Experimental and Numerical Simulation Studies of Failure Behaviour of Carbon Fibre Reinforced Aluminium Laminates under Transverse Local Quasi-static Loading

Teng Huang, Yaxin Huang*, Yuan Lin and Xuezhi Yin
College of Field Engineering, PLA Army Engineering University, Nanjing, Jiangsu Province, China

*Corresponding author email: puyu.wang@njust.edu.cn

Abstract. This paper investigated the failure behaviour of medium thick carbon fibre reinforced aluminium laminates (CARALL) panels under transverse local quasi-static contact crush experimentally and numerically. Four types of CARALL specimens with a 3/2 configuration were manufactured by hot-pressing process using two type of aluminium alloys (2024-T3, 7075-T6 aluminium alloy) and CFRPs with different lay-up ([0°/90°/0°]3, [45°/0°/-45°]3). Three dimensional Hashin progressive failure model in quadratic strain form with damage evolution laws defined by subroutine VUMAT based on ABAQUS was used to simulate the composite layers. The bilinear cohesive contact model was used to predict interfacial failure. Aluminium alloys were defined by Johnson-Cook model. Numerical predictions composing of load-deflection curves and failure mode were matched closely with experimental results. The results of the analysis shown that delamination in CFRP/Al interfaces was the initial damage of the tested CARALL panels. Matrix failure occurred after the delamination closely. The maximum load bearing was determined by fracture of aluminium alloy. Fibre breakage was responsible for complete failure of specimens.

Keywords: Numerical simulation analysis; Progressive damage analysis; Carbon fibre reinforced aluminium laminates; Transverse quasi-static loading; VUMAT.

1. Introduction

Composite materials can be applied in emergency bridging equipment, in order to satisfy their primary requirements: lightweight for transport facilities, modular feasibility, and faster construction. Fibre reinforced polymer (FRP) has shown its superiority in improving structural properties as earlier composite material used in emergency bridging equipment [1]. Nonetheless, the poor impact resistance and residual strength properties of FRP have restricted its more use in the field of emergency bridging equipment which usually work in harsh environmental conditions. Glass fibre reinforced aluminium laminates (GLARE) and carbon fibre reinforced aluminium laminates (CARALL) was well known by high fatigue crack growth resistance, high strength/stiffness ratio and high impact resistance [2]. The presence of GLARE applied in the fuselage of Airbus A380 [3-5] proves that FMLs as classical laminates have become very efficient structural materials used in lightweight structure with the development of successful study on etched aluminium and on adhesive bonding [6]. Compared with GLARE, CARALL exhibit higher specific modulus [7], better impact resistance [8,9] considered as fibre-dominant damage, and higher strength [10,11]. However, the most important disadvantage of CARALL which prevented it from practical use was corrosion. In theory, CARALL can be fabricated into bearing structures for different engineering applications by arranging...
different orientation of carbon fibre prepregs and stacking sequences [12]. Thus CARALL show the potential practical use in emergency bridging equipment. In order to investigate the applicability of CARALL in bridge decks of emergency bridging equipment, it is necessary to study the load bearing properties of medium thick CARALL panels under simulated local uniform load of wheeled vehicle. Quasi-static indentation and dynamic load tests are basic measurements to evaluate the out-of-plan properties of FMLs panels. In previous research, most investigation objects were focused on GLARE [13-15] and a small number of studies were worked on CARALL. Bieniaś et al [16] compared the impact behaviour and damage characterization between CARALL and CFRP. The failure sequence were not studied from their research. Jakubczak et al [17] compared the mechanical response of FMLs in the form of glass and carbon fibre aluminium laminates to dynamic and static loads together. Romli [18] investigated the failure behaviour of CARALL with different lay-up under quasi-static indentation and visible failure modes were observed. Most previous researches [16-18] used experimental methods to study failure behaviours of CARALL panels under quasi-static load, which have difficulties in successfully capturing the hidden failure modes and process before any macro failure occur. Therefore, it is important to predict mechanical response of CARALL panels under quasi-static load by numerical simulations.

Finite element methods based on progressive damage model have been proven effective to simulate the failure behaviour of composite materials [19-21]. Over the past decades, several failure criteria have been developed including Tsai-Wu criteria [22] and Hashin criteria [23-24]. Compared with Tsai-Wu criteria, Hashin criteria can identify the detailed failure modes. It is worth noting that the failure criteria generally have two sorts of expressions including two dimensions which neglect the out of plane effect and three dimensions. Fan et al. [25] applied an elastoplastic material model to the aluminium layers of FMLs, while 2D Hashin criteria was applied to predict the the damage initiation of the fibre layers. Delamination was not modelled. Dhaliwal et al. [26] modeled the carbon fibre layers using 2D Chang–Chang failure criteria implemented in LS-DYNA. However, the built-in 2D failure criteria for composite layers were not suitable for thick layers of composite laminates. Thus, composite layers simulated by 2D failure model might result in imprecise prediction of the whole laminates. Yu et al. [27] used the Johnson–Cook model to simulate damage of aluminium layer with different properties of aluminium alloy (e.g. 1060-O, 2024-T3, 6061-T6 and 7075-T6), while the damage initiation and evolution of CFRP was modeled by Hashin 3D progressive damage model. Liu et al. [28] compared the Abaqus in-built 2D progressive damage model using continuum shell elements with the 3D Hashin progressive model using solid elements for predicting the tensile failure in single-lap bolted composite joints. Jia et al. [29] wrote a user-defined subroutine (VUMAT) for ABAQUS/EXPLICIT solver to analyse thick composite structural failure. The results proved 3D model was much more suitable for out of plane loading.

