling of laminated composite arches on curved case and found that the bimodularity ratio of the material strongly affects the postbuckling behavior of the beam, leading to stable response when the material is stiffer in tension than in compression and that warping effects play a significant role in the buckling loads of composite beams.

Besides the experimental methods, finite element method (FEM) has been used to investigate the opening configurations and the bearing capacity and buckling stability of composite structure. Arbelo et al. [13] carried

out the buckling analysis of composite shell structure with opening under compression load by FEM. The effects of panel, opening size, and the ratio of opening radius to plate thickness on buckling load are studied in their work. Ubaid et al. [14] explored the mechanical properties of composite laminates with multiple openings through experiments and simulations. Riccio et al. [15] studied the compressive behavior of an omega-stiffened panel with large notch damage and found that the panel with large notch damage started at the notch edges and propagated toward the panel edges in the direction perpendicular to the loading direction, which leads to a net tension failure mode. Sellitto et al. [16] studied the compressive behavior of a notched omega-stiffened composite panel by comparing the experimental and numerical results and found that the ultimate load, buckling behavior, strain distribution, and failure have good agreement; and the buckling of the structure can overcome the initial influence of the large notch damage. Muc et al. [17] studied the buckling and postbuckling behaviors of laminated plated and shell structures. Their numerical analysis showed that the postbuckling behavior was associated with the increase in deformations, and the fracture of the plate may occur if the deformation continues to increase. Baltacci et al. [18] studied the buckling analysis of laminated composite circular plates with circular holes and subjected to uniform radial load by using FEM. The effects of the factors, hole sizes, location of the holes, thickness, and boundary conditions on the critical buckling load were investigated. It is found that the critical buckling load decreases as the hole size and thickness variation in the composite circular plate increase, and increases as the distance between the location of the hole and the center of the composite circular plate increases. Zhang et al. [19] used the 3D progressive damage analysis model to study the damage mechanism of open-hole composite laminates under longitudinal loads and found that the fiber damage of 0° plies propagates mostly in line, and as long as any damage in 0° ply spreads to the outer edge of the specimen and the specimen loses its loading capacity. The conclusion of their work is that the damage of 0° ply is recommended to represent the damage extent of composite structures.

To compensate for the negative effect of the opening, many efforts have been made to understand the reinforcement methods. Shi et al. [20] proved that properly designed ribs can effectively improve the structural buckling and postbuckling-bearing capacity of stiffened composite cylindrical shells with openings under axial compression load. Other scholars have also studied the stability reinforcement analysis of composite cylindrical shells with openings [21,22].

It is noted that most of the studies mentioned above focus on the composite structure with single-opening configuration and their features. The investigation on the bearing properties arising from different configuration of the openings as well as the reinforcement method is limited. In order to reduce the influence of openings and reinforce structures, it is necessary to study different openings and the reinforcement methods of composite structure.

According to the bearing mode of the beam, it is known that the beam web mainly bears shear load under the bending moment. The common failure mode of the beam web under shear load is buckling instability and consequently failure. In this study, experimental research and numerical simulation are conducted to study the influence of different opening configurations and different structural reinforcement methods of composite materials on the buckling bearing capacity and strength performance of beam web under shear load. By comparing the different opening configurations and reinforcement methods, the design of the opening configuration in beam web structure is experimentally and numerically optimized. Due to the common usage of the openings in the composite laminates, this work provides a guideline for the structural design in the civil aviation industry and is worthy of further research.

2 Scheme of measurements

2.1 Measurement setup

This section describes the scheme of the measurements. To investigate the effect of the opening configuration on the buckling stability and bearing performance of a component of a beam web made of composite materials, a sample holding section was designed to apply the shear

load to the samples, as shown in Figure 1. Figure 1(I) illustrates the test loading mode and it is seen that the boundary condition for the sample is simply supported at the edges of the sample, and it carries a quasi-static shear load in plane by the tensile load applied in the diagonal direction. The arrows in Figure 1(I) denote the directions where the shear load is applied. The cross section of the sample is shown in Figure 1(II), the strain measurement positions are shown in Figure 1(III).

Strain rosettes were placed in the diagonal direction. Strain gauges were placed at the upper, lower, left, and right positions of the samples; and they were close to the edges of the opening.

