Research Article

Teng Huang, Dongdong Zhang*, Jun Yang, Yuan Lin, and Yaxin Huang

Compressive bearing capacity and failure mechanism of CFRP–aluminum laminate column with single-channel cross section

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Abstract: The axial compressive bearing capacity, failure modes, and failure mechanisms of carbon fiber-reinforced aluminum laminate (CARALL) columns with single-channel cross sections were studied in detail. In this study, two types of short CARALL specimens with a 5/4 configuration were first fabricated using 2024-T3 aluminum alloy and different fiber orientations ([0°/90°/0°]_3, [45°/0°/-45°]_3) via a pressure-molding thermal-curing forming process. The short CARALL columns were then subjected to static loading tests to determine their axial compressive behaviors in terms of ultimate bearing capacity and failure modes. Thereafter, the user-defined FORTRAN subroutine VUMAT, which is based on ABAQUS, was used to investigate the failure mechanism of the proposed CARALL columns. Meanwhile, based on the classic laminated panel mechanics theory, a theoretical method was proposed to predict the safe bearing capacity of the designed compressive CARALL columns. The results indicated that the ultimate failure of both types of short CARALL columns was a strength failure caused by the delamination of the layers. When the short CARALL columns were subjected to an axial compressive load, the fiber spread angle of the carbon fiber-reinforced polymer prepregs in the laminate panels had a significant influence on the resistance to interlaminar delamination. A smaller fiber layer angle resulted in greater resistance to interlaminar delamination. Setting a certain number of fiber layers with angles between 0° and 45° could increase the toughness of the compression column member against interlaminar shear delamination at the initial stage. Comparisons of the experimental, numerical, and theoretical results demonstrated good agreement, indicating that the proposed theoretical method is feasible for predicting the safe bearing capacity of CARALL columns with a single-channel cross section and can be applied to the design of compressive laminate pillar components.

Keywords: Carbon fiber-reinforced aluminum laminates (CARALL), Column with channel cross section, Compressive bearing capacity, Failure mode, Failure mechanism

1 Introduction

The increasing requirements of advanced lightweight civil engineering structures have prompted researchers to develop new lightweight composite materials with excellent mechanical properties [1]. In particular, the use of new materials and structures is an effective way to improve the structural performance and bearing capacity of decomposable bridges [2–6]. The main structural components of decomposable bridges are tension or compression bars and beams. Achieving lightweight and high-strength components is an effective way to realize lightweight structures. Carbon fiber-reinforced polymer (CFRP) materials are known to exhibit excellent characteristics, such as low self-weight, increased strength, and good corrosion resistance, which can greatly improve the bearing capacity of components. However, the current high cost, low shear properties, and poor impact resistance of the resin matrix prohibit the full utilization of these materials in civil engineering structures.

By combining CFRP and metal materials to form a composite component, the inherent shortcomings of the CFRP and metal materials can be ameliorated, and the composite components can thus provide excellent comprehensive performances. Fiber-metal laminate (FML) is a new composite material that has been widely used in aircraft manufacturing [7, 8]. Carbon fiber-reinforced aluminum laminate (CARALL) is an effective FML composed of CFRP and
Compressive bearing capacity and failure mechanism of CFRP/aluminum layers alternately stacked and joined together using adhesives [9–11]. Its lightweight and high-strength characteristics are the key design considerations and the reasons that CARALL is replacing traditional structural materials. Studies on the basic mechanical properties of CARALL composite materials have been carried out [7–31] and have assessed tensile, compression, bending, shear, interlayer delamination, and fatigue performances. CARALL has also been proven to have a broad range of potential applications in different industries [5, 6]. Predictably, the future application of CARALL in emergency decomposable bridging systems is promising.

However, research on specific cross-section members of CARALL composites for engineering applications seems to be very limited. It is noted that in decomposable bridge structures, special cross-sectional members involve box-shaped, I-shaped, and channel cross-section beams and columns [2]. Among the representative compressive columns in engineering practice, the flanges and webs of laminated panel members are often thick and short. The compression pillar members of this type of short CARALL column always exhibit strength failure rather than buckling failure modes under axial compression loadings. Therefore, the present study focused on the axial compressive bearing capacity of short CARALL columns with a special channel cross section.

Most of the existing research has focused on the axial compressive performances of glass fiber-reinforced aluminum laminate (GARALL) columns [32–45]. However, the application of existing theoretical methods to GARALL columns requires the prerequisite of physical tests on the calculated objects. These theoretical methods can only be used to calculate the buckling and post-buckling bearing capacities of GARALL columns according to the relevant deformation and stress–strain data obtained from these tests. Thus, the existing theoretical methods for GARALL columns cannot be directly applied to CARALL columns with strength failure modes. Because reliable prediction methods for the bearing capacity of compressive pillar members are of great importance for structural design and safety controls, specialized theoretical methods should be developed for short CARALL columns with channel cross sections.