The aim of this paper is to study mechanical behaviour and failure modes of CARALL medium thick panels with two types of Aluminium alloys layers (2024-T3, 7075-T6) and two layup configurations of the CFRP ([0°/90°/0°]3, [45°/0°/-45°]3) under simulated local uniform load of wheeled vehicle experimentally and numerically. 3D Hashin progressive model used for CFRP implemented by user-subroutine VUMAT was written for ABAQUS/Explicit solver to predict complex failure modes including fibre tension failure, fiber compression failure, matrix tension failure and matrix compression failure. Johnson-Cook flow stress model was used to to predict the mechanical response of the Aluminium alloys layers and the adhesive layers with Al/CFRP was modeled by surface-based cohesive contacts. Numerical mechanical responses and failure modes were compared and validated by experimental ones. Besides, failure sequences for CARALL panels were elaborated based on the established model.

2. Experimental Procedures

2.1. Object of the Study

The CARALL panels are manufactured from unidirectional carbon fiber composite and aluminium alloy sheets by hand lay-up method. The prepreg used in this experiment was carbon fiber reinforced epoxy resin material (T700/YPH-307) with fiber volume content of 57% and thickness of 0.125 mm
provided by Sichuan XinWanXing Carbon Fibre Composites Co. Ltd. Different properties of aluminium alloy materials used in the CARALL was 2 mm thick. First of all, the surfaces of the aluminium sheet were washed with water to keep the surface clean, and then the phosphoric acid anodizing according to HB/Z 1987–1991 standard was conducted for the surfaces to improve the bonding effects between CFRP layers and aluminium layers. Additionally, a layer of epoxy resin was laid between the aluminum and fiber layer as an adhesive layer, which could also isolate carbon fibre from aluminium to prevent galvanic corrosion. Finally, the hand-layup laminates were sealed in a vacuum bag and cured in an autoclave. Panel 3/2 consists of three layers of aluminium alloy and two layers of CFRP. There are nine plies of carbon fiber in each layer of CFRP. Details of the laminates are given in Table 1.

Table 1. Specimen notations, layup sequence and dimensions for CARALL fibre metal laminates.

| Specimen designation | Layup sequence | Aluminium | Total thickness (mm) | Length (mm) | Width (mm) |
|----------------------|----------------|-----------|----------------------|-------------|------------|
| CARALL-A             | Al/[0/90/0]/Al/[0/90/0]/Al | 7075-T6   | 8.25                 | 500         | 408        |
| CARALL-B             | Al/[45/0/-45]/Al/[45/0/-45]/Al | 7075-T6   | 8.25                 | 500         | 408        |
| CARALL-C             | Al/[45/0/-45]/Al/[45/0/-45]/Al | 2024-T3   | 8.25                 | 500         | 408        |
| CARALL-D             | Al/[0/90/0]/Al/[0/90/0]/Al | 2024-T3   | 8.25                 | 500         | 408        |

2.2. Transverse Local Quasi-Static Contact Crush Test and Boundary Conditions
In order to test the load bearing performance of CARALL panels under transverse local uniform distributed load and meet the surrounding clamped boundary conditions of the bridge deck structure, special clamping system simulating boundary constraints of CARALL panels and loading block simulating wheeled load shown in Figure 1 were designed and prepared. The experimental auxiliary device was made by steel. Considering the reuse and easy fixation, the boundary constraint of the fixed end of the panels was simulated by adding a cover plate and bolting. Each side was secured with two 8.8-class M10 high-strength bolts. The size of the loading block was designed with reference to the grounding dimension of wheeled load. The test on CARALL was implemented using MTS 1000KN universal testing machine made in Germany. As a control group, CARALL-A was stopped to be loaded when the load dropped for the first time. Other tests on panels were not stopped until the load dropped significantly. Tests were performed at a constant velocity of 2 mm/min. The force and corresponding deflection were recorded by MTS universal test systems. Figure 2 shows the transverse local quasi-static contact crush test setup.
Figure 1. Configuration of the loading block and the clamping system (dimensions in mm).

Figure 2. Schematic of transverse local quasi-static contact crush test setup.

3. Progressive Damage Models for CARALL

Commercial Finite Elements Method software ABAQUS 6.12 was conducted for numerical analyses of the transverse quasi-static loading test on CARALL. First, the damage and fracture of composite materials are highly material nonlinear problems. Second, the results of the standard solution are poorly convergent because of the degradation of material properties. Third, it takes a long time to calculate and is difficult to obtain the bearing capacity of the structure. Considering the problems mentioned above, this paper used explicit time integration scheme with ABAQUS/Explicit to simulate the quasi-static tests. In the explicit analysis, displacement loading of 55 mm along the loading direction was set up to the loading block within 0.07 s. During this time, kinetic energy was less than 1% of the internal energy, which is a valid evidence to solving quasi-static problems in an explicit
analysis. The amplitude curve used to define displacement as a function of time was set to smooth step.

3.1. Discrete Model of CARALL Specimen

Schematic of a finite element analysis model is presented in Figure 3. The aluminium layers and the CFRP layers were modeled by eight node solid brick elements (C3D8R). Each CFRP ply with a particular orientation was meshed with one solid element in thickness direction. Owing to limitation of computing resources, the size of element was decided to be 1×1 mm2 in the area which is under pressure and 5×5 mm2 in the rest. The delamination between Aluminium layers and CFRP layers was modeled by a cohesive zone model using the surface-based cohesive contact, and a shared nodes connection was defined between adjacent CFRP plies. The coefficient of friction of 0.3 provided by Shi is proper for the interfaces between Aluminium and CFRP layers [30]. Both loading block and fixtures were modeled by means of R3D4 rigid finite elements. Fixtures were fixed in all degrees of freedom. General contact with a coefficient of friction which is equal to one was adopted to assumed for the interaction between the loading block and specimen, while the tie constraint was defined to simulate the interaction between the fixtures and specimen.

![Finite element model of transverse local quasi-static loading test.](image)

Figure 3. Finite element model of transverse local quasi-static loading test.

