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EFFECTS OF TEMPERATURE AND ENVIRONMENT ON MECHANICAL PROPERTIES OF TWO CONTINUOUS CARBON-FIBER AUTOMOTIVE STRUCTURAL COMPOSITES

M. B. Ruggles-Wrenn

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Metals and Ceramics Division

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M. B. Ruggles-Wrenn

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EFFECTS OF TEMPERATURE AND ENVIRONMENT ON MECHANICAL PROPERTIES OF TWO CONTINUOUS CARBON-FIBER AUTOMOTIVE STRUCTURAL COMPOSITES

M. B. Ruggles-Wrenn

ABSTRACT

The Durability of Carbon-Fiber Composites Project was established at Oak Ridge National Laboratory (ORNL) by the U.S. Department of Energy to develop experimentally based, durability-driven design guidelines to assure the long-term (15-year) structural integrity of carbon-fiber-based composite systems for automotive structural applications. The project addressed characterization and modeling the durability of a progression of carbon-reinforced thermoset materials, each of which has the same urethane matrix. The primary purpose of this report is to provide the individual specimen test data. Basic mechanical property testing and results for a reference $[\pm45°]_{3S}$ crossply composite and a quasi-isotropic, $[0/90°/\pm45°]_S$ version of the reference crossply are provided. The matrix and individual ±45° stitch-bonded mats are the same in both cases. Although the composite utilized aerospace-grade carbon-fiber reinforcement, it was made by a rapid-molding process suitable for high-volume automotive use. Behavioral trends, effects of temperature and environment, and corresponding design knockdown factors are established for both materials. The reference crossply is highly anisotropic with two dominant fiber orientations — 0/90° and ±45°. Therefore properties were developed for both orientations.

1. INTRODUCTION

Development of lighter weight, more fuel-efficient automobiles represents a technology area where advanced materials can be successfully applied. The fuel efficiency of automobiles can be significantly enhanced by using lightweight materials, such as polymer matrix composites, in primary structural components. However, while significant effort is being devoted to material development and processing, commercial application of composite materials lags behind due, in part, to the lack of specific design guidance and an understanding of the material performance under actual service conditions. There is a recognized need for improved structural design methods and criteria that address deformation and failure behavior of composite materials.

The Durability of Carbon-Fiber Composites Project was established at Oak Ridge National Laboratory (ORNL) by the U.S. Department of Energy to develop the experimentally based, durability-driven design guidelines necessary to assure long-term (15-year) integrity of carbon-fiber-based composite systems that can be used to produce large structural automotive components. The plan for characterizing and modeling the durability of carbon-fiber composites was to focus on the following sequence of materials, each of which has the same urethane matrix:

- reference $[\pm45°]_{3S}$ crossply composite,
- $[0/90°/\pm45°]_S$ quasi-isotropic composite, and
- chopped-fiber composite.

The present report is a companion report to ORNL/TM-2003/114 and describes basic tensile, compressive, shear, and flexure property testing and results for the reference crossply and quasi-isotropic carbon-fiber composites produced by a rapid molding process suitable for high-volume automotive applications. The two composites had the same Baydur 420 IMR urethane matrix. The quasi-isotropic composite utilizes the same ±45° stitched-mat reinforcement as the reference crossply composite. The basic ply information from the reference crossply could thus be used as a basis for predicting and better understanding the behavior of the quasi-isotropic material.

Materials and specimen designs are presented in Chapter 2. Chapter 3 is dedicated to behavior of the crossply carbon-fiber composite. Experimental arrangements are described and tensile, compressive and shear test results are summarized for both fiber orientations. Effects of temperature and environment are assessed, corresponding design knockdown factors are established. In addition, effects of prior thermal cycling are discussed. Chapter 4 focuses on the quasi-isotropic carbon-fiber composite, giving a summary of tests and test results, as well as design knockdown factors to account for the effects of temperature and environment. Concluding remarks are made in Chapter 5.

2. MATERIALS AND SPECIMENS

The matrix for both materials used in this study was produced by the Bayer Corporation and identified as Baydur 420 IMR (Internal Mold Release). The basic matrix structure is a urea-urethane. The carbon-fiber laminate preforms consisted of Thornel T300 continuous fibers in tows of 6000 filaments. Stitch-bonded mats made of two unidirectional plies in a ±45° configuration were used. Six mats, $[\pm 45]_{3S}$, were used for the crossply laminate. Four mats, $[0/90,\pm 45°]_S$, were used for the quasi-isotropic laminate. The laminate thicknesses were 3.2 and 2.2 mm for the crossply and the quasi-isotropic materials, respectively. The fiber content for both carbon-fiber laminates was approximately 40 vol %.

Basic properties were established from stiffness, tensile, compressive, shear, and flexure tests. Untabbed dogbone-shaped tensile specimens were used[1] in all stiffness and tensile tests, which were performed according to the test method described in Ref. 1. Flat specimens with tabs were used in compression tests.[1] The tab material was G-11 composite, an epoxy reinforced with woven fiberglass cloth. The adhesive used for bonding the tabs to the test specimens was Hysol EA 93009NA A/B for the -40°C and 23°C tests and XEA 9364 A/B for the 120°C tests. Compression tests employed an IITRI fixture (Procedure B in ASTM D 3410[2]). The test method was as described in Ref. 1. The V-notched beam (Iosipescu) shear specimens and shear test method were as described in Ref. 1. The uniaxial flexural strength tests were performed according to the three-point-bend test method specified in the ASTM Standard D 790.1 (Ref. 3).