In this study, two types of short CARALL columns with different layup configurations were first fabricated via a pressure-molding thermal-curing forming process. The specimens were subsequently subjected to static loading tests to determine their ultimate bearing capacities and failure modes. Second, the user-defined FORTRAN subroutine VUMAT, which uses ABAQUS software, was used to investigate the failure mechanism of the designed columns. Finally, based on the classic laminated panel mechanics theory, a theoretical method was proposed to predict the safe bearing capacity of the designed compressive columns, which could be used in the design and computation procedure of CARALL compressive columns with a single-channel cross section.

2 Experimental procedures

2.1 Specimen preparation

The test samples used in this study were compression columns made from CARALL plates with a single-channel cross section, as shown in Figure 1. The laminated members of the tested compression columns featured a 5/4 configuration. Namely, they were designed by stacking 5 aluminum alloy sheets and 4 CFRP layers. Two types of CARALL columns, with different layup configurations for the carbon fiber ([0°/90°/0°]₃, [45°/0°/−45°]₃), were fabricated for the test. Herein, the longitudinal direction of the single-channel cross-sectional column is defined as the 0° direction of the carbon fiber.

![Figure 1: Global dimension and shape of a single-channel cross-sectional compression column.](image)

The CARALL specimens were manufactured using T700 carbon fiber-reinforced epoxy resin prepregs (with a fiber volume content of 57% and a nominal thickness of 0.15 mm) and 2024-T3 aluminum alloy sheets (with a nominal thickness of 0.367 mm). The T700 carbon fiber-reinforced epoxy resin prepregs were provided by Sichuan Xin-Wan-Xing Carbon Fiber Composites Co., Ltd. Each layer of the CARALL specimens was assigned a designation in a top-to-bottom sequence, as shown in Figure 2. The two types of
Table 1: Specimen notations, layup sequence, and dimensions of fiber and metal laminates.

| Specimens | Layup sequence | Length (mm) | Width (mm) | Height (mm) | Thickness (mm) |
|-----------|----------------|-------------|------------|-------------|----------------|
| DCYG-A    | Al/[0/90/0]3/Al/[0/90/0]3/Al/[0/90/0]3/Al | 300         | 40         | 100         | 3.635          |
| DCYG-B    | Al/[45/0−45]3/Al/[45/0−45]3/Al/[45/0−45]3/Al | 300         | 40         | 100         | 3.635          |

CARALL specimens, with different carbon fiber layup configurations, referred to as [0°/90°/0°]3 and [45°/0°/−45°]3, were denoted by DCYG-A and DCYG-B, respectively. The notations, layup configuration, and dimensions of the designed CARALL specimens are presented in Table 1.

Before the lamination procedure, a phosphoric acid anodizing procedure was performed on the aluminum alloy sheet according to the HB/Z 1987-1991 standard to ensure the bonding effects between the aluminum layers and CFRP layers. Thin epoxy films were then placed between the CFRP and aluminum layers as adhesive layers, which could also isolate the carbon fiber prepreg layers from the aluminum layers to prevent galvanic corrosion. Afterward, the hand-
layup laminates were placed on the female and male dies of a vulcanizing machine (see Figure 3). Finally, the channel cross-sectional CARALL specimens were fabricated using the pressure-molding thermal-curing forming process, as shown in Figure 4.

### 2.2 Axial compression test

To obtain the real bearing capacity and failure mode of each compression column, test benches were specially designed and prepared for the experiments. The test benches consisted of square plates made of Q235 steel for the upper and lower supports (see Figure 5a). The use of these special supports with the benches was expected to provide a constraint that was close to the ideal natural constraint condition. In this study, the so-called natural constraint condition was considered to be the condition wherein the supports did not apply a lateral force around the end of the compression columns. Under this condition, the end of the compression column had a certain constraint length. Within the constraint length range, the lateral displacement of each node for the rod ends approached zero. In the presented axial compression test, the natural constraint supports simulating the lateral displacement (with zero value) of the compression bar ends were made of Yassong 331 resin AB adhesive (see Figure 5b).

A WANCE computer-controlled electrohydraulic servo universal testing machine was used to conduct the axial compression test with direct pressure at both ends of the tested compression column. The test loading rate was 1 mm/min. The load–displacement data were recorded by the microcomputer control system of the testing machine, and the load–strain data were collected by the high-speed static strain testing and analysis system (DH3820) provided by China Donghua Testing Technology Co., Ltd. Figure 6 depicts the general arrangement for the compression tests of the fabricated columns. Five groups of axial compression tests were carried out on DCYG-A and DCYG-B laminated plates. Among these plates, the five groups of DCYG-A-type specimens were numbered DCYG-A-1, DCYG-A-2, DCYG-A-3, DCYG-A-4, and DCYG-A-5. The five groups of DCYG-B-type specimens were numbered DCYG-B-1, DCYG-B-2, DCYG-B-3, DCYG-B-4, and DCYG-B-5.