3.2. Johnson-Cook Model of Aluminium Layers

Johnson–Cook flow stress model was used for aluminium layers to predict the mechanical response and is expressed as:

\[
\sigma = \left[ A + B \varepsilon_p^n \right] \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - T^m \right]
\]  

(1)

where \(A\), \(B\) and \(C\) are material parameters, \(\varepsilon_p\) is the equivalent plastic strain, \(n\) and \(m\) are material constant, \(\dot{\varepsilon}\) and \(\dot{\varepsilon}_0\) are the reference strain and equivalent plastic strain rate. \(T^*\) is the homologous temperature is equal to zero because the effect of temperature variation is not taken into account in this work.

Failure is assumed to occur when the damage parameter \(D\) equals to one, which is predicted using the following law:

\[
D = \sum \left( \frac{\Delta E_{pl}}{E_p^f} \right)
\]  

(2)
To simulate the ductile damage in the aluminium layers, Johnson–Cook damage criterion was used here to judge damage initiation by equivalent plastic strain, which is expressed as:

$$\bar{\varepsilon}_{D}^{\text{pl}} = \left( d_1 + d_2 e^{-d_3 \eta} \right) \left( 1 + d_4 \ln \frac{\dot{\varepsilon}_{\text{pl}}}{\dot{\varepsilon}_0} \right)$$  \hspace{1cm} (3)

where $\eta$ is the stress triaxiality parameter and $d_1$-$d_4$ are material parameters. The material properties and parameters used in Johnson–Cook model are listed in Table 2.

### Table 2. Material properties of aluminium alloy.

| Materials properties | 2024-T3[31] | 7075-T6[32] |
|----------------------|-------------|-------------|
| Elastic parameters   | $E=70$GPa, $\mu=0.33$ | $E=70$GPa, $\mu=0.33$ |
| Yield surface parameters | $A=369$MPa, $B=684$MPa | $A=546$MPa, $B=678$MPa |
| $C=0.0083$MPa, $m=1$, $n=0.73$ | $C=0.024$MPa, $m=1$, $n=0.71$ |
| Failure parameters   | $d_1=0.13$, $d_2=0.13$ | $d_1=-0.068$, $d_2=0.451$ |
| $d_3=-1.5$, $d_4=0.011$ | $d_3=-0.952$, $d_4=0.036$ |
| Fracture energy      | $G_{ic}=8$KJ/m² | $G_{ic}=8$KJ/m² |

### 3.3. Failure Criteria and Damage Evolution Law of CFRP Layers

Considering the limitations of 2D Hashin’s failure criteria, a three-dimensional failure criteria which was based on 3D Hashin criteria in quadratic strain and characters mechanical properties of composite material was developed through user-subroutine VUMAT. In the criteria, four different damage initiation mechanisms are involved, which are as follows:

**Fibre tension:**

$$\left( \frac{\varepsilon_{11}}{\varepsilon_{11}^{0c}} \right)^2 + \left( \frac{\varepsilon_{12}}{\varepsilon_{12}^{0c}} \right)^2 + \left( \frac{\varepsilon_{13}}{\varepsilon_{13}^{0c}} \right)^2 \geq 1 \hspace{0.5cm} (\varepsilon_{11} \geq 0)$$  \hspace{1cm} (4)

**Fibre compression:**

$$\left( \frac{\varepsilon_{11}}{\varepsilon_{11}^{0c}} \right)^2 \geq 1 \hspace{0.5cm} (\varepsilon_{11} < 0)$$  \hspace{1cm} (5)

**Matrix tension:**

$$\left( \frac{\varepsilon_{22} + \varepsilon_{33}}{\varepsilon_{22}^{0c} \cdot \varepsilon_{22}^{0c}} \right)^2 + \frac{1}{\varepsilon_{22}^{0c}} \left( \varepsilon_{22} - \varepsilon_{22} \varepsilon_{33} \right) + \left( \frac{\varepsilon_{12}}{\varepsilon_{12}^{0c}} \right)^2 + \left( \frac{\varepsilon_{13}}{\varepsilon_{13}^{0c}} \right)^2 \geq 1 \hspace{0.5cm} (\varepsilon_{22} + \varepsilon_{33} \geq 0)$$  \hspace{1cm} (6)

**Matrix compression:**

$$\left( \frac{\varepsilon_{22} + \varepsilon_{33}}{\varepsilon_{22}^{0c} \cdot \varepsilon_{22}^{0c}} \right)^2 + \frac{\varepsilon_{22} + \varepsilon_{33}}{\varepsilon_{22}^{0c} \cdot \varepsilon_{22}^{0c}} + \left( \frac{\varepsilon_{12}}{\varepsilon_{12}^{0c}} \right)^2 + \left( \frac{\varepsilon_{13}}{\varepsilon_{13}^{0c}} \right)^2 \geq 1 \hspace{0.5cm} (\varepsilon_{22} + \varepsilon_{33} < 0)$$  \hspace{1cm} (7)

where $\varepsilon_{11}$, $\varepsilon_{22}$, $\varepsilon_{33}$ are components of strain tensor which are along the fiber direction, along the transverse direction of fibre, along the stacking direction, $\varepsilon_{12}$, $\varepsilon_{13}$, $\varepsilon_{23}$ are in-plane and out-of-plane shear strains. $\varepsilon_{11}^{0c}$, $\varepsilon_{11}^{0c}$ are initial tensile and compressive failure strains in the longitudinal direction. $\varepsilon_{22}^{0c}$, $\varepsilon_{22}^{0c}$ are initial tensile and compressive failure strains in the transverse direction. $\varepsilon_{12}^{0c}$, $\varepsilon_{13}^{0c}$, $\varepsilon_{23}^{0c}$ are initial in-plane and out-of-plane shear failure strains. These initial failure strain components are defined as follows:

$$\varepsilon_{11}^{0c} = \frac{X^T}{C_{11}}, \hspace{0.5cm} \varepsilon_{11}^{0c} = \frac{X^C}{C_{11}}$$  \hspace{1cm} (8)
\[ \epsilon_{22}^{0,T} = \frac{Y^T}{C_{22}}, \quad \epsilon_{22}^{0,C} = \frac{Y^C}{C_{22}} \]  

(9)

\[ \epsilon_{12}^{0} = \frac{S_{12}}{C_{12}}, \quad \epsilon_{13}^{0} = \frac{S_{13}}{C_{13}}, \quad \epsilon_{12}^{0} = \frac{S_{23}}{C_{23}} \]  

(10)

where \( Y^T, Y^C \), \( Y^T, Y^C \) denote the longitudinal tensile strength, the longitudinal compressive strength, the transverse tensile strength, the transverse compressive strength respectively. \( S_{12}, S_{13}, S_{23} \) are shear strength in three planes of material. \( C_{ij} \) is the stiffness coefficient.