In the case of the crossply laminate, two fiber orientations were considered: 0/90° relative to the specimen axis and ±45°. These orientations result in two extremes of behavior. Under tensile loading, the behavior of the 0/90° specimens is fiber dominated, while for the ±45° fiber orientation, the behavior is matrix dominated. In the case of the 0/90° fiber orientation, the tab material and adhesive used for bonding the tabs to Iosipescu shear specimens were the same as for the compression specimens. For the ±45° fiber orientation, the tabs were cut from the same material as the specimens. The beam specimens were 25.4 mm x 76.2 mm. The loading rollers had a radius of 12.7 mm. The surface fibers in the 0/90° beams were at 90° to the beam axis, thus placing a weaker ply at the specimen surface. Poisson's ratio measurements were carried out using three specimens for each fiber orientation according to the test method described in Ref. 1.

In the case of the quasi-isotropic laminate, all tension and compression specimens were cut so that the surface fibers were at 90° to the specimen axis, thus placing a weaker ply at the specimen surface. All shear specimens were cut so that the surface fibers were at 0° to the specimen axis. The tab material and adhesive used for bonding the tabs to Iosipescu shear specimens were the same as for the compression specimens The uniaxial flexural strength tests were performed according with the three-point-bend test method specified in the ASTM Standard D 790.1 (Ref. 3). The uniaxial flexure tests employed 12.7 mm x 76.2 mm beam specimens. The loading rollers had a radius of 4.4 mm. Half of all beam specimens were cut so that the surface fibers were longitudinal (at an angle of 0° relative to the beam axis). These are referred to as L beams. Remaining beam specimens were cut with transverse surface fibers, and are referred to as T beams.

3. CROSSPLY CARBON-FIBER COMPOSITE

3.1 TENSILE PROPERTIES

3.1.1 Experimental Arrangements

All tests were performed in an air environment. A servocontrolled MTS axial-torsion mechanical testing machine together with an MTS digital TestStar Materials Testing Workstation was used for computerized testing and data acquisition. The load (engineering stress), strain, and displacement were measured and recorded; the digitized test data were stored on both hard and floppy disks. The data acquisition intervals were established on the basis of load, i.e. a data point was recorded whenever the load changed by 44.5 N. After the test the digitized data can be recalled for processing and interpretation. The entire history is available for analysis.

Specimens were mounted in mechanical wedge grips. Strain measurement was accomplished with an MTS 632.17E-20 averaging extensometer of 25.4-mm gage length. For the 0/90° specimens, elastic modulus, E, was measured in three load-controlled cycles between load levels of 2960 (corresponding to ≈ 10% of the UTS) and 6630 N (corresponding to ≈ 22% of the UTS) with a frequency of 0.1 Hz. In the case of the ±45° specimens, the load controlled cycles were between 445 N (corresponding to ≈ 5% of the UTS) and 1447 N (corresponding to ≈ 15% of the UTS). The recorded elastic modulus was established as the average value obtained during cycling. Tensile tests to failure were conducted in displacement control at a rate of 0.025 mm/s.

3.1.2 Room-Temperature Behavior

In-air room-temperature tensile stiffness values were established from 243 stiffness tests for the 0/90° fiber orientation and from 115 stiffness tests for ±45° fiber orientation. Results of stiffness tests are summarized in Tables 1 and 2 for the 0/90° and for the ±45° fiber orientations, respectively. In addition to the values of elastic modulus, E, Tables 1 and 2 include corresponding averages, standard deviations, and coefficients of variation.

Results of 91 tensile tests for the 0/90° fiber orientation are summarized in Table 3. Presented in Table 4 are results of 116 tensile tests for the ±45° fiber orientation. The ultimate tensile strength, UTS, and failure strain, ε_f, are shown in Tables 3 and 4 together with the overall average, A, standard deviation, S, and coefficient of variation, C_V, for each of the properties determined.

Stiffness and tensile test results are recapitulated in Tables 5 and 6, for the 0/90° and the ±45° fiber orientations, respectively. Shown in Tables 5 and 6 are the number of stiffness and tensile tests conducted on specimens from each particular plaque and the plaque averages of the tensile properties E, UTS, and ε_f. Plaques are referred to using the ORNL nomenclature. Tables 5 and 6 permit an assessment of plaque-to-plaque variations in tensile properties. Overall averages of the tensile properties are included at the bottom of Tables 5 and 6.

The effect of strain rate on tensile behavior was investigated in thirty-two tests conducted at the following constant strain rates: 10^{-6}, 10^{-4}, 10^{-2}, and 10 s^{-1}. Four tests were performed at each strain rate for each fiber orientation. Results are summarized in Tables 7 and 8, for the 0/90° and the ±45° fiber orientations, respectively.