### 2.3 Failure modes and ultimate bearing capacity of specimens

During the loading process, no evident buckling failure characteristics were observed. The typical failure modes of the DCYG-A and DCYG-B laminated compression columns are shown in Figure 7 and Figure 8. As expected, for all the DCYG-A and DCYG-B type CARALLs with a single-channel cross section, the specimens had a strength failure mode in the middle of the short pillar members. The ultimate
strength failure of all the compression columns was mainly caused by the short length and large wall thickness of the compression column specimens. Figure 8 also shows that under the action of an axial compression load, the initial failure of the laminated compression columns was caused by the local buckling of the flange. Afterwards, the delamination failure area between each layer gradually expanded, leading to the collapse of the column members in the middle and the compression column losing its bearing capacity. The delamination failure between all the fiber and metal layers was the main factor that finally caused the loss of the bearing capacity of the designed compressive laminated columns with a single-channel cross section.

Additionally, the ultimate bearing capacities of the specimens corresponding to the above experimental failure modes are summarized in Table 2. As shown in the table, the maximum ultimate bearing capacities of the DCYG-A and DCYG-B laminated columns were 195.91 kN and 174.36 kN, respectively. The average ultimate bearing capacity of the DCYG-A laminated columns was approximately 1.12 times that of the DCYG-B-type columns. The results indicated that for the short compression laminated columns subjected to axial compression loadings, the designed members with a fiber layup of 0°/90°/0° had a larger bearing capacity than the members with a fiber layup of 45°/0°/−45°.

### Table 2: Bearing performance parameters of DCYG-A and DCYG-B compression columns.

| Specimen designation | Fiber layup | Failure mode | Ultimate bearing capacity (kN) |
|----------------------|-------------|--------------|---------------------------------|
| DCYG-A-1             | 0°/90°/0°   | Strength failure in the middle of a compression column | 189.165                          |
| DCYG-A-2             | 0°/90°/0°   | Strength failure in the middle of a compression column | 193.896                          |
| DCYG-A-3             | 0°/90°/0°   | Strength failure in the middle of a compression column | 193.769                          |
| DCYG-A-4             | 0°/90°/0°   | Strength failure in the middle of a compression column | 195.905                          |
| DCYG-A-5             | 0°/90°/0°   | Strength failure in the middle of a compression column | 194.020                          |
| DCYG-B-1             | 45°/0°/−45° | Strength failure in the middle of a compression column | 170.635                          |
| DCYG-B-2             | 45°/0°/−45° | Strength failure in the middle of a compression column | 174.356                          |
| DCYG-B-3             | 45°/0°/−45° | Strength failure in the middle of a compression column | 172.496                          |
| DCYG-B-4             | 0°/90°/0°   | Strength failure in the middle of a compression column | 173.905                          |
| DCYG-B-5             | 0°/90°/0°   | Strength failure in the middle of a compression column | 171.020                          |

### 3 Numerical simulation

#### 3.1 Finite element model of the compression column member

A numerical simulation based on the commercial finite element (FE) software ABAQUS 6.12 was conducted to simulate the compressive bearing capacities of the DCYG-A- and DCYG-B-type channel cross-sectional laminated columns with different fiber layups. The explicit time integration method was employed in the FE analysis, which was re-
Compressive bearing capacity and failure mechanism of CFRP/bar.

Table 3: Material properties of the aluminum alloy used.

| Material properties          | 2024-T3 |
|-----------------------------|---------|
| Elastic parameters          | $E = 70$ GPa, $\mu = 0.33$ |
| Yield surface parameters    | $A = 369$ MPa, $B = 684$ MPa, $C = 0.0083$ MPa, $m = 1, n = 0.73$ |
| Failure parameters          | $d_1 = 0.13, d_2 = 0.13, d_3 = -1.5, d_4 = 0.011$ |
| Fracture energy             | $G_{IC} = 8$ KJ/m$^2$ |
| Plastic parameters          | Plastic strain $\varepsilon = 0, \text{yield stress } \sigma = 300$ MPa |

Table 4: Material properties of used T700 carbon fiber/epoxy prepregs.

| $E_1$ (MPa) | $E_2$ (MPa) | $E_3$ (MPa) | $\nu_{12} = \nu_{13} = \nu_{23}$ | $G_{12}$ (MPa) | $G_{13}$ (MPa) | $G_{23}$ (MPa) |
|-------------|-------------|-------------|----------------------------------|----------------|----------------|----------------|
| 101,510     | 7800        | 7800        | 0.32                             | 4000           | 4000           | 3600           |
| $P$ (kg/m$^3$) | $X^T$ (MPa) | $X^C$ (MPa) | $Y^T$ (MPa) | $Y^C$ (MPa) | $Z^T$ (MPa) | $Z^C$ (MPa) |
| 2032        | 2050        | 1240        | 50                                | 150            | 50             | 150            |
| $S_{12}$ (MPa) | $S_{13}$ (MPa) | $S_{23}$ (MPa) | $G_{RC}$ (kJ/m$^2$) | $G_{fcc}$ (kJ/m$^2$) | $G_{mnc}$ (kJ/m$^2$) | $G_{mcc}$ (kJ/m$^2$) |
| 93          | 93          | 50          | 40                                | 40             | 0.25           | 0.75           |

ferred to as the ABAQUS/explicit method. Figure 9 shows a schematic diagram of the established FE model of the compressive laminated columns.