2.2 Samples

In this study, the samples for the experiments are based on the “I-shaped” beams. The cross sections of nine test samples are shown in Figure 2. The opening is placed in the middle of each web sample, and the diameter or the equivalent diameter of each opening is at least 100 mm. The size of the composite sample is 400 mm × 280 mm. The shapes of the openings in the samples are circular, oblong, and rhombic. All samples are of line symmetric. The two symmetric lines are perpendicular to each other and one of them lays horizontally across the center of the opening, as shown in Figure 2.

Figure 2 illustrates the configuration of the test samples. Samples a1, b1, and c1 were utilized to investigate the effect of the three opening shapes on the buckling stability and bearing performance. Note that the opening area of the sample with the oblong opening (b1) is significantly larger than those of the samples with the circular and rhombic openings (a1 and c1). Samples a2 and a3 are the reinforced samples with circular openings using

Figure 1: Schematic diagram of the sample-holding section. (I) Test loading mode. (II) Sample section. (III) Strain measurement position.

Figure 2: Samples for the experiments. a1, b1, and c1: samples with circular, oblong, and rhombic openings; a2, b2, and c2: those reinforced by ribs; a3, b3, and c3: those reinforced by thickening the web. In sub-figures a2, b2, and c2 of Figure 2, the dimensions and the positions of the ribs used for reinforcement are shown in detail.

rib reinforcement and thickening reinforcement, respectively. Samples b2 and b3 are the reinforced structures with oblong openings, and c2 and c3 are those with rhombic openings. The sizes of the openings in a2 and a3 are identical to that in a1 and it is the same with these in b and c groups. Other properties of the composite materials used for these samples are summarized in Tables 1 and 2. All the openings are in the center of the sample, and all the stiffeners are the same.

3 Analysis of test results

3.1 Data acquisition

The test results of a1/a2/a3/b1/b2/b3/c1/c2/c3 are shown in Figures 3–11. Each figure has two subfigures. The left-hand side subfigure in each figure is the load–displacement curve which records the change in the displacement with the increase in the shear load. The right-hand side

Table 1: The composite skins with different configuration

Structure	Plies
Web	[45/−45/0/45/−45/0/−45/90/45] _s
Flange	[45/−45/0/0/45/90/−45/0/0/−45/45/45/−45/0/0/0/−45/0/0/0/45/90/45/0/0/0/−45/0/0/0/−45/45]
Web flange	[45/−45/0/0/45/90/−45/0/0/−45/90/45] _s
Thickening reinforcement	[45/−45/0/0/45/90/−45/0/0/−45/90/45] _s

Table 2: The mechanical properties of the ply

Parameter	Ply
E_{11}	152,000 MPa
E_{22}	7,600 MPa
ν_{12}	0.35
G_{12}	3,900 MPa
Thickness	0.18 mm

subfigure of each figure possesses 16 curves which represent the measured strain in 16 different positions on the measured sample.

In the test process, the holes of test appear buckling first, and load displacement has some undulations, and then the buckling has larger deformation with the tensile load increasing. When having some damage sounds, at last the samples have inner or surface damage and some load-strain curves have sudden shifts. The failure mode involves the diagonal hole edge failure and then the

surface layer failure. According to the measured load-displacement curves, composite material webs were linear elastic in the whole process of destruction. Moreover, the measured strain steadily increased at the bulking process until broken, which implies that the test samples were in elastic region during the buckling tests and the plastic behaviors did not appear.

By comparing curves and test video, each sample's bulking and initial failure capacity are obtained. The sample test results are summarized in Table 3.

3.2 Data analysis

According to Table 3, the buckling carrying capacity of a1 as a reference is 100%; Table 4 shows the calculation of the relative proportions of other sample's carrying capacities. By the same way, considering the initial failure carrying capacity of Sample a1 as a reference, the relative

Figure 3: a1-type test curve. **Figure 4:** a2-type test curve.

Figure 5: a3-type test curve.

Figure 6: b1-type test curve.

Figure 7: b2-type test curve.

proportions of other sample's initial failure strength are calculated as shown in Table 5.

In the second column of Table 3, the comparison of a1, b1, and c1 demonstrates that Sample c1 has the highest bending carrying load among the three samples.

