IMPACT AND COMPRESSION AFTER IMPACT PERFORMANCE OF A NOVEL MULTIFUNCTIONAL INTER-WOVEN WIRE FABRIC COMPOSITE

Minqiang Jiang[1], Xiaoye Cong[2], Zhenghua Cao[3], Xiaoling Liu[4] and Xiaosu Yi[5]

[1] University of Nottingham Ningbo China, 199 Taikang East Road Ningbo, 315100, China, Minqiang.Jiang2@nottingham.edu.cn
[2] University of Nottingham Ningbo China, 199 Taikang East Road Ningbo, 315100, China, Xiaoye.Cong@nottingham.edu.cn
[3] AVIC Composite Co., Ltd., High-tech Park, Shunyi District, Beijing, 101300, China, caozh@avic.com
[4] University of Nottingham Ningbo China, 199 Taikang East Road Ningbo, 315100, China, Xiaoling.Liu@nottingham.edu.cn
[5] University of Nottingham Ningbo China, 199 Taikang East Road Ningbo, 315100, China, Xiaosu.Yi@nottingham.edu.cn

Keywords: Compression after impact, Compressive residual strength, Inter-Woven Wire Fabric, Multifunctional composites

ABSTRACT

A novel multifunctional Inter-Woven Wire Fabric composite with high electrical conductivity and enhanced interlaminar fracture toughness was manufactured. The impact and compression after impact performance of the composite were investigated. The results demonstrated that the conductive weft yarns within the composites can act as interlaminar toughness enhancers, significantly improving the damage resistance of CFRP composites to a drop-weight impact event, as well as the corresponding compressive residual strength properties.

1 INTRODUCTION

Carbon fiber reinforced plastic (CFRP) composites have been widely used in aircraft structures in recent decades due to their excellent mechanical properties including high specific strength, high specific modulus, and outstanding corrosion resistance. However, the vulnerability of composite structures to low velocity impact events [1, 2] is one of the most critical issues that restricts the widespread application of composite material in aerostructures. Besides, the lower electrical conductivity [3, 4] is another inherent challenge accompanying the use of CFRP in aircraft.

In our previous works [5, 6], we have proposed and manufactured a novel multifunctional composite based on Inter-Woven Wire Fabric (IWWF) [7], which was composed of conductive weft yarns and carbon fiber warp yarns. The recent investigation results [6] demonstrate that the conductive weft yarns within the composite were act both as electrically conductive paths and interlaminar toughness enhancers simultaneously.

In this work, we further investigated the impact and compression after impact performance of the Inter-Woven Wire Fabric composite, as well as a corresponding control composite. The results demonstrated that the IWWF composite revealed distinctly slighter impact damage situation and significantly improved compressive residual strength.

2 EXPERIMENT

2.1 Materials and composite preparation

Inter-Woven Wire Fabric prepreg was provided by Beijing Mega Material Innovation Work Co., Ltd (M2IW) and the University of Nottingham Ningbo China, woven by Toray T700 carbon fiber warp yarns and conductive weft yarns (twisted silver-coated polyester filaments yarns). A typical carbon fiber fabric prepreg was provided by Ningbo N^{2}IC New Materials Co., Ltd for control purposes, woven using the same warp yarns and polyethylene weft yarns. The weft densities of the control and IWWF were 13 yarns/10 cm and 26 yarns/10 cm, respectively. Both prepregs used the same epoxy resin YPH-42T with 40 wt% resin content.

To manufacture the samples, 16 ply quasi-isotropic panels were laid up by hand. The stacking sequence used was $[45/0/-45/90]_{2S}$ for both control composite (CC) samples and Inter-Woven Wire Fabric composite (IC) samples. The panels were cured in an OLMAR AT – 1300/2500 autoclave according to the supplier instructions (80 ℃ × 0.5 h and 130 ℃ × 2.0 h, 0.7 MPa). After cure, the panels were inspected by ultrasonic C-scan to confirm their quality before impact tests. They were then cut into 150 × 100 mm^2 specimens with around 4 mm thickness.