In finite element analysis, the strains computed at integration points in the structure are substituted into the failure criteria. Once the failure initiation criterion is satisfied, further loading will result in degradation of the materials stiffness as a function of the damage variable. The damaged stiffness matrix is illustrated as:

\[ C_{11}' = (1 - d_f)C_{11} \]  

(11)

\[ C_{22}' = (1 - d_f)(1 - d_m)C_{22} \]  

(12)

\[ C_{33}' = (1 - d_f)(1 - d_m)C_{33} \]  

(13)

\[ C_{12}' = (1 - d_f)(1 - d_m)C_{12} \]  

(14)

\[ C_{23}' = (1 - d_f)(1 - d_m)C_{23} \]  

(15)

\[ C_{13}' = (1 - d_f)(1 - d_m)C_{13} \]  

(16)

\[ C_{44}' = \left(1 - d_f\right)(1 - s_{nt} \times d_{nt})(1 - s_{mc} \times d_{mc})C_{44} \]  

(17)

\[ C_{55}' = \left(1 - d_f\right)(1 - s_{nt} \times d_{nt})(1 - s_{mc} \times d_{mc})C_{55} \]  

(18)

\[ C_{66}' = \left(1 - d_f\right)(1 - s_{nt} \times d_{nt})(1 - s_{mc} \times d_{mc})C_{66} \]  

(19)

\[ d_f = 1 - \left(1 - d_{f,t}\right)(1 - d_{f,c}) \]  

(20)

\[ d_m = 1 - \left(1 - d_{m,t}\right)(1 - d_{m,c}) \]  

(21)

\( S_{nt} \) and \( S_{mc} \) are provided to define reduction of shear stiffness caused by tensile and compressive failure in the matrix, which equal to 0.9 and 0.5, respectively.
Figure 4. Typical constitutive relation of composite materials in Abaqus model.

In the present work, linear evolution laws are used to reduce the stiffness coefficients. Figure 4 shows the typical curve of the linear evolution laws. The reduction of stiffness coefficients is controlled by damage variables $d_f$, $d_c$, $d_m$, and $d_m$, which represent the fibre tension damage, fibre compression damage, matrix tension damage, and matrix compression damage, respectively. The damage variables which take values between zero (undamaged state) and one (fully damaged state) evolve according to equations:

$$d_f = \frac{\delta_{11}^f (\delta_{11} - \delta_{11}^0)}{\delta_{11} (\delta_{11}^f - \delta_{11}^0)}$$  \hspace{1cm} (22)

$$d_c = \frac{\delta_{11}^c (\delta_{11} - \delta_{11}^0)}{\delta_{11} (\delta_{11}^c - \delta_{11}^0)}$$  \hspace{1cm} (23)

$$d_m = \frac{\delta_{22}^m (\delta_{22} - \delta_{22}^0)}{\delta_{22} (\delta_{22}^m - \delta_{22}^0)}$$  \hspace{1cm} (24)

$$d_m = \frac{\delta_{22}^m (\delta_{22} - \delta_{22}^0)}{\delta_{22} (\delta_{22}^m - \delta_{22}^0)}$$  \hspace{1cm} (25)

where $\delta_{eff}^i$ (i=1,2; j=t,c) is the equivalent displacement associated with the material is completely damaged for a particular failure mode, $\delta_{0i}^j$ (i=1,2; j=t,c) corresponds to the equivalent displacement of damage initiation in this failure mode. In order to avoid the dependence of the element failure behavior on the element scale, a characteristic length $L_c$ which equals to the cube root of the volume for solid element is introduced. Equations for failure displacements and relations between characteristic length and equivalent strains are listed below:

$$\delta_{11}^0 = \frac{2G_{fc}}{X^T}, \quad \delta_{11} = L_c \cdot \varepsilon_{11}, \quad \delta_{11}^0 = L_c \cdot \varepsilon_{11}^0 = L_c \cdot \frac{X^T}{C_{11}}$$  \hspace{1cm} (26)

$$\delta_{11}^c = \frac{2G_{fc}}{X^C}, \quad \delta_{11} = L_c \cdot \varepsilon_{11}^c = L_c \cdot \frac{X^C}{C_{11}}$$  \hspace{1cm} (27)

$$\delta_{22}^f = \frac{2G_{mc}}{Y^T}, \quad \delta_{22} = L_c \cdot \varepsilon_{22}, \quad \delta_{22}^0 = L_c \cdot \varepsilon_{22}^0 = L_c \cdot \frac{Y^T}{C_{22}}$$  \hspace{1cm} (28)
where $G_{ftc}$, $G_{fcc}$, $G_{mtc}$ and $G_{mcc}$ are the fracture energy corresponding to four failure mode mentioned above. The material properties of T700 carbon fibre/epoxy prepreg provided by the raw materials supplier are shown in Table 3.

