# EXPLORING THE TENSILE RESPONSE IN SMALL CARBON FIBRE COMPOSITE BUNDLES

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## Abstract

Small composite bundles, AS4 carbon fibre epoxy, with a restricted number of reinforcing fibres, ca. 20, showed a progressive failure when tested in tension. *In-situ* acoustic emission observations under tensile load reveal that numerous fibres fail before ultimate failure of the small composite bundle, suggesting that isolated and individual fibre failures occur without compromising the integrity of the neighboring fibres or the small composite bundle's overall mechanical performance. The average strength of the carbon fibres in small composite bundles was 9.6% higher than in standard lab-scale composite specimens using the same fibre type.

## 1. Introduction

Reducing the number of reinforcing fibres, i.e. composite size, can delay the formation of large broken fibre clusters which can cause the onset of catastrophic failure [1]; analytical modelling [2] proposes that, for a specific fibre embodiment, composites with fewer fibres than a critical threshold will present a positive size effect, so that the average strength of a small bundle will be higher than the average strength of individual fibres (for the same gauge length). To exploit this failure mechanism, experimental validation of the model is required with a stringently controlled number of fibres in a composite bundle; with AS4 carbon fibres a peak in strength is predicted between 16 to 32 fibres [2].

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## 2. Experimental

### 2.1. Materials

- AS4 carbon fibre sized, PAN, AS4C-GP-12K, HS-CP-3000 grade, 1% sizing, 6.9 µm diameter with nominal; tensile modulus 231 GPa, tensile strength 4385 MPa and 1.8% strain to failure, Hexcel (GB). N.B. HexPly 8552 composites with AS4 carbon fibres, 0° unidirectional properties; tensile modulus 141 GPa, tensile strength 2206 MPa and 1.6% strain to failure [3].
- PRIME 20ULV ultra-low viscosity epoxy, with PRIME 20LV resin with a slow (ULV) hardener, Gurit Ltd.(GB), tensile modulus 2.98 GPa, tensile strength 71.2 MPa, 6.28% strain to failure [4].

### 2.2. Small composite bundle sample preparation

To ensure that each sample had the desired number of reinforcing fibres, specimens were made individually and by hand. Care was taken to ensure that each small composite bundle had the same number of fibres throughout the specimen. Separating fibres was carried out on paper (glossy, white, 180 g cm$^{-2}$), teasing fibres from the tow, destroying surrounding fibres to leave the desired fibre in place, which ensured minimal handling. Fibres were consolidated onto a glass support, Figure 1, (borosilicate plate, Cambridge Glassblowing Ltd, UK) using double sided tape (180568, Office Depot, UK), with the fibres mounted by pressing the inverted support into the fibre situated on the paper. N.B. failure to use high grade glossy paper at this stage results in the double sided tape losing tackiness promptly, and restricts the number of fibres which can be mounted on any given double sided section. The process was continued until 20 carbon fibres were attached, then sections of tape (6991, Scarpa, UK) were placed to hold fibres together.

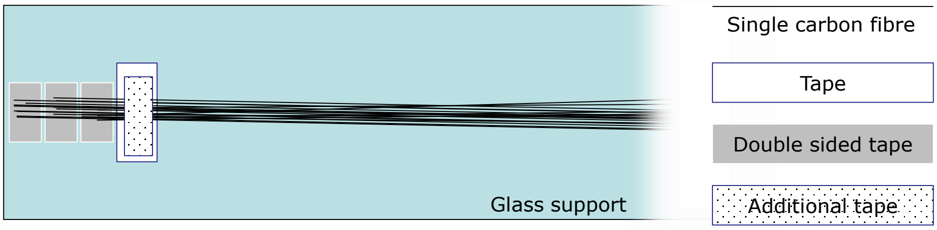


**Figure 1.** Schematic of carbon fibres and the arrangement of tape used on glass support to manufacture specimens (only one side shown).