2.2 Drop-weight impact test

Drop-weight impact tests were performed according to the ATSTM D7136 standard [8], using an Instron 9340 impact testing machine. The impactor has a mass of 5.265 kg and a hemispherical striker tip with a diameter of 16 mm. The impact energy for each specimen is 6 .7 J/mm. Five specimens were tested for each set of samples.

2.3 Compressive residual strength test (CAI test)

The compressive residual strength tests were implemented according to the ASTM D7137 standard [9]. An INSTRON 5980 series dual column floor testing system was used to conduct the uniaxial compression tests. The specimens were supported using a fixture following the standard. Before each test, 450 N compressive force was applied to the specimen/fixture assembly for preloading. Then the compressive force would reduce to 150 N and conduct the test. The crosshead displacement rate was set to 1.25 mm/min for each test. The aforementioned specimens with impact damage were tested for each set of samples.

3 EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Impactor force versus displacement histories of impacts

The impactor force versus displacement histories of CC and IC specimens are shown in Fig. 1. The circled area of each force-displacement curve represents corresponding absorbed energy, which is defined as the amount of energy dissipated in the form of damage with permanent deformation. The results show that the CC and IC specimens exhibited fairly consistent force-displacement responses to the impacts. The average peak forces of CC and IC specimens are 10423 N and 10646 N, respectively, which are considerably closing.

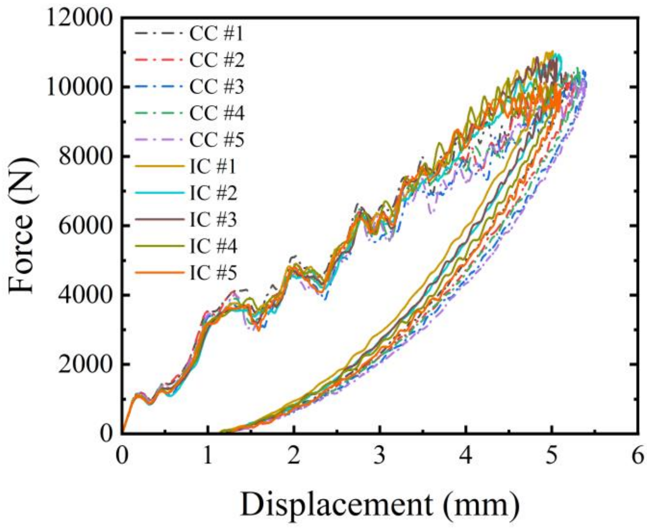

Figure 1: Force-displacement histories of impacts on CC and IC specimens.

3.2 Surface damage morphology and dent depths of specimens after impact

The surface photos of CC and IC specimens are shown in Fig. 2. All five CC specimens show intact surfaces except for center impact dent areas. For IC specimens, surface cracks with variable lengths can be identified on the surface of each specimen, besides the center impact dents.

The dent depths of each specimen were measured using a dial depth gauge, and the results are displayed in Fig. 3. The average dent depth of IC specimens is 0.235 mm, which is slightly higher than that of CC specimens at 0.218 mm. Besides, the coefficient of variation of IC specimens is 3.76%, which is also slightly higher than that of CC specimens at 2.70%.