3.1.3 Effects of Temperature

Effects of temperature on tensile properties of the crossply carbon-fiber composite, 0/90° fiber orientation, were assessed in thirty-three tensile tests on specimens from plaques C1 and C5 (6 tests at -40°C and 9 tests at each of the following temperatures: 23, 50, and 120°C). For the

±45° fiber orientation, the temperature effects were assessed in thirty tensile tests on specimens from plaque C11 (12 tests at 70°C and 6 tests at each of the following temperatures: -40, 23, and 120°C). Results are summarized in Tables 9 and 10, for the 0/90° and the ±45° fiber orientations, respectively. Virgin (room-temperature) stiffness, at-temperature stiffness, UTS, and failure strain are shown in Tables 9 and 10 together with the stiffness and strength temperature factors for each specimen. The stiffness temperature factor is defined as the ratio of at-temperature stiffness for a particular specimen to the virgin room-temperature stiffness. The strength temperature factor is defined as the ratio of the at-temperature UTS for a particular specimen to the average UTS obtained at room-temperature for specimens from the same plaque.

Results in Tables 9 and 10 were used to derive temperature multiplication factors to determine at-temperature stiffness and strength from room-temperature values. The factors are presented in Tables 11 and 12, for the 0/90° and the ±45° fiber orientations, respectively. The detailed derivation of the temperature multiplication factors can be found in Ref. 4.

For the 0/90° specimens, Poisson's ratio measurements were carried out by subjecting three tensile specimens to five load-controlled cycles between load levels of 2960 (corresponding to ≈ 10% of the UTS) and 6630 N (corresponding to ≈ 22% of the UTS) with a frequency of 0.1 Hz. In the case of the ±45° specimens, the load-controlled cycles were between 445 N (corresponding to ≈ 5% of the UTS) and 1447 N (corresponding to ≈ 15% of the UTS). Each specimen was tested at -40, 23, 70, and 120°C. Using very low loads ensures that damage was not introduced at each temperature. Poisson's ratio values are summarized in Tables 13 and 14, for the 0/90° and the ±45° fiber orientations, respectively.

The effects of prior thermal cycling on basic properties of the crossply carbon-fiber composite were investigated in six tensile and six compressive tests for each fiber orientation. In addition, short-beam shear specimens with a 3- by 6-mm cross-section (six for each fiber orientation) were included in this test series. The short-beam shear specimens were tested in three-point bending with a span of 12.5 mm. Prior to testing, specimens were subjected to 20 thermal cycles. A thermal cycle between –40 and 120°C (shown in Ref. 4) was chosen to reflect the automotive design temperature range. Tension and compression results are summarized in Tables 15 and 16 for the 0/90° and the ±45° fiber orientations, respectively. Results of the short-beam shear tests are presented in Tables 17 and 18 for the 0/90° and the ±45° fiber orientations, respectively.

3.1.4 Effects of Environment

Environmental screening tests were performed to determine which automotive fluids have a degrading effect on strength. Short-beam shear specimens, having the highest edge-to-face area ratio, were used in this study. All specimens were cut from the same plaque. The 0/90 specimens had 0° fibers on the surface. Details of the nine automotive fluids used in the screening can be found in Ref. 4. Twelve specimens were pre-exposed in each fluid, six for each fiber orientation. Exposure time for all fluids except battery acid was 1000 h. In the case of battery acid, exposure time was reduced to 115 h. Short-beam shear specimens were tested in accordance with the ASTM Standard D 2344[5]. Results are summarized in Tables 19 and 20 for the 0/90° and the ±45° fiber orientations, respectively. Note that results obtained for the unexposed short-beam shear specimens are given in Tables 17 and 18 above.

Effects of moisture on tensile properties of the crossply carbon-fiber composite were investigated with the purpose of establishing correlations between exposure time and weight change, and subsequently, strength and stiffness. For each fiber orientation, six specimens were exposed in room-temperature distilled water and six specimens, in 70% relative humidity (RH) air. All specimens were initially in the "as-received" condition. Effects of exposure in 23°C distilled water and in 70% RH air on tensile properties are summarized in Tables 21 and 22 for the 0/90° and the ±45° fiber orientations, respectively. Included in Tables 21 and 22 are the virgin stiffness, post-exposure stiffness and strength, as well as the values of percent change in strength and stiffness for given exposure times. The change in stiffness is calculated with reference to the virgin stiffness of each individual specimen. The change in strength is calculated with reference to the plaque average strength. A detailed discussion of moisture sorption and correlations between exposure time, weight change, and property changes can be found in Ref. 4.

In addition to these conditions, the effects of exposure to freezing temperatures on stiffness and strength of the material when saturated or nearly saturated with water were considered. Twelve tensile specimens for each fiber orientation were soaked in room-temperature distilled water for 1000 h. Six of the twelve specimens were tested after exposure. The remaining six specimens were exposed overnight to a temperature of –15°C and then tested. Changes in stiffness and strength due to exposure to distilled water, as well as to the water exposure followed by subfreezing overnight, were assessed and compared. As before, changes in stiffness were calculated with reference to the virgin stiffness for each specimen, while changes in strength were referenced to the plaque average strength. Results are summarized in Tables 23 and 24 for the 0/90° and the ±45° fiber orientations, respectively. Note that all 0/90° specimens came from a single plaque (C-15), as did the ±45° specimens (C-17).