During the FE modeling, different layers of the fiber and metal laminates were created by the offset isolated grid method. Hashin’s 3D progressive damage model developed in the VURMAT subroutine program was used as the material failure model of the CFRP layers. The 3D eight-node reduction integral C3D8R solid element was used for discrete element analysis of the CFRP and aluminum alloy. The elastic-plastic constitutive and Johnson–Cook plastic damage criteria were defined. The failure prediction of the interlayer interface lamination was realized using the cohesive zone model (CZM) method. The COH3D8 3D cohesive element was established by the VURMAT subroutine. The material properties of the aluminum alloy used in the Johnson–Cook model are listed in Table 3. The material properties of the T700 carbon fiber/epoxy prepregs provided by the raw material supplier are summarized in Table 4. The material properties of the T700 carbon fiber/epoxy prepregs provided by the raw material supplier are summarized in Table 4.

In the FE model, the supports at both ends of the compressive members were modeled using R3D4 rigid elements. The end supports were fixed within all degrees of freedom. The tie constraint was defined to simulate the interaction between the supports and compressive laminated columns. The lower end of the FE model of the pressed-column member was set as a full constraint. The upper end of the pressed-column model was coupled with all nodes by setting the reference point, and a displacement of 5 mm along the compressive column length was applied on the reference point for loading. The calculation time was set to 0.025 s. The numerical simulation results showed that the ratio of kinetic energy to internal energy was within 1%.

3.2 Comparison between numerical and experimental results

The ultimate bearing loads of the DCYG-A and DCYG-B type columns obtained in the numerical simulations were 195.86 kN and 175.62 kN, respectively. The differences between the experimental results and numerical predictions were approximately 1.3% and 1.8% for the DCYG-A and DCYG-B columns, respectively. Moreover, Figure 10 shows that the final failure modes obtained in the numerical simulations
were consistent with those of the experimental results. The final failure of the DCYG-A-type members was a strength failure caused by the delamination failure between laminated layers, which was the same as that of the DCYG-B-type members. During the strength failure, the aluminum alloy sheet failure, fiber layer matrix tensile or compression failure of the CFRP prepreg, and fiber layer shear failure were all tracked. The detailed failure process and failure mechanism of the single-channel cross-sectional compression columns are analyzed in the following section.

![Figure 10: Final failure modes of compression columns: (a) DCYG-A and (b) DCYG-B.](image)

### 3.3 Numerical failure process and failure mechanism

#### 3.3.1 Failure analysis of aluminum alloy sheet

According to the comparative analysis, the outer aluminum alloy sheet was the first to buckle, and the damage degree was the most serious when the compression column lost its bearing capacity. Therefore, the failure mechanism was first analyzed from the stress deformation process of the outer aluminum alloy layer of a laminated panel compression column. As shown in Figure 11, when the axial compression loads of the DCYG-A and DCYG-B columns reached 181.81 kN and 145.65 kN, respectively, the stress level of certain areas of the outer aluminum alloy sheet reached 300 MPa, and the plastic strain was zero. The stress distribution area of DCYG-B at 300 MPa was larger than that of DCYG-A. Moreover, when the stress level was less than 300 MPa, the stress distribution of DCYG-B was relatively uniform, and the distribution area was large. This was a factor in why the ultimate bearing capacity of DCYG-A was higher than that of DCYG-B.

![Figure 11: Stress area distribution of compression columns at 300 MPa: (a) DCYG-A and (b) DCYG-B.](image)

Figure 11 shows that when the axial compression load of DCYG-A increased from 181.81 kN to 195.86 kN, the stress level in some areas of the outer aluminum alloy sheet exceeded 300 MPa, and the size of these areas increased uniformly (see Figure 11a and Figure 12a). However, when the axial compression load reached the ultimate bearing capacity and gradually began to drop, the stress distribution was not uniform within the cross section of the compression member, and the maximum stress occurred at the junction of the flange and web. Moreover, with a reduction in the axial compression load, the maximum stress level of the aluminum alloy sheet continued to increase (see Fig-
Compressive bearing capacity and failure mechanism of CFRP

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Figure 13: Stress and deformation process of the outer aluminum alloy sheet of the DCYG-B column.

ure 12c). Once the axial compression load of the laminated columns reached 195.86 kN, the local buckling failures of the flange and web occurred simultaneously near the middle of the laminated pillar member (see Figure 12b), which is the most important cause for the bearing capacity loss of the laminated column. The local buckling failure of the flange and web of the channel cross-sectional column was the reason that the bearing capacity of the compression member decreased with an increase in the axial compression displacement, while the maximum stress level of the aluminum alloy sheet still increased.

Moreover, Figure 13 shows that the stress deformation process and law of the outer aluminum alloy sheet of the DCYG-B columns were basically consistent with those of the DCYG-A columns. However, the positions of the highest stress levels for the outer aluminum alloy sheet were different under different loading levels. The position of the highest stress level in the outer aluminum alloy sheet of the DCYG-B columns was in the web area in the middle of the compression members (see Figure 13a and b). Similarly, the local buckling failure of the webs and flanges was still the main factor in the loss of the bearing capacity of the DCYG-B columns with a single-channel cross section.