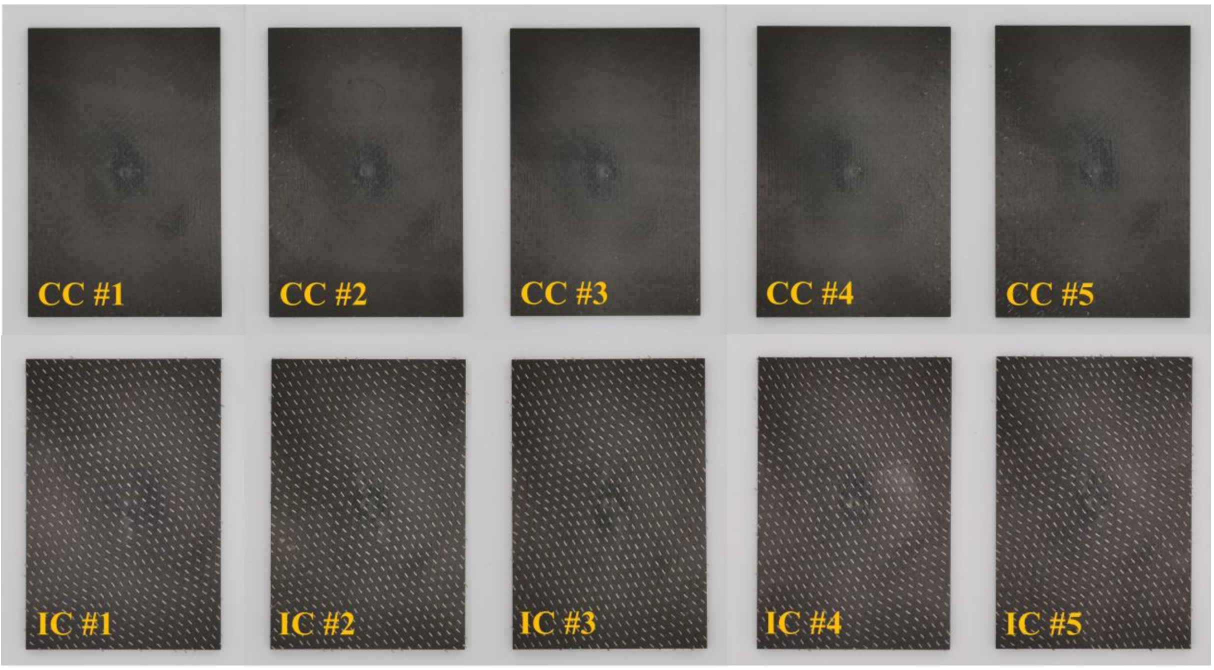

Figure 2: Surface damage morphology of CC and IC specimens after impact.

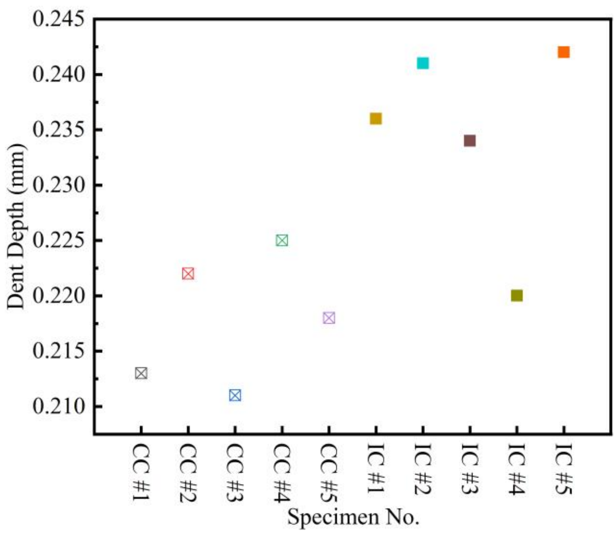

Figure 3: Dent depths of CC and IC specimens after impact.

3.3 Ultrasonic C-scan inspection of specimens after impact

Non-destructive ultrasonic C-scan inspection was conducted for each post-impact specimen. Inspections were made from the upper face (i.e., the impact damaged side) of the specimens to detect the damage development. The strobing gate was adjusted to capture the abnormal interlaminar wave signals, which were caused by the delamination regions. The C-scan inspection results are shown in Fig. 4. It could be found that the CC specimens show a quite consistent delamination situation. The delamination area is increasing gradually and significantly with the increase of damage depth. In comparison, the damage situations of IC specimens are inconsistent. The IC #1, IC #2, and IC #3 specimens show comparatively narrow delamination areas compared to IC #4 and IC #5. In addition, although the delamination areas are likewise gradually increasing with the increase of damage depth, the extent of the increase is obviously less than that of IC #4 and IC #5, as well as CC specimens.