### Table 3. Material properties of T700 carbon fibre/epoxy prepreg.

| $E_1$(MPa) | $E_2$(MPa) | $E_3$(MPa) | $v_{12} = v_{13} = v_{23}$ | $G_{12}$(MPa) | $G_{13}$(MPa) | $G_{23}$(MPa) |
|------------|------------|------------|------------------|--------------|--------------|--------------|
| 101,510    | 7800       | 7800       | 0.32             | 4000         | 4000         | 3600         |
| $\rho$(kg/m³) | $X^t$(MPa) | $X^s$(MPa) | $Y^t$(MPa) | $Y^s$(MPa) | $Z^t$(MPa) | $Z^s$(MPa) |
| 2032       | 2050       | 1240       | 50              | 150          | 150          |
| $S_{12}$(MPa) | $S_{13}$(MPa) | $S_{23}$(MPa) | $G_{mc}$(kJ/m²) [34] | $G_{mc}(kJ/m²)$ [34] |
| 93         | 93         | 50         | 40              | 40           |
| $G_{mc}(kJ/m²)$ [34] | $G_{mc}(kJ/m²)$ [34] |
| 0.25        | 0.75       |

3.4. Interfacial Failure Criteria and Damage Evolution Laws

The cohesive model can be achieved by using cohesive elements or cohesive contacts. Due to saving computation time, the delamination between Aluminium layers and CFRP layers in this paper was modeled by surface-based cohesive contacts which is capable of modeling the frictional behaviour of debonded or partially debonded surfaces [35]. The bilinear constitutive relationship of surface-based cohesive prior to damage initiation is expressed as follows:

$$
\begin{bmatrix}
\sigma_n \\
\sigma_s \\
\sigma_t
\end{bmatrix} =
\begin{bmatrix}
K_m & K_{sv} & 0 \\
K_{sv} & K_n & 0 \\
0 & 0 & K_t
\end{bmatrix}
\begin{bmatrix}
\delta_n \\
\delta_s \\
\delta_t
\end{bmatrix}
$$

(30)

where $\sigma_n$, $\sigma_s$ and $\sigma_t$ are normal contact stress in the pure normal mode, shear contact stress along the first shear direction, shear contact stress along the second shear direction, respectively. $\delta_n$, $\delta_s$ and $\delta_t$ are separation displacements corresponding to the three modes mentioned above. The quadratic stress criterion adopted to judge the damage initiation of interfacial failure is given as:

$$
\left(\frac{\sigma_n}{N_{max}}\right)^2 + \left(\frac{\sigma_s}{S_{max}}\right)^2 + \left(\frac{\sigma_t}{T_{max}}\right)^2 = 1
$$

(31)

where $N_{max}$, $S_{max}$ and $T_{max}$ represent the peak strength of fracture mode I, II and III, respectively. Once the damage initiation criterion is satisfied, the stresses associated with fracture modes are degraded by the damage variable $D$ which ranges from zero to one according to reduction laws:

$$
\sigma_n = \begin{cases} 
(1-D)\bar{\sigma}_n, & \bar{\sigma}_n \geq 0 \\
\bar{\sigma}_n, & \bar{\sigma}_n < 0 
\end{cases}
$$

(32)

$$
\sigma_s = (1-D)\bar{\sigma}_s
$$

(33)

$$
\sigma_t = (1-D)\bar{\sigma}_t
$$

(34)

The BK law (Benzegagh-Kenane) which is damage propagation criterion of mixed mode behavior based on energy is used to simulate damage evolution. $D$ is the damage evolution variable which means complete delamination, while the value equals to one. The expression of $D$ during a linear degradation stage is listed below:
\[ D = \frac{\delta_m' \left( \delta_{m}^{\max} - \delta_m^0 \right)}{\delta_{m}^{\max} \left( \delta_m' - \delta_m^0 \right)} \]  

(35)

where \( \delta_m^{\max} \) denotes maximum value of equivalent displacement during the entire loading process, \( \delta_m' \) is equivalent displacement corresponding to failure initiation and \( \delta_m^0 \) is equivalent displacement corresponding to complete damage. Subscript \( m \) accounting for the contact separation is caused by mixed effect of deformation in normal mode and shear mode, which can be calculated as:

\[ \delta_m^0 = \sqrt{\left( \delta_n \right)^2 + \delta_s^2 + \delta_t^2} \]  

(36)

\[ \delta_{m}^{\max} = \max(\delta_{m}^{\max}, \delta_m^0) \]  

(37)

\[ \delta_m' = \frac{2G_C}{T_0^{\text{eff}}} \]  

(38)

Here, \( G_C \) and \( T_0^{\text{eff}} \) are equivalent fracture toughness for complete damage and Equivalent stress at the beginning of damage, which can be expressed as:

\[ G_C = G_{IC} + \left( G_{IIC} - G_{IC} \right) \left( \frac{G_{II} + G_{III}}{G_{I} + G_{II} + G_{III}} \right)^\eta \]  

(39)

\[ T_0^{\text{eff}} = \sqrt{\left( \sigma_n \right)^2 + \left( \sigma_s \right)^2 + \left( \sigma_t \right)^2} \]  

(40)

where \( G_I, G_{II} \) and \( G_{III} \) are strain energy release rate in the normal, first and second shear directions. \( G_{IC}, G_{IIC} \) and \( G_{IIC} \) are Mode I, Mode II and Mode III fracture toughness respectively, and \( \eta \) is the damage parameter. Material properties of adhesive layers adopted from published literatures are listed in Table 4.

