Carbon Fiber Reinforced Composite Materials for Self-supporting Subway Train Cab

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Abstract. In order to meet the requirement of lightweight, the design of the subway self-supporting composite subway cab is highly desired. Here we designed and developed carbon fiber reinforced composite sheets with high strength and moduli to replace the aluminum alloy used in the traditional subway cab. The tensile, compression, bending, interlaminar shear properties, and high speed impact performance of composite sheets were investigated. The results showed that the composite sheets had good mechanical properties comparable to traditional aluminum sheets, while reducing the weight of the subway cab by more than 30%. This composite is expected to be a good promising material to make the new generation of subway cab.

1. Introduction

In recent years, the requirements of low-carbon and environmental protection have been urgently needed with the rapid development of the rail transit industry. Vehicle weight reduction is imminent to achieve the goals. New materials, new designs, and new manufacturing technologies are the main ways to reduce the weight of rail trains. The carbon fiber reinforced composite material has been recognized to be a promising material to reduce the weight of various transportations because of its superior properties such as light in weight, high strength, high temperature resistance, impact resistance, corrosion resistance, creep resistance, noise reduction, designability, high fatigue strength and low notch sensitivity[1].

Composite materials have been used for accessorial and non-structural components such as floor, door, luggage rack, window frame of rail trains in France, Switzerland, the United Kingdom, Japan, South Korea and other countries for a long time[2-8]. Recently composite materials are also used for manufacturing main load bearing parts for high speed trains such as the driver's cab, the upper apex and the head of the car[9-13]. With the rapid development of trains in China, more and more composite materials have also been used to build train parts such as front nose, air deflector and framework of the driver's cab. However, most applications of the composite materials are still limited to non-load bearing structural parts in rail trains, while the main load bearing structural parts, especially the car body and skeleton structure of driver's cab are mainly made from aluminum alloy, due to the strength and stiffness of traditional composite materials cannot meet the design standards of the car body. This greatly limits the wide applications of composite materials in the rail trains.

Here we designed and developed composite sheets with high strength and moduli for subway train cab. The traditional aluminium alloy metal skeleton was replaced by Composites integrally molded...
reinforcing skeleton to manufacture a full-composite subway train cab was fabricated to replace the aluminium alloy based one with comparable mechanical performance and significantly reduced weight by 30%. Here we would like to report the preparation and mechanical evaluation of these composites.

2. Materials and methods

2.1. Preparation of composite sheets for mechanical properties test

The raw material of 3k carbon fiber prepreg, carbon fiber unidirectional prepreg, glass fiber prepreg, aramid prepreg were prepared and cut into the desired shape. Then, the prepreg was laid according to the preset layer structure of 3 mm composite sheet (3K twill / 0° carbon fiber / ± 45° carbon fiber / aramid plain weave / 0° glass fiber / 90° glass fiber / aramid plain weave * 2 / 90° glass fiber / 0° glass fiber / aramid plain weave / ± 45° carbon fiber / 0° carbon fiber) and 2 mm composite sheet (4° carbon fiber / -45° carbon fiber / 0° glass fiber / 90° glass fiber / aramid plain weave t * 2 / 90° glass fiber / 0° glass fiber / -45° carbon fiber / 4° carbon fiber ). The prepreg piece should be aligned around, less air bubbles, smooth, and without residue of release paper and PE film During the laying process. The prepreg piece was put onto the corresponding position of the tempered glass scribbled with release agent. Then put them into the hot press tank to get the composite sheet.

The process conditions of hot press tank molding process was referenced Figure 1. Briefly, the temperature of hot press tank was raised from room temperature to 80 °C and kept for 30 minutes. Then, the temperature was raised 100 °C and kept for 30 minutes. And then the temperature was raised 130 °C and kept for 90 minutes and dropped to 60 °C at last. The pressure was maintained at 0.3 MPa during the temperature was between 80°C and 130 °C.

2.2. Preparation of sandwich structure composite sheets for high speed impact performance test

2.2.1. Preparation of inner and outer skin of sandwich structure composite sheets. The prepreg were prepared and cut into the desired shape of 1100 mm * 800 mm. Then preform of inner and outer skin is constructed by the structure of 3.32 mm outer skin (3K / aramid plain weave *3 / ± 45° glass fiber / ± 45° carbon fiber / ± 45° carbon fiber / ± 45°glass fiber / aramid plain weave * 3 ) and 2.34mm inner skin (± 45° glass fiber / ± 45° carbon fiber / aramid plain weave * 3 / ± 45° carbon fiber / ± 45°glass fiber). And then The inner and outer skins were made according to the hot pressing process at the temperature of 130 °C, the pressure of 0.6 MPa and holding time > 1 h.