This implies that the rhombic opening is able to carry the highest shear load without reinforcement. Hence, the rhombic opening is supposed to be the optimized configuration of the three opening configurations. To investigate the effect of the reinforcement method on the

Figure 8: b3-type test curve.

Figure 9: c1-type test curve.

Figure 10: c2-type test curve.

bending carrying load, the results of the samples labeled 1, 2, and 3 are compared in each group of samples with each opening configuration. In group a (samples with the circular opening), the bending carrying load peaks with Sample a3 which is made by using the thickening reinforcement method. This phenomenon has also been

observed with groups b and c, which implies that using the thickening reinforcement method can significantly improve the bending carrying load. Moreover, Table 4 shows the relative bending carrying loads of all nine samples. It is concluded in Table 4 that among all samples, Sample c3, which is the sample with the rhombic opening

Figure 11: c3-type test curve.

and reinforced by thickening the web, has the highest bending carrying load. This conclusion is consistent with the data analysis using Table 3. Therefore, the analysis of the experimental results illustrates that the rhombic opening is the best configuration of the three openings and the relatively better reinforcement method is thickening the web; and that these two factors could be combined to provide the optimized configuration of a composite laminate with an unavoidable opening in aviation industry. In the third column of Table 3, the comparison of a3, b3, and c3 demonstrates that Sample c3 has the highest carrying initial failure load. It indicates that the rhombic opening with thickening reinforcement method has the strongest carrying capacity and that the thickening reinforcement can significantly improve the initial failure carrying capacity. Table 5 compares the relative initial failure strength of the samples. As for the bearing capacity against failure, the reinforcement efficiency of the rib is very limited, and the bearing capacity is increased only by 1–7%. The limited improvement is due to the buckling resistance at the edge of the opening and the structure damages caused by the hole manufacture for

the reinforcement ribs. However, for thickening reinforcement, the bearing capacity of specimens with a, b, and c configuration is increased by 31.7, 46.9, and 23.6%, respectively. Note that the reinforcement efficiency is even higher when the opening area is larger.

It is concluded from Tables 3–5 that the thickening reinforcement provides more advanced buckling carrying capacity and higher initial failure load than those of the rib reinforcement. This is possibly due to the different-reinforce process. When using the rib reinforcement, it is necessary to drill holes on the samples to install the ribs. Drilling holes lead to the break of the composite fibers and small cracks near the edges of the drilled holes. Due to the

Table 3: Test results

Types	Test bending carrying loads (kN)	Initial failure load (kN)
a1	73.6	145.4
a2	81.4	147.5
a3	124.4	191.6
b1	52	87.4
b2	57.6	92.6
b3	108.4	128.4
c1	90	183.6
c2	98.4	196.6
c3	145.75	227

Table 4: Comparison of the relative buckling load

	a (%)	b (%)	c (%)
Unreinforced structure bulking carrying ratio	100	70.6	122
Bulking carrying ratio by reinforcement rib	110.5	78.3	133.7
Bulking carrying ratio by thickening reinforcement	169	147.3	198

Note: a1 is a referent used for comparing with other samples.

Table 5: Comparison of relative initial failure strength

	a (%)	b (%)	c (%)
Unreinforced structure initial failure strength ratio	100	60	126.3
Initial failure strength ratio by reinforcement rib	101.3	63.68	135.2
Initial failure strength ratio by thickening reinforcement	131.7	88.3	156.1

Note: a1 is a referent used for comparing with other samples.

Table 6: Weight comparison of the samples

Sample	Weight (kg)	Relative weight (%)
a1	0.987	100
a2	1.111	112.5
a3	1.1	111.4
b1	0.94	95.2
b2	1.064	107
b3	1.05	106
c1	0.996	100.9
c2	1.12	113.4
c3	1.12	113.4

Note: a1 is a referent used for comparing with other samples.

Figure 12: The laminates layup of the panel.

broken fibers and the cracks, the buckling carrying capacity and the initial failure load decrease. By contrast, using thickening reinforcement maintains the continuous fibers, and hence the reinforcement efficiency is higher than that obtained by adding reinforcement ribs.

The weights of samples are summarized in Table 6, and taking the weight of sample a1 as a reference, other sample's weight relative proportions are calculated as shown in Table 6. As shown in Table 6, the weights of rib reinforcement and thickening reinforcement are almost the same. Since their bearing capacities are significantly different, it is concluded that the thickening reinforcement efficiency is higher than that of the rib reinforcement.