**Table 4.** Material properties of cohesive layers [33].

| \( \eta \) | \( K_{sn}=K_{st}=K_s \)(N/mm³) | \( N_{max} \)(MPa) | \( S_{max}=T_{max} \)(MPa) | \( G_{IC} \)(N/mm) | \( G_{IIC}=G_{III} \)(N/mm) |
|---|---|---|---|---|---|
| 1.45 | 10⁶ | 40 | 50 | 0.25 | 0.75 |

4. Results and Discussion

4.1. Experimental Analysis

Equilibrium curves obtained experimentally for four tested FML panels with different lay-up arrangement are presented in Figure 5. They looked like a convex parabola shape. Approximate linear response could be observed on the initiation of load-deflection curves. At the initial linear stage, the slope of the equilibrium path of CARALL-B was slightly larger than others’. The initial stiffness of rest three specimens were basically the same. As the deflection increased, the load value began to fluctuate up and down. This phenomenon is named as the “platform response” in this paper. No obvious damage corresponding to this phenomenon was observed during the experimental progress. Therefore, it conforms that it is necessary to employ progressive damage analysis to reveal the invisible failure mechanisms. Different trigger loads of platform response and corresponding deflection values were displayed in Table 5 from which the load of CARALL-B equals to 131 kN is larger than the load values of other panels (5%-11%). According to the description above, CARALL-B has better stiffness and load carrying capacity in the linear segment. After the stage of the platform, the resistance in the specimens was enhanced continuously and significantly with the increase of the deflection. Then, the load rose and fell violently until complete failure. Plastic deformation of failure specimens was obvious. This corresponded to the results as Bieniaś et al. [16] reported. As seen in Table 6, the ultimate loads of the tested planes are approximate 200 kN, even the largest differences between CARALL-B and others are only about 5% obtained experimentally. From Figure 5, it is
observed that the deflections corresponding to the ultimate loads of CARALL-C and CARALL-D using 2024-T3 aluminium layers are larger than that of the CARALL-A and CARALL-B. Based on all presented results, it is visible that at the initial linear stage, CARALL-B has better stiffness and higher load value by using 7075-T6 aluminium alloy and the fibre arrangement [45°/0°/-45°]3. Nonetheless, the lay-up of composite layers and yield strength of Aluminium alloy layers have rather not decisive influence on the ultimate load value of analytical FML panels under surrounding clamped boundary conditions. According to the experimental curves, it was speculated that the structure of the specimens were damaged during the experiment. Structural failure reduced the influence of strength of the aluminium and fiber laying orientations on the ultimate load. Additionally, 2024-T3 aluminium layers can contribute additional ductility of the specimens. The fibre arrangement [45°/0°/-45°]3 postpone complete failure of the specimen.

Figure 5. Load-deflection curves of tested CARALL panels.

Table 5. Experimentally obtained platform trigger loads and corresponding deflection for panels.

| Type of panels | platform trigger load(kN) | Deflection(mm) |
|----------------|---------------------------|----------------|
| CARALL-A: Al/[0/90/0]3/Al/[0/90/0]3/Al | 117.5 | 18.7 |
| CARALL-B: Al/[45/0/-45]3/Al/[45/0/-45]3/Al | 131 | 19.8 |
| CARALL-C: Al/[45/0/-45]3/Al/[45/0/-45]3/Al | 121.8 | 18.9 |
| CARALL-D: Al/[0/90/0]3/Al/[0/90/0]3/Al | 124.9 | 19.7 |

Table 6. Experimentally obtained critical loads and corresponding deflection for panels.

| Type of panels | Ultimate load(kN) | Deflection(mm) |
|----------------|-------------------|----------------|
| CARALL-A: Al/[0/90/0]3/Al/[0/90/0]3/Al | 200.2 | 30.8 |
| CARALL-B: Al/[45/0/-45]3/Al/[45/0/-45]3/Al | 189.7 | 29.1 |
| CARALL-C: Al/[45/0/-45]3/Al/[45/0/-45]3/Al | 198.8 | 37.2 |
| CARALL-D: Al/[0/90/0]3/Al/[0/90/0]3/Al | 201.9 | 35.4 |

Failure modes of the FML panels obtained experimentally are presented in Figure 6 and Figure 7. Since CARALL-A was stopped to be loaded when the load dropped for the first time, there was small fracture at the corners of pressure region in the aluminium alloy layer of CARALL-A. The aluminium layer of B/C/D panels contacted with the loading block broke along the short sides of the pressure area consistently. As shown in Figure 7, no obvious fibre and matrix damage were observed in CARALL-A. Moreover, small-scale fibre breakage/pull-out and matrix cracking could be observed in B/D specimens and local buckling occured at the edges of the planes. The delamination failure of the
CFRP/Al interfaces were observed at the edges of all specimens. The delamination was caused by the tensile stresses in the stacking direction and the shear stresses parallel to the interfaces. Due to the medium thick panels subjected to out-of-plane lateral load in this paper, the influence of interlaminar stresses are more significant. It was also found that the small area breakage of the fibers in CARALL-B and CARALL-D formed oblique crack surface, which is typical shear fracture mode of the fiber under compressive stress (in fiber direction). From all observed above, it was summarized as follows: thorough control trial, the first significant decrease in load might be mainly due to the initial failure of the aluminium layers. Due to the non-negligible out-of-plane effects, the failure modes of medium thick panels subjected to transverse quasi-static load are mainly delamination in CFRP/Al interfaces and fracture of aluminum layer. This phenomenon was similar to the results of Romli et al [18], which shown a laminate increased with thickness led to delamination on the metal-composite interface.

Figure 6. Aluminum alloy surface fracture observation of (a) CARALL-A, (b) CARALL-B, (c) CARALL-C and (d) CARALL-D.
4.2. FEM Analysis of FML Panels

The numerical model of panels used for analysis developed in finite element software ABAQUS was based on solid elements. The equilibrium curves obtained numerically and experimentally of tested FML panels were compared in Figure 8. The trend of curves obtained by numerical simulation agreed well with the experimental ones except a little discrepancy in the magnitude of the load values. The material parameters of Aluminium extracted from other literature should be responsible for the phenomenon. Furthermore, the initial defects of the panels also affected the accuracy of the model prediction, e.g. thermal residual stress and void presence in the specimens. It could be seen that the numerical model predicted the linear mechanical behavior of the specimens well and the numerical curves behaved a little stiffer than experimental ones. After linear segment, the load value fluctuated up and down, which was consistent with the platform segment obtained by the experiments. Comparing the experimentally and numerically determined platform trigger load in Table 7, it can be noticed that differences are close, with a 4.8% deviation for CARALL-A, a 4.1% deviation for CARALL-B, a 3.9% deviation for CARALL-C and a 6% deviation for CARALL-D. The divergence of ultimate load is comparatively higher, in which the biggest deviation is 8.9% (case denoted as CARALL-D) still within acceptable range.