In addition, when the stress level was approximately 300 MPa, the axial load acting on the compression column continued to increase until the compression bearing capacity of the columns was lost. In terms of the variation amplitude for the axial compression load, the compression toughness of a short column with a fiber layup of 45°/0°/−45° was better than that with a fiber layup of 0°/90°/0°. The variation amplitude of the axial compression load of the 45°/0°/−45° fiber layup laminated compression column members was 29.65 kN (from 145.65 kN to 175.26 kN), while the variation amplitude of the axial compression load of the 0°/90°/0° fiber layup laminated columns was only 14.02 kN (from 181.81 kN to 195.86 kN). This result indicated that for the compression column with the 0°/90°/0° fiber layup, the member failure was more abrupt.

3.3.2 Failure analysis of interlaminar delamination

According to the comparative analysis, there were large interlaminar delamination failure areas between the outer aluminum alloy sheet and the fiber layer of ply0-1-1 (or the fiber layer of ply45-1-1) and between the ply90-1-1 fiber layer and the ply0-1-1 fiber layer. The degree of damage was the most serious when the compression column lost its bearing capacity. Therefore, the evolution of the interlaminar delamination failure for each layer of the laminated panels was analyzed on the basis of the interlaminar delamination between the outer aluminum alloy sheet and the fiber layer of ply0-1-1 or the fiber layer of ply45-1-1 and between the ply90-1-1 fiber layer and the ply0-1-1 fiber layer. The first 0° CFRP fiber layer in the 5/4 laminated panels of DCYG-A was given the designation ply0-1-1. The first 45° CFRP fiber layer in the 5/4 laminated panel of DCYG-B was given the designation ply45-1-1. The first 90° fiber layer was given the designation ply90-1-1, as shown in Figure 2.

As shown in Figure 14a, when the axial compression load on the DCYG-A-type column reached approximately 392.27 N, the stratification evolution factors begin to appear between the aluminum alloy sheet layer and the fiber layer of ply0-1-1 at the end of the pillar member. When the axial compression load reached approximately 477.24 N, interlaminar delamination begins to appear between the ply90-1-1 fiber layer and the ply0-1-1 fiber layer at the end of the column (see Figure 14b). Moreover, the extension area of the inter-layer delamination failure was large. For the DCYG-B-type column, when the axial compression load reached 5.59 kN (see Figure 14c), local interlaminar delamination occurred between the outer aluminum alloy sheet and the fiber layer of ply45-1-1. However, once stratification occurred, the stratification region was relatively large. This indicated that in the initial state of axial compression of the laminated column with a single-channel cross section, the resistance of the 45° fiber layer to delamination was stronger than those of the 0° and 90° fiber layers. Once
interlayer delamination failure occurred, the failure area expansion speed was relatively fast, and the interlayer delamination failure zone between the $90^\circ$ fiber layer and the adjacent fiber layers rapidly expanded (see Figure 14a).

For the DCYG-A and DCYG-B columns, when the axial compression loads reached 181.81 kN and 145.65 kN, respectively, the stress level in some areas of the outer aluminum alloy sheet reached 300 MPa. At this time, the delamination failure areas between the outer aluminum alloy sheet and the ply0-1-1 or ply45-1-1 fiber layer, and between the ply90-1-1 fiber layer and the adjacent fiber layers, also expanded significantly (see Figure 15). Among these areas, the delamination failure area between the ply90-1-1 fiber layer and other fiber layers for the DCYG-A columns was the largest and had the fastest expansion speed, while the delamination failure area between the ply0-1-1 fiber layer and the outer aluminum alloy sheet was the smallest and the expansion speed was the slowest. For the DCYG-B columns, the size and expansion rate of the interlayer delamination failure area between the ply45-1-1 fiber layer and the outer aluminum sheet were between those of the ply0-1-1 and ply90-1-1 fiber layers.
When the axial compression loads of the two types of compressive columns reached their ultimate bearing capacities, the delamination failure area evidently increased compared with that of the previously mentioned results (see Figure 14 and Figure 15). The failure area of the interlaminar delamination between the ply90-1-1 fiber layer and the adjacent fiber layers of the DCYG-A-type column was the largest (see Figure 16b), while the delamination failure area between the ply0-1-1 fiber layer and the outer aluminum alloy sheet was the smallest (see Figure 16a). Failure delamination between the 0° fiber layer and the outer aluminum alloy sheet mainly occurred at the flange and at the connection between the web and flange. Interlaminar delamination failure occurred between the 90° fiber layer and the adjacent fiber layer on the web and flange within a large area.

In terms of the DCYG-B column (see Figure 16c), the failure degree and area of the delamination between the ply45-1-1 fiber layer and the outer aluminum alloy sheet on the flange was greater than that of the previously mentioned results (see Figure 14c and Figure 15c). However, compared with the delamination failure between the 90° fiber layer and the adjacent fiber layer of the DCYG-A column, its failure area and degree were smaller. Moreover, the connection between the flanges and webs was completely stratified along the length of the pillar member. This result fully indicated that when the axial compression load reached a certain value, the non 0° fiber layers in the laminated panel compression columns had a relatively weak ability to resist inter-layer delamination. A larger fiber laying angle was associated with a weaker resistance of the fiber layer to interlayer delamination.