Once the carbon fibres were secured in the sections of tape, they were cut from their support. When free, taped bundles were then suspended using a binder clip (979366, Office Depot, UK) and a small weight attached to the freestanding section of tape (SamplKlip, stainless steel, 20-4000-100, 0.575 g, Buehler, UK). Low viscosity epoxy solution was then pipetted onto the suspended bundles until fully saturated. Bundled coated fibre samples were then cured following the manufacturer's recommended procedure, curing at room temperature for 24 h and 50 °C for 16 h [4]. Composite bundle samples were then mounted in card frames similar to those routinely used in single fibre tensile tests (British Standard BS EN ISO 11566, 1996 using Araldite Rapid Adhesive, Bostik Findley Ltd., UK in the tabbing regions), Figure 2 (A). Card templates were modified with an extended tabbed region at one end (fibre extended throughout) for acoustic emission sensor placement, as shown in Figure 2 (B). The small composite bundles produced had a circular cross-section, shown in Figure 3 (A) and (B), with periodic beads of epoxy which formed during impregnation (Figure 3 (C)).

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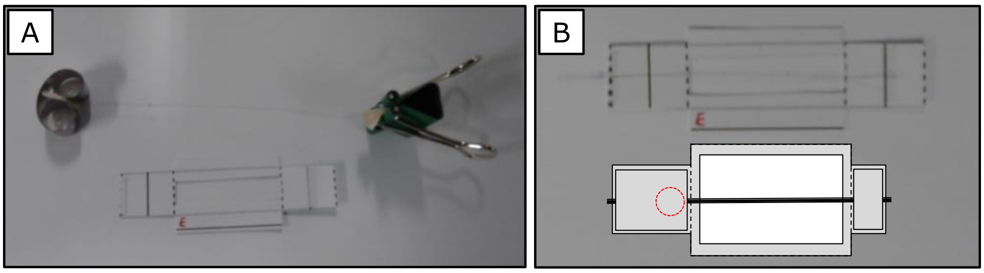


**Figure 2.** (A) Photograph of small composite bundle held between binder clip and weight with card frame for tensile test shown below. (B) Small composite bundle mounted in the card frame with schematic indicting the placement of acoustic emission sensor.

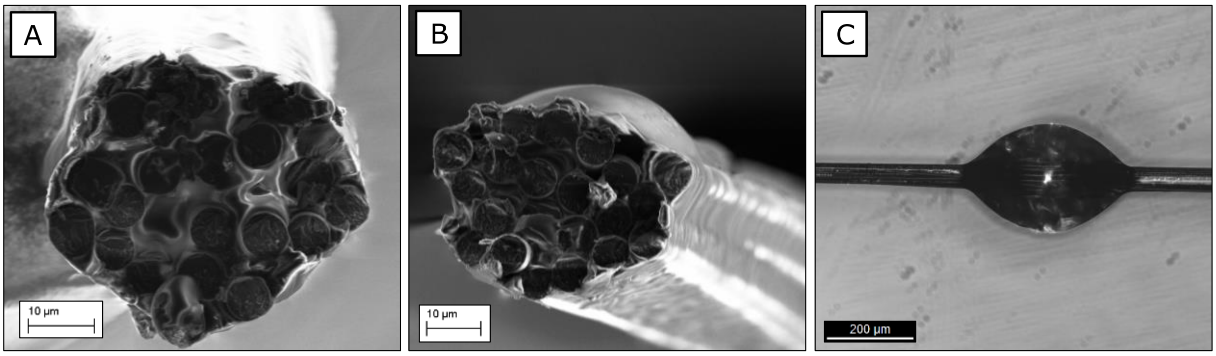


**Figure 3.** (A) and (B) Scanning electron micrograph of small composite bundles, and (C) an optical micrograph of the side view of a bundle with an epoxy bead formed during impregnation.