The effects of exposure in windshield washer fluid (30% distilled water and 70% methanol) were investigated. Windshield washer fluid was selected as a practical exposure condition, because methanol in windshield washer fluid is a "lighter molecule". Exposure times were 50, 100, and 1000 h. Results are summarized in Tables 25 and 26 for the 0/90° and the ±45° fiber orientations, respectively. Virgin stiffness, post-exposure stiffness, UTS and failure strain are given in Tables 25 and 26 for each specimen. Also included in Tables 25 and 26 are environmental knockdown factors for design. Stiffness design factor is defined as the ratio of post-exposure stiffness to virgin stiffness of that particular specimen. Strength design factor is calculated as the ratio of the post-exposure UTS to the average UTS obtained in tensile tests on unexposed specimens from the same plaque.

3.2 COMPRESSIVE PROPERTIES

All tests were performed at room temperature in an air environment. Specimens were mounted in an IITRI Compression Test Fixture according to the ASTM Standard D 3410[3]. Compressive tests to failure were conducted in displacement control at a rate of 0.025 mm/s. Strain measurement was accomplished with two strain gages mounted in the gage section of the specimen, one strain gage on each side of the specimen. In most tests the two strain gages produced strain measurements that were approximately the same. The two strain measurements were averaged and the average strains were used for reporting data. The data acquisition intervals were established on the basis of load, i.e. a data point was recorded whenever the load changed by 44.5 N. For the 0/90° specimens, compressive stiffness, E_C, was calculated using linear regression for the initial stress-strain slope between the loads of 2960 and 6630 N. In the case of the ±45° the load interval between 445 and 1447 N was used in calculations.

Eighteen 0/90° and six ±45° compression specimens were tested at room temperature. Test results are summarized in Table 27, where compressive stiffness, E_c and ultimate compressive strength (UCS) are given together with failure strain for each specimen. The effect of temperature on compressive properties of the 0/90° fiber orientation was investigated in eight tests each at -40, 50, and 120°C. In the case of the ±45° fiber orientation, effects of temperature were assessed in six compression tests each at -40, 23, 70, and 120°C. Test results are summarized in Tables 28 and 29 for the 0/90° and ±45° fiber orientations, respectively. Results in Tables 28 and 29 were used to derive temperature multiplication factors to determine at-temperature compressive stiffness and strength from room-temperature values (See Ref 4). The factors are presented in Tables 30 and 31 for the 0/90° and ±45° fiber orientations, respectively.

Effects of 1000-h exposure in 23°C distilled water on compressive properties of the crossply composite were investigated using six pre-exposed specimens each for the 0/90° and ±45° fiber orientations. Results are summarized in Table 32, where compressive stiffness, UCS and failure strain are given together with knockdown design factors for each specimen. The stiffness (strength) design factor is defined as the ratio of the post-exposure stiffness (strength) to the average stiffness (strength) obtained in compression tests on unexposed specimens from the same plaque.

Effects of exposure to windshield washer fluid on compressive strength of the crossply carbon-fiber composite were investigated using twelve pre-exposed specimens (six pre-exposed for 50 h and six for 100 h) each for the 0/90° and ±45° fiber orientations. Results are summarized in Table 33. Note that in the case of windshield washer fluid, compressive stiffness values were not measured. Application of strain gages, required for compressive stiffness determinations, would have resulted in excessive loss of the absorbed methanol due to evaporation during gage installation.

3.3 SHEAR PROPERTIES

In-air room-temperature shear properties of the crossply carbon-fiber composite were established based on twenty-one Iosipescu shear tests for the 0/90° fiber orientation, and on six tests for the ±45° fiber orientation. Test results are summarized in Table 34.

For each fiber orientation, the effect of temperature on shear properties was investigated in six tests each at -40, 70, and 120°C. Test results are summarized in Tables 35 and 36 for the 0/90° and ±45° fiber orientations, respectively. Results in Tables 35 and 36 were used to derive temperature multiplication factors to determine at-temperature stiffness and strength from room-temperature values (See Ref 4). The factors are presented in Tables 37 and 38 for 0/90° and ±45° fiber orientations, respectively.

Effects of 1000-h exposure in 23°C distilled water on shear properties of the crossply composite were investigated using six pre-exposed specimens each for the 0/90° and ±45° fiber orientations. Results are summarized in Table 39, where shear modulus, shear strength, and knockdown design factors are presented for each specimen. The stiffness (strength) design factor is defined as the ratio of the post-exposure stiffness (strength) to the average stiffness (strength) obtained in compression tests on unexposed specimens from the same plaque.

Effects of exposure to windshield washer fluid on shear strength of the crossply carbon-fiber composite were investigated using twelve pre-exposed specimens (six pre-exposed for 50 h and six for 100 h) each for the 0/90° and ±45° fiber orientations. Results are summarized in Table 40. Note that in the case of windshield washer fluid, shear modulus values were not measured. Application of strain gages, required for shear specimens, would have resulted in excessive loss of the absorbed methanol due to evaporation during gage installation.

3.4 UNIAXIAL AND BIAXIAL FLEXURAL PROPERTIES

3.4.1 Uniaxial flexural properties

The uniaxial flexural strength tests were performed in accordance with the three-point bend test method specified in ASTM Standard D 790[5]. The specimen width was 25.4 mm, the overall specimen length was 76.2 mm, and the support span was 50.8 mm (see Ref. 4). The loading rollers had a radius of 12.7 mm.