4 Theoretical analysis of the improvement of the thickening reinforcement

4.1 Classic laminate theory

For thin-walled composite structures (i.e., the thickness of the laminate is much smaller than other dimensions of

the structure), the bearing capacity of the laminate can be regarded as a plane stress state. According to the stress-strain relationship, the generalized constitutive relation of the laminate (including the membrane bending coupling) can be obtained.

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ \text{Symmetry} & & & D_{11} & D_{12} & D_{16} \\ & & & D_{12} & D_{22} & D_{26} \\ & & & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix}. \quad (1)$$

So stiffener matrix coefficient of laminate can be expressed as

$$\begin{cases} A_{ij} = \sum_{k=1}^N (\tilde{Q}_{ij})_k (z_k - z_{k-1}), \\ B_{ij} = \frac{1}{2} \sum_{k=1}^N (\tilde{Q}_{ij})_k (z_k^2 - z_{k-1}^2), \\ D_{ij} = \frac{1}{3} \sum_{k=1}^N (\tilde{Q}_{ij})_k (z_k^3 - z_{k-1}^3). \end{cases} \quad (2)$$

z_k is distance between the central plane of layer k and the bottom surface, as shown in Figure 12 ($\tilde{Q}_{ij})_k$ is the stiffener of layer k . A_{ij} , D_{ij} , and B_{ij} are the tensile stiffness coefficient, bending stiffness coefficient, and tensile and bending coupling stiffness coefficient, respectively.

4.2 Theoretical analysis

To investigate the mechanism of the beneficitation arisen from the thickening reinforcement, Figure 13 shows the distribution of the tensile and bending stiffness parameters of the original beam web and the thickening-reinforced beam web in polar coordinate system. In the original beam web ply design, the two parameters of tensile stiffness cross each other in the 45° direction, which indicates that the composite mechanical properties in this direction are the best under the web ply design. After the design of thickening reinforcement, the tensile stiffness parameters A_{11} and A_{22} have the greatest influence on the beam web in 0° and 90° directions, respectively. This is because the overall mechanical properties of beam webs are changed after adding 0° and 90° ply to the beam web. Compared with the original beam web overlay design, the overall tensile stiffness parameter increases by about 20%.

In the original beam web ply design, due to the large proportion of $\pm 45^\circ$ ply mode, the bending stiffness

Figure 13: Tensile stiffness/bending stiffness parameters of web and reinforce web. (I) Web A_{ij} . (II) Web D_{ij} . (III) Reinforce web A_{ij} . (IV) Reinforce web D_{ij} .

parameters of D_{11} and D_{22} are the largest in the direction of 45° and 135° , respectively, and form a cross in the direction of nearly 50° at the same time, which indicates that the bending bearing capacity of beam web near 50° is the strongest.

After the thickening reinforcement design, the proportion of 0° and 90° ply increases, and the bending stiffness parameters have great influence. The bending stiffness parameters of D_{11} and D_{22} are the largest in the direction of 15° and 105° , respectively, and form a cross in the direction of nearly 50° which indicates that the bending bearing capacity of beam web is the strongest

in the near 50° direction. After the design of thickening reinforcement, the bending stiffness parameters of beam web are increased by about one time compared with the original structure. Compared with configuration 1, the bending stiffness parameters of D_{11} and D_{22} are basically the same in the direction of 45° compared with configuration 1, but the bending stiffness of D_{11} and D_{22} is higher and more coordinated in the range of 360° .

Through theoretical analysis, it is found that compared with the original structure, the thickness reinforcement of beam web increases six layers of ply design, but it is very effective to improve the tensile stiffness and

bending stiffness parameters and enhances the tensile and bending bearing capacity of the beam web. This implies that by properly designing the composite layout of the thickening reinforcement, the reinforcement efficiency can be improved.

5 Finite element analysis (FEA) of loading buckling of samples

5.1 FEM analysis

In order to further research carrying capacity of the composite spar web, this section developed an FEA model for the samples and compares the test results to the simulated results by CAE software analysis. The FEA software Patran & Nastran is used to establish the FEA model. All the FEM models use the 2D shells and Quad 4 elements to simulate the mechanical web based on the plane stress theory.