## 2.3. Composite bundle characterization and test equipment

The morphology of composite bundles was investigated by optical microscope (Leica DM2500) with a DFC295 camera (Leica Application Suite v4.0.0, Leica ∞/1.1 HI PLAN 40x/0.50), and through field emission gun scanning electron microscope (FEG-SEM) using Leo-Gemini 1525, SmartSEM software interface V05.05.03.00, 2010, Carl Zeiss NTS Ltd., UK with consumables bought through Agar Scientific, UK. Primary tensile tests were carried out on TST350 tensile stress tester (Linkam Scientific Instruments Ltd., UK) with a 200 N load cell and a cross-head speed of 15 µm $s^{-1}$ in combination with acoustic emission detection. Secondary tensile tests were carried out on Instron 5969, 1 kN load cell used with BlueHill3 software V3.41.2350 and a cross-head speed of 15 µm $s^{-1}$ in combination with optical video gauge, high speed camera and acoustic emission detection. Optical video gauge iMETRUM MG223B PoE E0022522 from iMETRUM Ltd (GB) using a iMETRUM material lens 233093 with a magnification 0.193, focal length 309 mm, triggered to record in sync with Instron 5969 using an iMETRUM multifunction box, NI USB 6211 and processed using the associated iMETRUM Video Gauge Software V5.3.2. Video gauge points of reference were droplets of epoxy formed on the composite bundles during curing and were lit using an LED array (Microbeam 512, Flolight, USA). High speed camera was used to validate failure within the gauge length; the Phantom v12.1 with PCC Version 1.3.697.0, Vision Research (Ameteck, USA) using focal length 100 mm, f/2, Zeiss Makro-Planar T* ZE lens. Acoustic emission (AE) events were recorded on PICO miniature, range 20 kHz to 500 kHz, AE sensor in conjunction with 1283 USB AE node interface and AEwin for USB software (vE5.30, Mistras Group Inc., Physical Acoustics Corporation, USA). Acoustic detection settings were set at 50 ms, 25 µs, 150 µs, 300 µs for time drive rate, peak definition time, hit definition time and hit lockout time, respectively. The AE sensor was held in a bespoke jaw fittings in both instances, which allowed the sensor face to be in contact with the tabbed sample region used with couplant gel (Sonagel W, Sonatest, UK). The ambient background threshold noise was 45

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and 65 dB for Linkam TST350 and Instron 5969 test rigs respectively, below which signals were not considered significant.

## 3. Results

Composite bundle stresses are calculated with respect to the carbon fibre cross-sectional area, determined by counting the reinforcing elements in each specimen (nominal $V_f$); then to aid comparison, stresses were also reduced to $V_f$ = 60%, in-line with conventional composites, and presented in Table 1. Stress-strain curves stresses, shown in Figure 4, are calculated using actual bundle cross-sections measured in the SEM. The average individual carbon fibre tensile strength for small composite bundles, is 9.6% higher than conventional composites, but lower than strengths reported for single fibre tensile tests (9.7% decrease). Primary tests were carried out on the Linkam TST350 with acoustic emission detection of carbon fibre fracture events monitored *in-situ*. Unfortunately, ambient background acoustic emission noise on the Instron 5969 rig was relatively high, ca. 65 dB, which meant the detection of acoustic events was restricted. Optical video gauge confirmed strain-to-failures for samples on the order of 1.6% to 2% for the secondary tests with high speed video confirming that failure point was within the gauge region. In the majority of instances a strain hardening behavior was observed, as predicted for carbon fibre [5]. In some instances the failure of small composite bundles is prolonged, for example in Figure 4 (#1, #4, #5, #7, #9 and #10), with progressive failure before ultimate failure.

**Table 1.** Small composite bundles tensile properties

| Sample | $X_t$ (MPa) | $E_t$ (GPa) |
|---|---|---|
| Linkam | | |
| Average individual carbon fibre contribution (in small composite bundles) | 4001 ± 240 | NA |
| Average small composite bundles ($V_f$ = 60 %) | 2400 ± 144 | NA |
| Instron | | |
| Average individual carbon fibre contribution (in small composite bundles) | 3922 ± 206 | 241 ± 39 |
| Average small composite bundles ($V_f$ = 60 %) | 2353 ± 123 | 144 ± 24 |
| Calculated from Hexcel data sheet [3] | | |
| Individual carbon fibre contribution in 0° HexPly 8552 composite ($V_f$ = 61%)* | 3614 | 231 |

*effective volume fraction if a concurrent tensile modulus is considered in a composite and single fibre