For each fiber orientation, uniaxial flexure properties were established based on six tests each at 23 and 120°C. Results are presented in Table 41. The strength values are reported in terms of the modulus of rupture (MOR), which is the maximum bending stress at rupture calculated using simple elastic beam theory for an isotropic, homogeneous material. Because the MOR calculations ignore the composite inhomogeneity, results are somewhat qualitative, but nonetheless useful for establishing environmental and temperature multiplication factors. Likewise the "modulus of elasticity" values tabulated are just apparent values based on the assumption that the composite is homogeneous, isotropic, and elastic.

Effects of 1000-h exposure in 23°C distilled water on uniaxial flexure properties of the crossply composite were investigated using six pre-exposed specimens each for the 0/90° and ±45° fiber orientations. Results are summarized in Table 42, where MOR and a corresponding knockdown design factor are given for each specimen. Effects of exposure to windshield washer fluid on uniaxial flexural properties of the crossply carbon-fiber composite were investigated using twelve pre-exposed specimens (six pre-exposed for 50 h and six for 100 h) each for the 0/90° and ±45° fiber orientations. Results are summarized in Table 43.

3.4.2 Biaxial flexural properties

The test specimen together with the support and loading arrangement used for biaxial flexural tests were as described in Chap. 8 of Ref. 4. The specimen outside diameter was 94 mm, and the nominal thickness was 3.2 mm. The load-ring diameter was 38.1 mm, while the support-ring diameter was 88.9 mm. Six specimens were tested each at room temperature, and at 120°C. Results are summarized in Table 44 for the ±45° composite fiber orientation. Biaxial flexure results are presented in terms of the failure load and used in this way to establish temperature multiplication factors, which are defined as the ratios of the at-temperature failure load to the average room-temperature failure load.

Effects of 1000-h exposure in 23°C distilled water and of 100-h exposure in windshield washer fluid on biaxial flexure properties of the crossply composite were investigated using six pre-exposed specimens for each condition. Results are summarized in Table 45 for the ±45° composite fiber orientation, where maximum load and a corresponding knockdown design factor are given for each specimen.

4. QUASI-ISOTROPIC CARBON-FIBER COMPOSITE

4.1 TENSILE PROPERTIES

4.1.1 Room-Temperature Behavior

Experimental arrangements were as described in Sect. 3.1.1. Elastic modulus, E, was measured in three load-controlled cycles between load levels of 445 N (corresponding to ≈ 3% of the UTS) and 2224 N (corresponding to ≈ 15% of the UTS) with a frequency of 0.1 Hz. Results of stiffness and tensile tests are summarized in Tables 46 and 47. Values of elastic modulus, E, obtained in 456 stiffness tests are presented in Table 46. The ultimate tensile strength, UTS, and failure strain, ε_f, produced in 86 tensile tests to failure are summarized in Table 47. Also given in Tables 46 and 47 are the overall average, A, standard deviation, S, and coefficient of variation, C_V, for each of the material properties determined.

Stiffness and tensile test results are recapitulated in Table 48, where the number of stiffness and tensile tests conducted on specimens from each particular plaque and the plaque averages of the tensile properties E, UTS, and ε_f, are given. Plaques are referred to using the ORNL nomenclature. Table 48 permits an assessment of plaque-to-plaque variations in tensile properties. Overall averages of the tensile properties are included at the bottom of Table 48.

The effect of strain rate on tensile behavior was investigated in four tests conducted at each of the following constant strain rates: 10^{-6}, 10^{-4}, 10^{-2}, and 10 s^{-1}. Results are summarized in Table 49.

4.1.2 Effects of Temperature

Effects of temperature on tensile properties of the quasi-isotropic carbon-fiber composite were assessed in six tests at each of the following temperatures: -40, 23, 50, 70, and 120°C, and in five tests at -10°C. All 35 tests in the temperature study were conducted on specimens from a single plaque Q11. Results are summarized in Table 50, where the virgin (room-temperature) stiffness is shown together with the at-temperature stiffness, UTS, and failure strain. Also given in Table 50 are stiffness and strength temperature factors for each specimen. Stiffness temperature factor is defined as the ratio of at-temperature stiffness for a particular specimen to the room-temperature stiffness. Strength temperature factor is defined as the ratio of the at-temperature UTS for a particular specimen to the average UTS obtained at room-temperature for specimens from the same plaque. Results in Table 50 were used to derive temperature multiplication factors to determine at-temperature stiffness and strength from room-temperature values. The factors are presented in Table 51. The detailed derivation of the temperature multiplication factors can be found in Ref. 6.

Poisson's ratio measurements were carried out by subjecting five tensile specimens to 5 load-controlled cycles between 445 N (corresponding to ≈ 3% of the room-temperature UTS) and 2224 N (corresponding to ≈ 15% of the room-temperature UTS) at a frequency of 0.1 Hz. Each specimen was tested at -40, 23, 70, and 120°C. Using very low loads ensures that damage was not introduced at each temperature. Poisson's ratio values summarized in Table 52.

The effects of prior thermal cycling on basic properties of the quasi-isotropic carbon-fiber composite were investigated in six tensile, four compressive, and four shear tests. Prior to testing, specimens were subjected to 26 thermal cycles. A thermal cycle between –40 and 120°C (shown in Ref. 6) was chosen to reflect the automotive design temperature range. Results are summarized in Table 53. Results in Table 53 demonstrate that thermal cycling has no significant effect on fiber-dominated properties.