Figure 7. Photographs of failed specimens from the side view: (a) CARALL-A, (b) CARALL-B, (c) CARALL-C and (d) CARALL-D.
Figure 8. Comparison of experimental and numerical load-deflection curves of (a) CARALL-A, (b) CARALL-B, (c) CARALL-C and (d) CARALL-D.

Table 7. Experimentally obtained and numerical estimated platform trigger loads and critical loads for panels.

| Type of panels | Experimental test Trigger load (kN) | Ultimate load (kN) |
|----------------|-------------------------------------|--------------------|
|                | FEM       | Experimental test | FEM |
| CARALL-A       | 117.5     | 123.1             | 200.2 | 208.8 |
| CARALL-B       | 131       | 136.4             | 189.7 | 201.4 |
| CARALL-C       | 121.8     | 126.6             | 198.8 | 206.4 |
| CARALL-D       | 124.9     | 132.5             | 201.9 | 219.84 |

Figure 9 presents the predicted failure mode of aluminium layers after ultimate load which were contacted with loading block. Aluminium layer of CARALL-A was fractured at the corners of pressure zone. The fractured area of B/C/D panels developed along the short side of the indenter, which was consistent with experimental observation. Delamination damage patterns in interfaces between aluminium and CFRP layers are depicted in Figure 10. It clearly shows adhesive delamination was mainly distributed at the edge of the tested panels and the area under transverse loading, which corresponded well with experimental results. There were no large-area fiber and matrix failure observed in CFRP layers by simulated results. The above description confirms that the established VUMAT model can accurately predict the mechanical response and failure modes of the tested panels and is valid for further investigation.
4.3. Failure Sequence

Geometrical symbols of different shapes were marked on the load-deflection curves to characterize the sequences of typical failure mechanisms in Figure 11. The numerical results revealed that failure sequences of the tested panels with different aluminium alloy materials and fibre orientations were same. Delamination in CFRP/Al interfaces occurred prior to other failure mechanisms, followed by
platform response closely. Matrix failure initiated in platform segment. Afterwards, aluminium layer fracture lead to the first drop on the load, which was consistent with previous experimental inferences. The specimen still maintained some bearing capacity after aluminium failure. While fibre tension failure initiated, the specimen lose its carrying capacity. It was observed that the deflections corresponding to the delamination of four specimens were similar, which were independent of the properties of aluminium and fibre orientations. Deflections corresponding to the aluminium fracture initiation of CARALL-C and CARALL-D were larger than that of CARALL-A and CARALL-B, due to lower yield strength of 2024-T3 aluminium layers. Moreover, deflections corresponding to the fibre failure initiation of CARALL-B and CARALL-C were bigger than that of CARALL-D, which presented that CFRP layers with (45/0/-45) provided better ductility under transverse quasi-static load. The corresponding failure evolution patterns of CARALL-D to the characteristic points were presented in Figure 12. The deletion of the unit in programming of user-subroutine VUMAT was controlled by the fiber tensile fracture. It indicated that delamination failure initiated in CFRP1/Al2 interface at the deflection of 19.78 mm, meanwhile there were no fibre damage observed but a little matrix tension damage found in CFRP1 Layers. Furthermore, light ductile damage occurred in Al3 layer, which could be ignored since the damage variable value was too small. Matrix tension failure initiated in 0° ply of CFRP1 at deflection of 21.12 mm, closely following interfacial failure. The delamination failure evolved rapidly in CFRP1/Al2 interface at this deflection level. No fiber damage was found and ductile damage of aluminium alloy did not change significantly from the previous state. Combining with the failure sequence analysis above, it was obvious that the so-called platform phenomenon occurred due to delamination initiation and rapid expansion of delamination failure in CFRP/Al interfaces. The failed areas were mainly distributed at the corner of pressure zone, which was the reason why there was no visible damage observed in the course of the experiments. When the evolution of delamination failure became slower, the load would continue to rise as the deflection increased. By the time that aluminium layer fracture initiated in lower surface of Al1, fiber damage was found in 0° ply of CFRP1 but was still working. It could be noticed that local delaminated area in CFRP1/Al2 interface propagated at the edge of the panel and matrix failure spread around the shape of the loading block. As the fracture of the aluminum alloy expanded, the bridging stress of the fiber increased until the fiber broke in the fracture region of the aluminum alloy. When fibre tension damage developed into failure in CFRP1 layers at the deflection of 41.11 mm, aluminium layer fracture propagated along the short side of the pressure area with massive delamination resulting in failure of the specimen. Combined with previous experimental anlysis, it was found that delamination failure of the CFRP/Al interfaces led to the change of original structure. As the load went up, the delamination area was getting larger. Structural failure reduced the influence of strength of the aluminium and fiber laying orientations on the ultimate load.

Figure 11. Failure sequence of tested panels: (a) CARALL-A and CARALL-B; (B) CARALL-C and CARALL-D.
5. Application of CFRP `Aluminum Alloy Laminates

At present, it is relatively difficult to develop composite Bridges completely. In this paper, the related technology and theory of the application of carbon fiber reinforced aluminum alloy laminate as a new type of hybrid composite material as the bridge panel (figure 13 and figure 14) of an assembled highway steel bridge are studied.

Figure 13. Steel bridge of highway ZB-200.

Figure 14. ZB-200 highway steel bridge deck.

In the first place, according to the actual structural principal scale (3.042m×0.84×0.12m) of the zb-200 assembled highway steel bridge deck (figure 15), the design of the bridge deck structure composed of
all CFRP aluminum alloy laminates was carried out. Then, the performance of the designed bridge deck was evaluated by means of numerical simulation analysis, especially the VUMAT model which has been verified.