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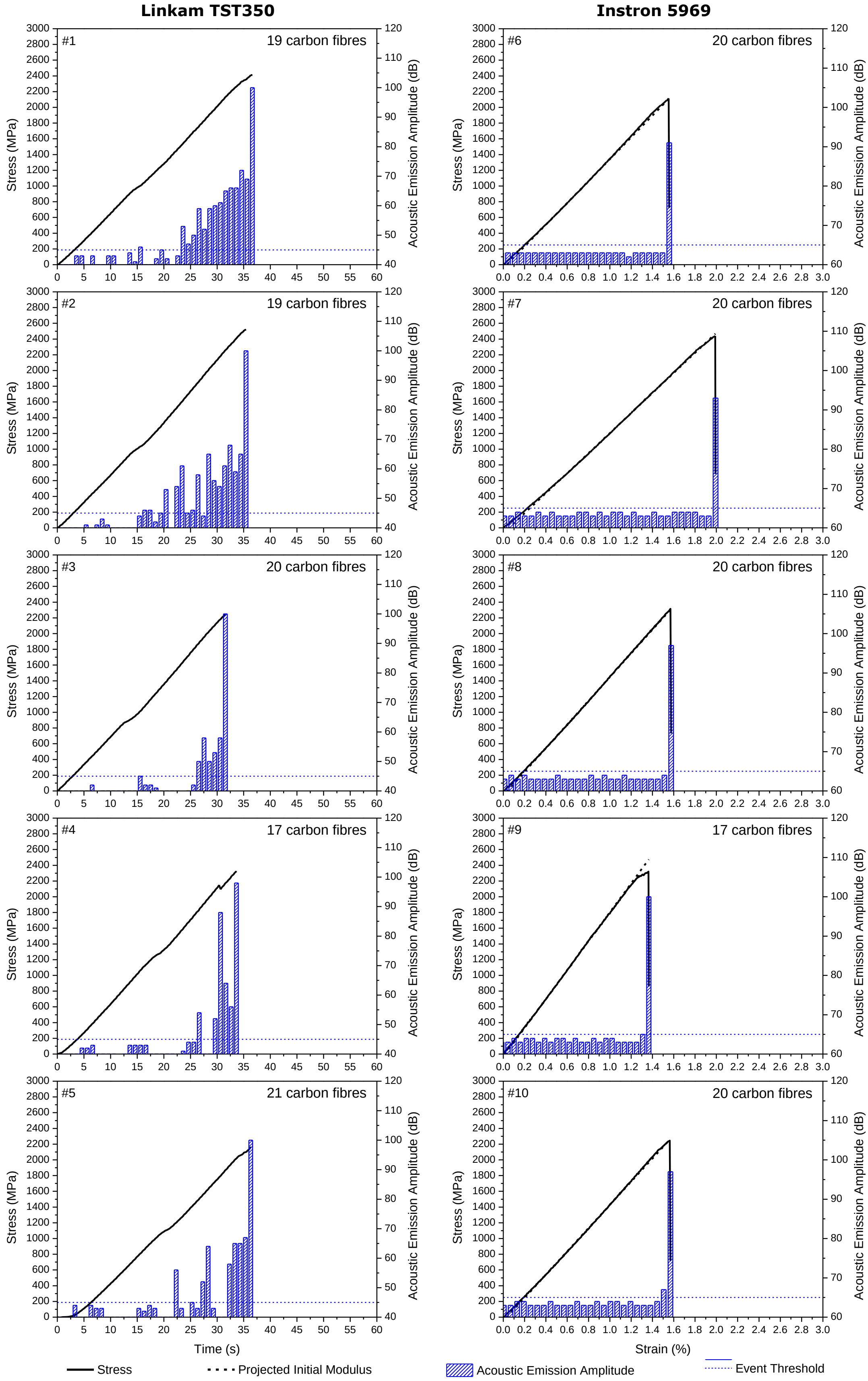


**Figure 4.** Small composite bundles, primary tests stress-time plots #1 to #5 (Linkam TST350), and secondary stress-strain plots #6 to #10 (Instron 5969) with optical video gauge determined strain.

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## 4. Conclusions

Small composite bundles containing ca. 20 carbon fibres were manufactured and tested in tension. The test results showed a progressive failure of the bundles, with acoustic emission indicating multiple carbon fibre fracture events prior to ultimate composite failure. The strength of small composite bundles was slightly higher (average 9.6%) than that typically observed in standard composite specimens (with approximately a million fibres in the cross-section of the specimen). The potential to combine multiple small composite bundles, as sub-bundles in a hierarchical arrangement, with a different matrix between sub-bundles, may yield a high performance yet (pseudo)ductile response under tension.

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