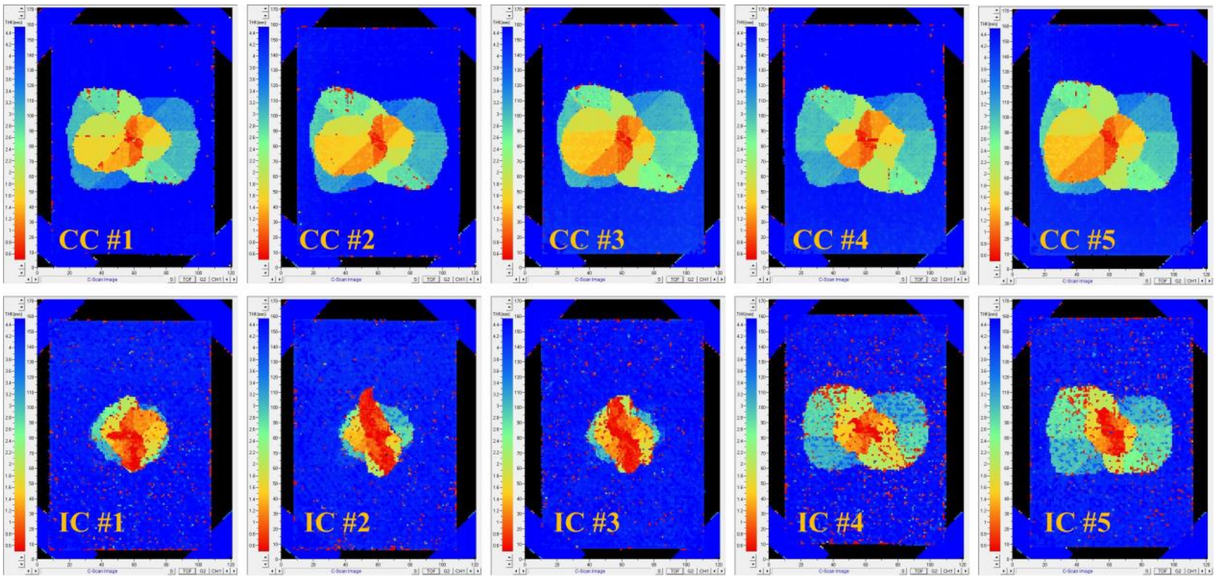

Figure 4: C-scan inspection results of CC and IC specimens after impact.

3.4 Compressive residual strength properties

The stress-displacement curves of compressive residual strength tests are shown in Fig. 5. It could be found that all CC and IC specimen shows consistent slopes during the linear increase regions, which indicates that their stiffnesses are highly consistent.

The compressive residual strength test results of CC and IC specimens are illustrated in Fig. 6. The average ultimate compressive residual strength of IC specimens is 190.8 MPa, which is 21% higher than that of CC specimens. In addition, the coefficient of variation of IC specimens is 7.48%, which is slightly higher than that of CC specimens at 6.86%.

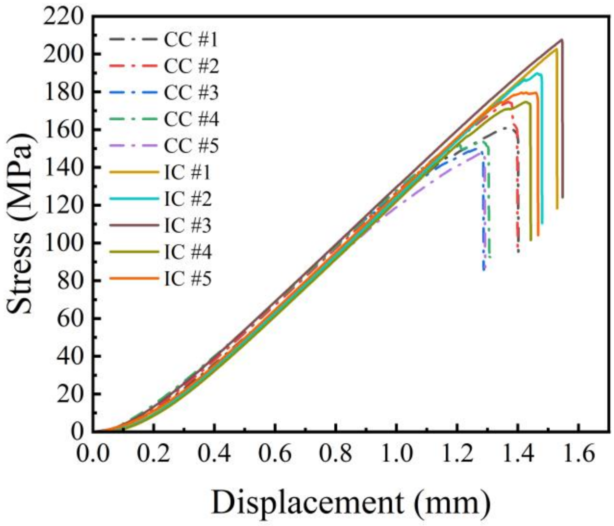

Figure 5: Stress-displacement curves of compressive residual strength tests.

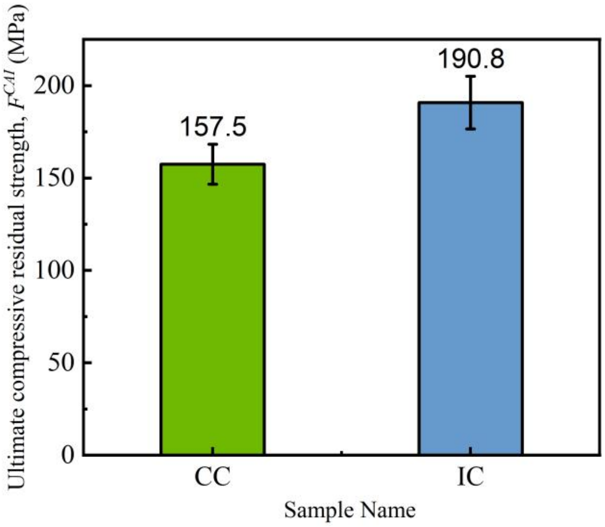

Figure 6: Ultimate compressive residual strengths of CC and IC specimens.