From the perspective of the sizes and failure degrees of the delamination failure areas of the various fiber layers described above, when the laminate compression column members lost their ultimate bearing capacities, the delamination failure scale and degree between the ply0-1-1 or ply90-1-1 fiber layer and other layers of the DCYG-A-type member were similar (see Figures 17a and b). The delamination failure between the ply45-1-1 fiber layer and the outer aluminum sheet was the most serious in the DCYG-B-type columns (see Figure 17c).

### 3.3.3 Failure analysis of fiber tensile and compression

According to the comparative analysis, the fiber tensile and compression failure areas of the ply0-1-1 fiber layer for the DCYG-A column and that of the ply45-1-1 fiber layer for the DCYG-B column were large. The damage degree was the most serious when the compression columns lost their bearing capacity. Therefore, the evolution of the fiber tensile and compression failure for each layer described above was also analyzed on the basis of those for the ply0-1-1 and ply45-1-1 fiber layers. As shown in Figure 18, both the DCYG-A and DCYG-B type columns have very low degrees of fiber tensile and compression damage in the ply0-1-1 and ply45-1-1 fiber layers. Even when the bearing capacity of the compressive columns was completely lost, no fiber tensile damage occurred and only local fiber compression damage appeared.

![Figure 18: Fiber tensile and compression failure area distribution of compression columns at final failure state: (a) DCYG-A and (b) DCYG-B types.](image-url)
The degree of fiber compression damage in the ply45-1-1 layer was slightly more serious (see Figure 18b).

### 3.3.4 Failure analysis of matrix tensile and compression

Using the previously mentioned method, a comparative analysis was first performed. Based on the extent and degree of matrix tensile and compression damage to each fiber layer, the key objects for analysis were determined to be the ply0-1-1 and ply45-1-1 fiber layers. As shown in Figure 19a, the matrix stretching and compression damage range of the ply0-1-1 fiber layer of the DCYG-A type columns was small, while the degree of damage was low, and the occurrence time was relatively late. The damage did not occur until the compression member completely lost its bearing capacity. In contrast, the matrix stretching and compression damage range of the ply45-1-1 fiber layer of the DCYG-B type columns was slightly larger, while the degree of the matrix compression damage was more serious (see Figure 19b).

### 3.3.5 Shear failure analysis of the fiber layer

In terms of the shear damage failure of the fiber layer, the shear damage of the ply0-1-1 fiber layer of the DCYG-A columns was still the most serious, but the shear damage of the fiber layer occurred late, after the compression columns lost their bearing capacity, and the degree of shear damage was also very low (see Figure 20a). The shear damage of the

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**Figure 19:** Matrix tensile and compression failure area distribution of compression columns at final failure state: (a) DCYG-A and (b) DCYG-B.

**Figure 20:** Fiber layer shear failure area distribution of compression columns at different states: (a) DCYG-A and (b) DCYG-B.
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In general, for a laminate compressive column component with a single-channel cross section, the most important factor affecting the bearing performance was the interlaminar shear delamination damage failure between the layers of the laminate panel. The fiber tensile and compression damage failure, matrix tensile and compression damage, and fiber layer shear damage failure were secondary factors influencing the bearing capacity. However, the resistance to interlaminar delamination of the 0° fiber layer was the strongest, and this resistance decreased with the gradual increase in the fiber laying-angle from 0° to 90°. Therefore, the utilization of more 0° fiber layers could improve the axial compression bearing capacity of short columns, and the use of a certain number of fiber layers with fiber laying angles between 0° and 45° could increase the toughness of compression pillar columns against interlaminar shear delamination at the initial stage.

4 Theoretical prediction of safe bearing capacity

In the design of laminated columns, the laminates are composed of one-way plates stacked along the direction of thickness. The parameters of each one-way plate forming the laminates are symmetric with respect to the geometric middle surface, which is called a symmetric laminate. In this section, on the basis of the classic laminate theory and the characteristics of the symmetric laminates, a theoretical method is proposed for predicting the safe bearing capacity of channel cross-sectional compression columns. The total internal force in the cross section of the laminates is the sum of the internal forces in the cross section of each layer. If the stresses of all the one-way plates and the stresses on the middle moment are integrated along the thickness of the laminates, the resultant force and resultant moment on the unit width of the cross section of the laminates can be obtained, which are represented by \( N_x, N_y, N_{xy}, M_x, M_y, \) and \( M_{xy} \) (see Figure 21).