4.1.3 Effects of Environment

Effects of moisture on tensile properties of the quasi-isotropic carbon-fiber composite were investigated with the purpose of establishing correlations between exposure time and weight change, and subsequently, strength and stiffness. One group of specimens was exposed in 23°C distilled water. Another group was exposed in 70% relative humidity (RH) air. All specimens were kept in 40% RH air for one week prior to exposure. Effects of exposure in 23°C distilled water and in 70% RH air on tensile properties are summarized in Tables 54 and 55, respectively. Included in Tables 54 and 55 are the virgin stiffness, post-exposure stiffness and strength, as well as the values of percent change in strength and stiffness for given exposure times. The change in stiffness is calculated with reference to the virgin stiffness of each individual specimen. The change in strength is calculated with reference to the plaque average strength. A detailed discussion of moisture sorption and correlations between exposure time, weight change, and property changes is given in Ref. 6.

The effects of exposure in windshield washer fluid (30% distilled water and 70% methanol) on tensile properties were investigated. Windshield washer fluid was selected as a practical exposure condition because methanol in windshield washer fluid is a "lighter molecule". Exposure time was 100 h. Test results are summarized in Table 56, where virgin stiffness, post-exposure stiffness and UTS are given for each specimen. Also included in Table 56 are environmental knockdown factors for design. Stiffness design factor is defined as the ratio of post-exposure stiffness to virgin stiffness of that particular specimen. Strength design factor is calculated as the ratio of the post-exposure UTS to the average UTS obtained in tensile tests on unexposed specimens from the same plaque.

4.2 COMPRESSIVE PROPERTIES

All tests were performed at room temperature in an air environment. Test procedure was as described in Sect. 3.2. Compressive stiffness, E_C, was calculated using linear regression for the stress-strain slope between the loads of 445 and 2224 N. Forty specimens from 9 different plaques were tested at 23°C. Test results are summarized in Table 57.

The effect of temperature on compressive properties of the quasi-isotropic carbon-fiber composite was investigated in five tests each at -40, 70, and 120°C. All compression specimens in the temperature-dependence study came from plaque Q18. Test results are summarized in Table 58. Results in Table 58 were used to derive temperature multiplication factors to determine at-temperature compressive stiffness and strength from room-temperature values (See Ref 4). The factors are presented in Table 59.

Effects of 1000-h exposure in 23°C distilled water on compressive properties of the quasi-isotropic composite were investigated using six baseline and five pre-exposed specimens from plaque Q18. Results for the pre-exposed specimens are summarized in Table 60, where compressive stiffness, UCS and knockdown design factors are presented for each specimen. The stiffness (strength) design factor is defined as the ratio of the post-exposure stiffness (strength) to the average stiffness (strength) obtained in compression tests on unexposed specimens from the same plaque.

Effects of 100-h exposure to windshield washer fluid on compressive strength of the quasi-isotropic composite were investigated using six baseline and six pre-exposed specimens from plaque Q18. Results are summarized in Table 61. Note that in the case of windshield washer fluid, compressive stiffness values were not measured. Application of strain gages, required for compressive specimens, would have resulted in excessive loss of the absorbed methanol due to evaporation during gage installation.

4.3 SHEAR PROPERTIES

In-air room-temperature shear properties of the quasi-isotropic carbon-fiber composite were established based on eight Iosipescu shear tests on specimens from a single plaque. Test results are summarized in Table 62.

The effect of temperature on shear properties of the quasi-isotropic carbon-fiber composite was investigated in five tests each at 70 and 120°C and in four tests at -40°C. All specimens came from plaque Q18. Test results summarized in Table 63. Results in Table 63 were used to derive temperature multiplication factors to determine at-temperature stiffness and strength from room-temperature values (See Ref 4). The factors are presented in Table 64.

Effects of 1000-h exposure in 23°C distilled water on shear properties of the quasi-isotropic composite were investigated using six pre-exposed specimens from plaque Q18. Results are summarized in Table 65, where shear modulus, shear strength, and strength factors are presented for each specimen. The stiffness (strength) design factor is defined as the ratio of the post-exposure stiffness (strength) to the average stiffness (strength) obtained in shear tests on unexposed specimens from the same plaque.

Effects of 100-h exposure in windshield washer fluid on shear strength of the 3-mm-thick composite were investigated using six pre-exposed specimens from plaque Q18. Results are summarized in Table 66. Note that in the case of windshield washer fluid, shear stiffness values were not measured. Application of strain gages, required for compressive and shear specimens, would have resulted in excessive loss of the absorbed methanol due to evaporation during gage installation.

4.4 UNIAXIAL AND BIAXIAL FLEXURAL PROPERTIES

4.4.1 Uniaxial flexural properties

The uniaxial flexural strength tests were performed in accordance with the three-point bend test method specified in ASTM Standard D 790[5]. The specimen width was 12.7 mm, the overall specimen length was 76.2 mm, and the support span was 50 mm (see Ref. 6). The loading rollers had a radius of 4.4 mm.

Seventy-two specimens were tested. All came from a single plaque, Q19. The UTS for this plaque was determined to be 346 MPa. Thirty-six specimens were cut so that the surface fibers were longitudinal (at an angle of 0° relative to the beam axis). These are referred to as L beams. The other 36 beams were cut so that surface fibers were transverse. They are referred to as T beams.