3.5 Discussions

The investigation demonstrated that the IC specimens formed less delamination areas during the drop-weight impact tests and exhibited obvious higher ultimate compressive residual strengths. The main reason could be reasonably attributed to the existence of conductive weft yarns. As we discussed in our previous work [6], the conductive weft yarns can influence the crack forming trajectory, and induce longer and more complex crack propagation, resulting in higher interlaminar fracture energy consumption in the unit delamination area. Hence, the IC specimens appeared fewer delamination areas compared to CC specimens with the same absorbed energy during impact tests. It is noticed that the delamination areas of each IC specimen are highly differentiated. This phenomenon implies that the content of conductive weft yarns is right around the threshold for the corresponding impact energy. It deserved to further investigate the damage resistances of different IWWF composites under various impact energy.

4 CONCLUSIONS

The results demonstrated that the conductive weft yarns can act as interlaminar toughness enhancers, significantly improving the damage resistance of CFRP composites to a drop-weight impact event, as well as the corresponding compressive residual strength properties. The average ultimate compressive residual strength of IC specimens is 190.8 MPa, improving 21% compared to that of CC specimens. The IWWF technology continues to represent a promising route for multifunctional composite development and manufacturing.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support from Ningbo Science and Technology Innovation 2025 Major Special Project No. 2020Z058.

REFERENCES

[1] D.D.R. Cartié, P.E. Irving, Effect of resin and fibre properties on impact and compression after impact performance of CFRP, *Composites Part A: Applied Science and Manufacturing*, **33**, 2002, pp. 483-493 (doi: 10.1016/S1359-835X(01)00141-5).

[2] M.A. Caminero, I. García-Moreno, G.P. Rodríguez, Damage resistance of carbon fibre reinforced epoxy laminates subjected to low velocity impact: Effects of laminate thickness and ply-stacking sequence, *Polymer Testing*, **63**, 2017, pp. 530-541 (doi: 10.1016/j.polymertesting.2017.09.016).

[3] M. Guo, X. Yi, C. Rudd, X. Liu, Preparation of highly electrically conductive carbon-fiber composites with high interlaminar fracture toughness by using silver-plated interleaves, *Composites Science and Technology*, **176**, 2019, pp. 29-36 (doi: 10.1016/j.compscitech.2019.03.014).

[4] I. Gaztelumendi, M. Chapartegui, R. Seddon, S. Flórez, F. Pons, J. Cinquin, Enhancement of electrical conductivity of composite structures by integration of carbon nanotubes via bulk resin and/or buckypaper films, *Composites Part B: Engineering*, **122**, 2017, pp. 31-40 (doi: 10.1016/j.compositesb.2016.12.059).

[5] M. Jiang, X. Cong, X. Yi, X. Liu, C. Rudd, A Stochastic Overlap Network Model of Electrical Properties for Conductive Weft Yarn Composites and their Experimental Study, *Composites Science and Technology*, **217**, 2021, pp. 109075 (doi: 10.1016/j.compscitech.2021.109075).

[6] M. Jiang, Y. Hu, C. Rudd, Z. Cao, X. Liu, X. Yi, Simultaneously improving electrical properties and interlaminar fracture toughness: A novel multifunctional composite based on Inter-Woven Wire Fabric, *Composites Communications*, **39**, 2023, pp. 101563 (doi: 10.1016/j.coco.2023.101563).

[7] X. Yi, Y. Xiao, C. Rudd, X. Liu, Q. Liao, X. Cong, C. Zhu, X. Ma, Thickness direction conductive laminated composite material and manufacturing method therefor, 2019, WIPO, China, WO2019227474A1.

[8] ASTM D7136M-20: Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impacct Event, American Society for Testing Materials, 2020.

[9] ASTM D7137M-17: Standard Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates, American Society for Testing Materials, 2017.