With regard to orthogonally laid and balanced oblique symmetric laminates, the internal force equations of the laminates are as follows:

\[
\begin{bmatrix}
N_x \\
N_y \\
N_{xy}
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} & 0 \\
A_{21} & A_{22} & 0 \\
0 & 0 & A_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_0^x \\
\varepsilon_0^y \\
\gamma_{xy}
\end{bmatrix}
\]  

(1)

Without losing generality, different profiles composed of symmetrical laminates with different fiber layups are subjected to axial loading (see Figure 22). A stress analysis can be carried out according to the classic lamination theory, assuming that the loading direction deforms uniformly. The laminated compressive column can be regarded as special-section members composed of several laminated panels, each of which constitutes the flanges and webs of I-shaped and Z-shaped compression column members. Because each laminate composed of a flange and web is a symmetrical laminate and only bears an axial compression load, \( N_y \) and \( N_{xy} \) in equation (1) are equal to zero. Therefore, equation (1) can be reduced to equation (2).

\[
\begin{bmatrix}
N_x \\
0 \\
0
\end{bmatrix} =
\begin{bmatrix}
A_{11} & A_{12} & 0 \\
A_{21} & A_{22} & 0 \\
0 & 0 & A_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_0^x \\
\varepsilon_0^y \\
\gamma_{xy}
\end{bmatrix}
\]  

(2)

In this case, equation (2) can be expanded to obtain the calculation formula for the axial load \( N_x \) of a laminated compression column under the action of an axial load, which can be expressed as follows:

\[
N_x = \left( A_{11} - \frac{A_{12}^2}{A_{22}} \right) \varepsilon_0^x = E_x S_x \varepsilon_0^x
\]

(3)

\[
E_x S_x = \left( A_{11} - \frac{A_{12}^2}{A_{22}} \right)
\]
In equation (3), $E_x$ and $S_x$ are the elastic moduli of the laminated columns in the x direction and the total cross-sectional area of the laminate pillar members, respectively. $A_{11}$ and $A_{22}$ are the tension and compression stiffness in the in-plane x and y directions, respectively, and $A_{12}$ is the in-plane Poisson stiffness. $e_{x}^{0}$ is the axial strain of the compression pillar member. In this manner, load $N_{xi}$ of the ith one-way plate can be expressed as follows:

$$N_{xi} = E_{xi}S_{i}e_{x}^{0} = E_{xi}b_{i}d_{i}e_{x}^{0}$$

(4)

where $E_{xi}$, $b_{i}$ and $d_{i}$ denote the elastic modulus in the x direction, width, and thickness of the unidirectional plate, respectively. Evidently, the axial force of the laminated compression columns is as follows:

$$F = N_{x} = \sum_{i=1}^{n} N_{xi} = \sum_{i=1}^{n} E_{xi}b_{i}d_{i}e_{x}^{0}$$

(5)

where $n$ is the total number of one-way plates of the laminated compression column members.

For the laminated compression column with a single-channel cross-section shown in Figure 23, by assuming that the strain generated by the compression bar in the x direction is $e_{x}^{0}$, equation (5) can be used to calculate axial load $F$. Before calculation, the necessary one-way plate division should be carried out for the laminated layup members. In this study, the laminated column with a single-channel cross section had a 5/4 configuration, and each fiber layer was composed of 3 CFRP unidirectional plates with a laying angle of $0^\circ$/$90^\circ$/$0^\circ$ or $45^\circ$/$0^\circ$/$-45^\circ$. In this way, the entire laminated pillar member was composed of 5 aluminum sheets and 12 CFRP one-way plates. At the same time, the special shape of the single-channel cross section determined that the 5 aluminum sheet layers and 12 CFRP one-way plate layers were used for the two flange plates and one web plate, respectively (see Figure 24).

Here, if the total strain of the compression column is determined according to the principle that the plastic strain of the aluminum sheet is equal to 0, the safe bearing capacity of the laminated pillar member under an axial compression load can be calculated. At this time, the total strain of the entire compression column is as follows:

$$\varepsilon_{x}^{0} = \frac{[\sigma_{Al}]}{E_{Al}}$$

(6)

where $[\sigma_{Al}]$ is the plastic strain of the 2024-T3 aluminum alloy, which is equal to the yield stress at zero. $E_{Al}$ is the Young’s modulus of the 2024-T3 aluminum alloy. In this case, the formula for calculating the safe bearing capacity of the laminated compression pillar member can be deduced according to Figure 24 and equation (5). The specific formula is as follows:

$$[F] = \sum_{i=1}^{m} \sum_{j=1}^{n} E_{xi}b_{ij}d_{ij} \left[ \frac{[\sigma_{Al}]}{E_{Al}} \right] + \sum_{k=1}^{n} \sum_{l=1}^{m} b_{kl}t_{kl}[\sigma_{Al}]$$

(7)

where $b_{ij}$ and $d_{ij}$ are the width and thickness of the unidirectional CFRP sheet, respectively. $E_{xi}$ is the Young’s modulus of elasticity in the x direction for the unidirectional CFRP sheets, where $i$ increases from 1 to 12, and $j$ increases from 1 to 3. $b_{kl}$ and $t_{kl}$ are the width and thickness of the aluminum alloy sheet layer, respectively, where $k$ increases from 1 to 5, and $l$ increases from 1 to 3.