2.2.2 Preparation of sandwich structure composite sheets. 59 mm polymethacrylimide (PMI) close-cell foam board with 75% porosity was cut into the predetermined size by a woodworking saw. The inner and outer skins and the foam were bonded by an epoxy film. And then the sandwich structure
The composite sheet was compounded according to the hot pressing process at the temperature of 130 °C, the pressure of 0.3 MPa and holding time > 1 h. The composite sheet was cut into the test sample with the size of 1000*700mm by the computer numerical control (CNC).

2.3. **Resin content and porosity test of composite sheets**

The Resin content and porosity of composite sheets were evaluated according to the standard of American Society for Testing Materials (ASTM) D3171-2015. The data from 3 specimens were averaged.

2.4. **Mechanical properties test of composite sheets**

Composite sheets with a thickness of 2 mm and 3 mm were prepared and cut into the test standard size. The mechanical properties of the composite sheets were evaluated by tension, compression, bending, interlayer shear tests using an Instron 5985 universal testing machine according to the standards of ASTM. The data from 5 specimens were averaged.

2.4.1. **Tensile test of composite sheets.** The tensile mechanical properties of the composite sheets were measured by 0° and 90° tensile test according to the standards of ASTM D3039-2014. The sections of the test specimen were rectangle, and the sizes of them were 250 mm * 25 mm * 3 mm and 250 mm * 25 mm * 2 mm. 2 mm thick reinforcing pieces were adhbid to both ends of the specimen. The test was at a tensile rate of 2 mm / min using extensometer to measure the longitudinal strain.

2.4.2. **Compressive test of composite sheets.** The compressive mechanical properties of the composite sheets were measured by 0° and 90° compressive test according to the standard of ASTM D3410-2016. The sections of the test specimen were rectangle, and the sizes of them were 150 mm * 10 mm * 3 mm and 150 mm * 10 mm * 2 mm. The test was at a compressive rate of 1.5 mm / min using a strain gauge adhbid in the middle of the specimen to measure the vertical strain.

2.4.3. **Bending test of composite sheets.** The bending mechanical properties of the composite sheets were measured by 0° and 90° compressive test according to the standard of ASTM D7264-2015. The sections of the test specimen were rectangle, and the sizes of them were 120 mm * 15 mm * 3 mm and 120 mm * 15 mm * 2 mm. The distance between the fulcrum of test specimen was 97 mm for 0° compressive test and 65 mm for 90° compressive test and the test was at a compressive rate of 1 mm / min.

2.4.4. **Interlayer shear mechanical properties test of composite sheets.** The interlayer shear mechanical properties of the composite sheets were measured according to the standard of ASTM D2344-2013. The sections of the test specimen were rectangle, and the sizes of them were 20 mm * 6 mm * 3 mm. The distance between the fulcrum of test specimen was 12 mm and the test was at a compressive rate of 1 mm / min.

2.5. **Mechanical properties test of open-cell composite sheets**

The mechanical properties of open-cell composite sheets were measured by compressive test according to the standard of ASTM D6484-2014. The sections of the test specimen were rectangle, and the sizes of them were 300 mm * 36 mm * 3 mm and 300 mm * 36 mm * 2 mm and the diameter of the hole was 5.6 mm. The test was at a compressive rate of 1 mm / min.

2.6. **High speed impact performance test of sandwich structure composite sheets**

High speed impact performance of composite sheets was measured by a bird collision experiment equipment (F-17 NZ-II) at 20 °C and 45% relative humidity according to the standards of UIC CODE 651-2002. The sizes of the test specimen was 1000 mm * 700 mm * 60 mm. A 1.0 kg aluminum bullet...
impactor impacted the specimen at a speed of 304.93 km/h ($V_{\text{max}} + 160$ km/h, $V_{\text{max}}$ was the maximum design speed) during the test.

3. Results and discussion

3.1. Resin content and porosity test of composite sheets
The resin content of 2 mm sandwich structure composite sheets was $35.56 \pm 0.3\%$, and the specimen has a Low porosity of $0.52 \pm 0.16\%$ to keep the composite sheets have an excellent performance.

3.2. Mechanical properties test of composite sheets

3.2.1. Tensile mechanical properties test of composite sheets. The $0^\circ$ tensile strength of the 2 mm and 3 mm composite sheets were $356.37 \pm 8.10$ MPa and $626.24 \pm 20.5$ MPa and the $90^\circ$ tensile strength of the 2mm and 3mm composite sheets were $525.32 \pm 20.20$ MPa and $376.49 \pm 13.62$ MPa respectively (Table 1.). The $0^\circ$ tensile modulus of the 2 mm and 3 mm composite sheets were $32.65 \pm 0.36$ GPa and $43.51 \pm 0.37$ GPa and the $90^\circ$tensile modulus of the 2 mm and 3 mm composite sheets were $32.53 \pm 0.40$ GPa and $30.30 \pm 0.67$ GPa respectively (Table 1.). They were all comparable to aluminium alloy sheets (6082) used in the subway cab now according to the standards of TB/T3260-2011.