Figure 15. Zb-200 bridge deck (unit: mm).

5.1. Structural Design of Carbon Fiber Reinforced Aluminum Alloy Bridge Panel

The carbon fiber reinforced aluminum alloy bridge panel adopts the same main scale as the zb-200 assembled highway steel bridge deck, and its overall structure adopts the panel structure combined with the plane frame. The panel adopts carbon fiber reinforced aluminum alloy laminate, whose laminate structure is the same as the specimen CARALL-B, the main body materials are 7075-T6 aluminum alloy and T700 prepreg, and the fiber laminate is [45/0/-45]. The laminate structure is 3/2 type (two layers of carbon fiber and three layers of aluminum alloy). According to the different plane frame structure of the supporting deck panels, the bridge decks of the following three kinds of plane frame structures are designed. Longeron type bridge deck: it is composed of a deck panel and five I-section longerons (figure 16). The I-section longerons are composed of two channel-section laminated plate members (figure 17). The longitudinal beam is evenly arranged in the width direction of the deck panel.

Figure 16. Longeron type bridge deck.

Figure 17. Laminated -channel-section member (unit: mm).

Grid-type bridge deck: it is composed of a deck panel, 5 I-section longitudinal beams, 2 channel sections (half of I-section) longitudinal beams and 11 rows of diaphragm (ribs)(figure.18). Where, the longitudinal beam is evenly distributed in the width direction of the panel, and the diaphragm is evenly distributed in the length direction of the deck panel.
Crossbeam type bridge deck: it is composed of a deck panel, two I-section longitudinal beams and four I-section beams (figure 19). The longitudinal beam and the width of the panel coincide with each other, and the beam is evenly distributed in the length of the deck panel.

5.2. Numerical Simulation Analysis of Carbon Fiber Reinforced Aluminum Alloy Bridge Panel

In the numerical simulation analysis of carbon fiber reinforced aluminum alloy bridge deck panel, the most unfavorable load condition of the bridge panel is determined according to the actual driving practice of the bridge under load. The design control load of the bridge panel is wheeled load, LT-60 is selected as the load grade, and the maximum axial pressure is 140kN. Thus, the most unfavorable load condition of the bridge panel is as follows: the size of a single tire is 0.5m×0.2m, the wheel load is 70 kN, and the action position is the center of the main scale of the plane of the bridge panel (figure 20).

After the most unfavorable load condition of the bridge deck was determined, the verified VUMAT model was applied and the commercial finite element software ABAQUS 6.12 was used to simulate and analyze the carbon fiber reinforced aluminum alloy bridge deck. The maximum stress of longitudinal girder type bridge deck is 313.6MPa and the maximum deflection is 11.85mm (figure 21). The maximum stress of grid-type bridge deck is 251.6MPa and the maximum deflection is 8.45mm (figure 22). The maximum stress of crossbeam type bridge deck is 841.3MPa and the maximum deflection is 19.30mm (figure 23). According to the calculation, the dead weight of the bridge deck of the longitudinal beam, grid type and transverse beam type is 76.354kg, 100.172kg and 84.300kg respectively. Compared with the dead weight of the steel bridge deck of the zb-200 highway with 210kg, its dead weight is reduced by 64%, 52% and 60% respectively. The dead weight decreases significantly, which can greatly improve its erection and mobility performance. Among them, the longitudinal girder bridge deck has the minimum dead weight, and the control effect of stress level and maximum deflection is also relatively good. It is recommended to use the longitudinal girder bridge deck.
6. Conclusions
In the presented study, experimental and numerical methods have been performed to analyse mechanical response and failure mechanisms of medium thick CARALL panels subjected to transverse local quasi-static loading. In the finite element analysis, the progressive damage model based on three-dimensional Hashin criteria in quadratic strain form through user-subroutine VUMAT
has been carried out by Abaqus explicit solution. The delamination between aluminium layers and CFRP layers has been modeled by surface-based cohesive contacts and Johnson–Cook flow stress model has been used for aluminium layers. Load-deflection curves and failure mode obtained experimentally which were consistent with numerical ones confirmed the model built up was proper and effective. The primary conclusions are as follows:

1. According to the experimental results, the ultimate load depended on sequence of prepreg layers and the properties of aluminium alloy, but the relative difference was quite small with 5%. By comparison with 7075-T6 aluminium, 2024-T3 aluminium layers can contribute additional ductility and postpone failure of the specimens. Due to better stiffness and higher platform response load in the linear segment, CARALL-B with 7075-T6 aluminium and [45/0/-45] had better load carrying capacity than others.

2. The numerical and experimental results revealed the progressive failure mechanisms of medium CARALL panels under transverse local quasi-static loading. Delamination in CFRP/Al interfaces occurred first, followed by matrix failure initiation of CFRP layer in delaminated area. With the development of deformation, the specimens lose maximum load bearing because of the fracture of aluminium under loading block. The fracture of the aluminum alloy lead to the evolution of delamination in the fracture area and the increase of the fiber bridging stress which resulted in fiber failure. Platform phenomenon was caused by rapid expansion of delamination failure. Hence improving the adhesive ability between aluminium and CFRP layer is the key to increasing the load carrying capacity of medium thick panels subjected to transverse local quasi-static loading.

3. The steel bridge deck panel of ZB-200 highway steel bridge can be prepared with CFRP aluminum alloy laminates. When preparing CFRP aluminum alloy bridge deck panel, because the preparation technology of CFRP aluminium alloy channel section laminated panel members is mature, its I-beam can be made by superposition of channel section laminated panel members. In addition, as for the longitudinal girder, grid and longitudinal girder type bridge deck panel, the longitudinal girder type bridge deck panel has the advantages of good bearing capacity and low dead weight, and the use of longitudinal girder type CFRP aluminum alloy bridge deck has better bearing capacity and economic benefits.

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