The strength values are reported in terms of the modulus of rupture (MOR), which is the maximum bending stress at rupture calculated using simple elastic beam theory for an isotropic, homogeneous material. Because the MOR calculations ignore the composite inhomogeneity, results are somewhat qualitative, but nonetheless useful for establishing environmental and temperature multiplication factors.

The MOR values at -40, 23, 70, and 120°C were established based on 6 tests on L beams and 6 tests on T beams at each temperature (a total of 48 tests). Results are presented in Table 67. Temperature multiplication factors (defined as the ratio of at-temperature MOR to the room-temperature MOR value) present the MOR at each temperature in terms of the room-temperature baseline value.

The effects of environment on uniaxial flexure properties of quasi-isotropic carbon-fiber composite were assessed using the standard exposures in 23°C distilled water and windshield washer fluid. For each standard exposure, six L beams and six T beams were tested. Test results and the resulting fluid strength-multiplication factors are presented in Tables 68 and 69 for exposures in distilled water and windshield washer fluid, respectively.

4.4.2 Biaxial flexural properties

The test specimen together with the support and loading arrangement used for biaxial flexural tests were as described in Chap. 8 of Ref. 6. The specimen outside diameter was 94 mm. The load-ring diameter was 38.1 mm, while the support-ring diameter was 88.9 mm. Six specimens were tested at room temperature, and six at 120°C. Results are summarized in Table 70. Biaxial flexure results are presented in terms of the failure load and used in this way to establish temperature multiplication factors, which are defined as the ratios of the at-temperature failure load to the average room-temperature failure load.

To explore fluid effects, six specimens presoaked for 100 h in windshield washer fluid and five specimens presoaked for 1000 h in room-temperature distilled water were also tested. All tests were conducted in the laboratory air environment. Results are summarized in Table 71.

5. SUMMARY

5.1 CROSSPLY CARBON-FIBER COMPOSITE

- The crossply carbon-fiber composite is highly anisotropic with a fiber-dominated 0/90° orientation and a matrix-dominated ±45° orientation. The room-temperature 0/90° stiffness is more than four times the corresponding ±45° value. This difference increases to almost seven times at 120°C.
- For the 0/90° fiber orientation, the room-temperature compressive strength, which is matrix-dominated, is only about 0.90 of the tensile strength, which is strongly fiber dominated. This difference increases with increasing temperature.
- For the ±45° fiber orientation, the compressive strength is greater than the tensile strength over the temperature range, except near 120°C, where it drops below the tensile strength by about 1.2%.
- Basic properties at different temperatures were established for both fiber orientations. Temperature factors for determining baseline properties at different temperature from room-temperature values were provided.
- The ±45° strength and stiffness increase with increasing strain rate. The 0/90° strength and stiffness appear to be relatively independent of strain rate.
- Effects of exposure in distilled water and windshield washer fluid were investigated. A stiffness reduction factor of 0.93 covers degrading effects for the two standard bounding fluid exposures, 1000 h in room-temperature distilled water and 100 h in windshield washer fluid.
- Uniaxial and biaxial flexure properties were established, effects of temperature and environment on flexure were assessed.

5.2 QUASI-ISOTROPIC CARBON-FIBER COMPOSITE

- Room-temperature stiffness values in tension and compression are comparable.
- Room-temperature tensile strength is approximately 1.5 times compressive strength. The low compressive strength is most likely due to specimen geometry. Thin compressive specimens are likely to fail in a buckling mode at a lower stress.
- Basic properties at different temperatures were established. Temperature factors for determining baseline properties at different temperature from room-temperature values were provided.
- Strain rate effects were found to be relatively small, except at the fastest rate examined.
- Prior thermal cycling was found to have a significant effect on matrix-dominated properties.
- The study of fluid effects revealed that the moisture absorption process reaches saturation at about 3000 h for both room-temperature distilled water and for 70% RH air.
- A single reduction factor of 0.94 can be used to bound the effects of both standard exposures (1000 h in room-temperature distilled water and 100 h in windshield washer fluid) on stiffness and strength.
- Uniaxial and biaxial flexure tests were conducted. Effects of temperature and environment on uniaxial and biaxial flexure were explored.

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4. J. M. Corum, R. L. Battiste, S. Deng, K. C. Liu, M. B. Ruggles, and Y. J. Weitsman, *Durability-Based Design Properties of Reference Crossply Carbon-Fiber Composite*, ORNL/TM-2000/322, Oak Ridge National Laboratory, Oak Ridge, Tenn., 2000.
5. ASTM Standard D 2344, *Test Methods for Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short Beam Method*, American Society for Testing and Materials.
6. J. M. Corum, R. L. Battiste, S. Deng, M. B. Ruggles-Wrenn, and Y. J. Weitsman, *Durability-Based Design Criteria for a Quasi-Isotropic Carbon-Fiber Automotive Composite*, ORNL/TM-2002/39, Oak Ridge National Laboratory, Oak Ridge, Tenn., 2002.