| Thickness | Tensile strength (MPa) | Tensile modulus (GPa) |
|-----------|------------------------|-----------------------|
|           | $0^\circ$ | $90^\circ$ | $0^\circ$ | $90^\circ$ |
| 2 mm      | 356.37 ± 8.10 | 525.32 ± 20.20 | 32.65 ± 0.36 | 32.53 ± 0.40 |
| 3 mm      | 626.24 ± 20.5  | 376.49 ± 13.62 | 43.51 ± 0.37 | 30.30 ± 0.67 |

3.2.2 Compressive mechanical properties test of composite sheets. The $0^\circ$ compressive strength of the 2 mm and 3 mm composite sheets were $288.74 \pm 12.56$ MPa and $238.01 \pm 18.16$ MPa and the $90^\circ$ compressive strength of the 2mm and 3mm composite sheets were $264.63 \pm 15.56$ MPa and $222.77 \pm 16.94$ MPa respectively (Table 2.). The $0^\circ$ compressive modulus of the 2 mm and 3 mm composite sheets were $61.31 \pm 0.90$ GPa and $78.38 \pm 4.48$ GPa and the $90^\circ$ compressive modulus of the 2 mm and 3 mm composite sheets were $66.91 \pm 2.94$ GPa and $55.11 \pm 1.04$ GPa respectively (Table 2.). They were all comparable to aluminium alloy sheets (6082) used in the subway cab now according to the standards of TB/T3260-2011.

| Thickness | Compressive strength (MPa) | Compressive modulus (GPa) |
|-----------|---------------------------|--------------------------|
|           | $0^\circ$ | $90^\circ$ | $0^\circ$ | $90^\circ$ |
| 2 mm      | 288.74 ± 12.56 | 264.63 ± 15.56 | 61.31 ± 0.90 | 66.91 ± 2.94 |
| 3 mm      | 238.01 ± 18.16 | 222.77 ± 16.94 | 78.38 ± 4.48 | 55.11 ± 1.04 |

3.2.3 Bending mechanical properties test of composite sheets. The $0^\circ$ bending strength of the 2 mm and 3 mm composite sheets were $687.73 \pm 13.08$ MPa and $865.17 \pm 58.29$ MPa and the $90^\circ$ bending strength of the 2 mm and 3 mm composite sheets were $776.86 \pm 57.33$ MPa and $538.98 \pm 43.19$ MPa respectively (Table 3.). The $0^\circ$ bending modulus of the 2 mm and 3 mm composite sheets were $50.89 \pm 2.36$ GPa and $62.61 \pm 1.35$ GPa and the $90^\circ$ bending modulus of the 2mm and 3mm composite sheets were $40.06 \pm 0.89$ GPa and $39.79 \pm 1.40$ GPa, respectively (Table 3.). They were comparable to than aluminium alloy sheets (6082) used in the subway cab now according to the standards of TB/T3260-2011.

3.2.4 Interlayer shear mechanical properties test of composite sheets. The interlayer shear strength of the 3mm composite sheets were $38.56 \pm 2.47$ MPa according to the results of interlayer shear mechanical properties tests.
3.3. Mechanical properties test of open-cell composite sheets

The tensile strength of the 2mm and 3mm open-cell composite sheets were 369.88 ± 25.01 MPa and 461.13 ± 15.60 MPa and the compressive strength of the 2mm and 3mm open-cell composite sheets were 219.55 ± 15.65 MPa and 203.83 ± 11.75 MPa respectively (Table 4.). They were all comparable to aluminum alloy sheets (6082) used in the subway cab now according to the standards of TB/T3260-2011.

### Table 3. Bending mechanical properties of composite sheets

| Thickness | Bending strength (MPa) | Bending modulus (GPa) |
|-----------|------------------------|-----------------------|
|           | 0° | 90° | 0° | 90° |
| 2 mm      | 687.73 ± 13.08 | 776.86 ± 57.33 | 50.89 ± 2.36 | 40.06 ± 0.89 |
| 3 mm      | 865.17 ± 58.29 | 538.98 ± 43.19 | 62.61 ± 1.35 | 39.79 ± 1.40 |

3.4. High speed impact performance test of sandwich structure composite sheets

The sandwich structure composite material meet the standard requirement of the subway according to the standards of UIC CODE 651-2002.

4. Conclusion

We designed and developed composite materials with high strength and moduli for subway train cab. The composite materials meet the standard requirements of the subway and can be used to manufacture a full-composite subway train cab to reduce the weight of the vehicle by 30% under the premise of ensuring the same performance.

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