Finally, according to equation (7), the safe bearing capacities of the compression column members with two kinds of fiber layup configurations are as follows. The safe bearing capacity of the compression pillar members with a $0^\circ$/$90^\circ$/$0^\circ$ fiber ply is 190.22 kN, and the safe bearing capacity of the compression pillar members with a $45^\circ$/$0^\circ$/$-45^\circ$ fiber ply is 151.08 kN.
Table 5: Comparison of safe bearing capacities of axial compression columns (unit: kN).

| Number of the specimen | Theoretical value | Experimental result | Relative error | Numerical solution | Relative error |
|------------------------|-------------------|---------------------|----------------|--------------------|----------------|
| DCYG-A-1               | 190.22            | 174.87              | 8.7%           | 181.81             | 4.6%           |
| DCYG-A-2               | 190.22            | 181.89              | 5.6%           | 181.81             | 4.6%           |
| DCYG-A-3               | 190.22            | 176.97              | 7.5%           | 181.81             | 4.6%           |
| DCYG-A-4               | 190.22            | 173.86              | 9.4%           | 181.81             | 4.6%           |
| DCYG-A-5               | 190.22            | 178.35              | 6.6%           | 181.81             | 4.6%           |
| DCYG-B-1               | 151.08            | 139.33              | 8.4%           | 145.65             | 3.0%           |
| DCYG-B-2               | 151.08            | 138.97              | 8.7%           | 145.65             | 3.0%           |
| DCYG-B-3               | 151.08            | 137.85              | 9.6%           | 145.65             | 3.0%           |
| DCYG-B-4               | 151.08            | 144.13              | 4.8%           | 145.65             | 3.0%           |
| DCYG-B-5               | 151.08            | 143.29              | 5.4%           | 145.65             | 3.0%           |

5 Comparison of safe bearing capacity obtained by different methods

When testing the bearing capacity under axial compression of 10 groups with $0^\circ/90^\circ/0^\circ$ and $45^\circ/0^\circ/-45^\circ$ fiber layup structures, the safe bearing capacity of each compression specimen was obtained by monitoring the stress level on the outer aluminum alloy sheet. Herein, when the stress at the monitoring point located in the outer aluminum alloy sheet reached 300 MPa, the corresponding axial compressive load was defined as the safe bearing capacity of the compression pillar member. In other words, when the plastic strain was zero, the axial compression bearing load was the so-called safe bearing capacity, as summarized in Table 5. Correspondingly, the numerical and theoretical results for the safe bearing capacity were obtained and compared with the experimental results. As shown in the table, the errors between the predicted values and numerical solutions, as well as between the predicted theoretical values and experimental results, were within 10%. This comparison indicated that the theoretical and numerical methods could be used in the design scheme to predict the safe bearing capacity of designed CARALL short columns subjected to axial compression loads.

6 Conclusions

The axial compression bearing capacity and failure mechanism of compressive short columns composed of the designed CFRP-aluminum alloy laminated panels with a single-channel cross section were experimentally tested and numerically studied. A theoretical method for predicting the safe bearing capacity of the designed laminated members was also proposed. The major findings of this research can be summarized as follows.

The final failure mode of the compression columns obtained by numerical simulation analyses was consistent with the test results. Because the member length-to-height ratio was small and the thickness of the laminate panel was large, all the specimens showed strength damage failure modes. The single-channel cross-sectional laminated compressive columns with a fiber overlay of $45^\circ/0^\circ/-45^\circ$ were the same as those with a fiber overlay of $0^\circ/90^\circ/0^\circ$, and the ultimate failure of the compressive components was mainly caused by the delamination failure between layers. The damage failure of the aluminum sheet, the tensile or compressive failure of the fiber matrix of the CFRP prepregs, and the shear failure of the fiber layer also occurred in the final collapsed state.

The resistance to interlaminar delamination of the $45^\circ$ fiber layers was weaker than that of the $0^\circ$ fiber layers, but stronger than that of the $90^\circ$ fiber layers. Therefore, when subjected to an axial compressive load, the fiber spread angle of the CFRP prepregs in the laminate panels had a significant influence on the resistance to interlaminar delamination. A smaller fiber laying angle led to greater resistance to interlaminar delamination. There were only 3 layers of CFRP prepregs with a $90^\circ$ laying angle in the column with the $0^\circ/90^\circ/0^\circ$ fiber layup configuration, while there were 6 layers of CFRP prepregs with a $45^\circ$ laying angle in the column with the $45^\circ/0^\circ/45^\circ$ fiber layup configuration. This is why the axial compression bearing capacity of the $[45^\circ/0^\circ/-45^\circ]_3$ type column was weaker than that of the $[0^\circ/90^\circ/0^\circ]_3$ type columns.

The axial compression loads resulting in initial delamination failures of the $0^\circ$, $90^\circ$, and $45^\circ$ fiber layers showed
significant discrepancies. This indicated that in the initial stage of the axial pressure loading action, the 45° fiber layer had greater resistance to interlaminar delamination. Therefore, the use of more 0° fiber layers could improve the axial compression bearing capacity of the laminated column members, and the use of a certain number of fiber layers with fiber laying angles between 0° and 45° could increase the resistance of the compression columns to interlaminar shear delamination at the initial stage.

The comparisons of the experimental, numerical, and theoretical results showed that they had good agreement. The proposed theoretical method based on the classic laminate theory and the principle of equal strain in the material mechanics is thus feasible for predicting the safe bearing capacity of the designed CFRP-aluminum alloy laminated panel with a single-channel cross section and could be applied to the design of compressive laminate pillar components.

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