The Z direction of the nodes at four edges of the sample is constrained. The degree of freedom node (0,0,0) is constrained by (0, 0, 0). The node (a, b, 0) is constrained with the load tensile direction by local coordinate. The distance is 5 mm between the nearby nodes at four edges. Unit load is applied to the nodes of four edges.

The model and loading conditions are shown in Figure 14 as well as the mesh of the FEA model. The finite element buckling analysis results of the test samples are shown in Figure 15.

Figure 15 shows the distribution of the bulking factor simulated by FEM models. Since the plies of sample web are symmetrical, both sides of the web demonstrate the same effect of bulking factor. According to the factor and boundary unit loads, the buckling capacity of each sample is calculated and shown in Table 7.

5.2 Comparison of FEM and experiment

As shown in Figure 16, the calculation of buckling load by FEA method is compared with those from the experiments. The error bars on the curve of the experimental results denote the acceptable error range of the experiments in practice which is $\pm 15\%$. This error is usually arisen from the variation in the samples due to the manufacture process, and the small change in the boundary condition due to the installation of the samples.

For Samples a1, b1, and c1, most of the buckling loads from the FEM simulations are similar with those from the experiments. The differences in the experimental and simulated buckling loads for Samples a1 and b1 are within the acceptable error range, which implies that the FEM models are valid. For the Sample c1, the difference is slightly higher than the upper limit of the error bar. This might be caused by the manufacture process of the sample and/or the boundary condition of the experiment. Moreover, the buckling load obtained by the experiment for Sample c3 agrees with that of the FEM model, which may imply that the FEM model for the samples in c group is still valid and the difference in those of the Sample c1 is due to the sample itself and the test error due to the experiment process.

As for the reinforcement method, the FEM results show trends similar to those of the experiments. It is also obvious from the FEM results that the rhombic opening and the thickening reinforcement method are beneficial for the buckling capability. The results of FEA are in good agreement with the experimental results of the cases without reinforcement and with the thickening reinforcement. However, in the analysis of reinforcement rib, there is a big difference between FEM calculation results and test results. The difference implies that the damages arisen from drilling holes for the connection fasteners and processing have great influence on the bearing capacity of beam web, and these structural damages are neglected by the FEM model.

Figure 14: FEA model.

Figure 15: FEA bending analysis of a/b/c types: (I) FEA bending analysis of Sample a1. (II) FEA bending analysis of Sample a2. (III) FEA bending analysis of Sample a3. (IV) FEA bending analysis of Sample b1. (V) FEA bending analysis of Sample b2. (VI) FEA bending analysis of Sample b3. (VII) FEA bending analysis of Sample c1. (VIII) FEA bending analysis of Sample c2. (IX) FEA bending analysis of Sample c3.

Table 7: FEA bending results

Type	Factor	Buckling capacity (kN)
a1	799.51	66.95
a2	1,204.9	100.90
a3	1,550.7	129.86
b1	637.9	53.41
b2	1,044	87.42
b3	1,455.2	121.8
c1	926.57	77.59
c2	1,359.8	113.87
c3	1,824.8	152.81

Figure 16: FEA simulation and test on buckling capacity.

6 Conclusion

This study used experiments to investigate the effect of the opening configuration on the buckling stability and bearing performance of a structural beam web used in a commercial aircraft made of composite materials. The buckling and strength analyses on three opening configurations (circular, oblong, and rhombic) were conducted using test samples with identical web surface size.

It is concluded from the experimental results that the rhombic opening has the minimum effect on the buckling stability and strength of the structure. To compensate the effect of the opening, it is concluded that thickening of the sample can more effectively improve the buckling stability and strength performance of beam web structure and hence has relatively higher structural reinforcement efficiency. By using the analytical analysis and the FEA model, it is found that the advantage of the thickening reinforcement is due to the continuous fibers and the well-designed fiber layup.

The research results are of great significance for the design of the opening form and the analysis of the bearing capacity of composite beam web structures in

aviation industry. By selecting the appropriate opening form and the reinforcement design method, the loss of bearing capacity due to the opening can be effectively improved, and the structure design efficiency can be significantly improved, which has economic benefits.

Conflict of interest: Authors state no conflict of interest.

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