Table 1. Summary of room-temperature stiffness values for the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)
C1-1	48.2	C2-11	49.0	C3-22	42.2	C4-33	41.4
C1-2	51.0	C2-12	48.1	C3-23	42.2	C4-34	40.1
C1-3	44.7	C2-13	47.3	C3-24	41.1	C4-35	39.0
C1-4	47.2	C2-14	46.7	C3-25	42.8	C4-36	39.5
C1-5	44.6	C2-15	44.9	C3-26	42.9	C5-1	47.0
C1-6	44.3	C2-16	46.9	C3-27	41.8	C5-2	46.8
C1-7	45.0	C2-17	49.4	C3-28	39.4	C5-3	41.9
C1-8	44.3	C2-18	49.0	C3-29	43.8	C5-4	44.3
C1-9	49.6	C2-19	45.3	C3-30	40.2	C5-5	45.4
C1-10	46.9	C2-20	44.5	C3-31	42.6	C5-6	46.8
C1-11	46.4	C2-21	44.6	C3-32	43.7	C5-7	44.1
C1-12	47.8	C2-22	47.4	C3-33	46.1	C5-8	46.0
C1-13	44.1	C2-23	44.3	C3-34	41.9	C5-9	46.5
C1-14	47.0	C2-24	46.3	C3-35	42.7	C5-10	43.6
C1-15	43.6	C2-25	44.1	C3-36	38.9	C5-11	45.4
C1-16	48.7	C2-26	44.2	C4-1	44.9	C5-12	47.3
C1-17	46.3	C2-27	42.2	C4-2	43.8	C5-13	48.2
C1-18	44.2	C2-28	42.0	C4-3	44.9	C5-14	47.2
C1-19	42.5	C2-29	43.3	C4-4	36.8	C5-15	45.4
C1-20	42.3	C2-30	45.8	C4-5	46.7	C5-16	45.6
C1-21	44.5	C2-31	48.8	C4-6	45.1	C5-17	44.1
C1-22	45.1	C2-32	48.7	C4-7	43.1	C5-18	42.7
C1-23	45.2	C2-33	44.9	C4-8	42.0	C5-19	43.9
C1-24	44.4	C2-34	43.7	C4-9	45.2	C5-20	43.8
C1-25	44.7	C2-35	45.6	C4-10	45.4	C5-21	44.4
C1-26	45.2	C2-36	42.3	C4-11	44.6	C5-22	43.5
C1-27	42.3	C3-1	46.7	C4-12	46.4	C5-23	38.7
C1-28	39.7	C3-2	44.3	C4-13	46.3	C5-24	41.6
C1-29	46.6	C3-3	41.8	C4-14	45.3	C5-25	43.1
C1-30	48.0	C3-4	44.3	C4-15	44.9	C5-26	44.5
C1-31	42.6	C3-5	47.2	C4-16	44.8	C5-27	42.3
C1-32	42.8	C3-6	45.4	C4-17	43.2	C5-28	40.3
C1-33	42.2	C3-7	42.5	C4-18	45.0	C5-29	43.0
C1-34	39.9	C3-8	43.1	C4-19	43.0	C5-30	42.9
C1-35	40.5	C3-9	45.5	C4-20	41.8	C5-31	42.6
C1-36	42.5	C3-10	45.7	C4-21	41.9	C5-32	41.2
C1-D-28	40.8	C3-11	46.3	C4-22	37.9	C5-33	42.3
C2-1	52.5	C3-12	50.1	C4-23	40.0	C5-34	43.3
C2-2	48.2	C3-13	48.8	C4-24	40.0	C5-35	42.4
C2-3	50.3	C3-14	47.2	C4-25	40.6	C5-36	40.3
C2-4	48.5	C3-15	43.9	C4-26	44.0	C12-1	46.2
C2-5	45.7	C3-16	46.4	C4-27	41.6	C12-19	41.3
C2-6	47.8	C3-17	43.1	C4-28	39.0	C12-29	44.4
C2-7	42.5	C3-18	46.1	C4-29	43.0	C12-36	40.9
C2-8	44.4	C3-19	43.5	C4-30	40.7	C13-1	41.7
C2-9	46.4	C3-20	43.7	C4-31	36.5	C13-9	45.6
C2-10	49.2	C3-21	39.5	C4-32	38.8	C13-19	36.5

Table 1. Summary of room-temperature stiffness values for the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)
C13-36	37.5	C19-19	49.1	C25-2	50.5	C48-5	48.8
C15-1	49.3	C19-36	43.2	C25-3	51.5	C52-13	44.9
C15-9	46.4	C21-1	48.7	C27-2	52.5	C52-15	49.2
C15-12	49.0	C21-9	50.3	C27-3	51.2	C52-17	49.7
C15-15	56.8	C21-19	50.0	C27-4	47.5	C52-19	44.5
C15-19	46.3	C21-36	53.7	C27-5	50.0	C52-21	47.2
C15-27	51.2	C22-1	49.3	C28-2	50.4	C56-1	44.1
C15-31	49.3	C22-9	50.3	C28-3	50.2	C56-9	46.7
C15-36	42.7	C22-19	49.8	C28-4	51.4	C56-19	49.6
C18-1	46.0	C22-36	44.5	C28-5	51.2	C56-36	48.7
C18-9	49.2	C23-1	47.0	C46-2	51.0		
C18-19	42.0	C23-9	49.2	C46-3	48.7	**Average**	45.2
C18-36	41.1	C23-19	48.5	C46-4	52.3	**SD**	3.76
C19-1	68.7	C23-36	48.9	C46-5	45.8	**COV(%)**	8.33
C19-9	46.8	C25-1	48.3	C48-4	50.5		

Table 2. Summary of room-temperature stiffness values for the crossply carbon-fiber composite, ±45° fiber orientation

Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)
C6-6	11.3	C32-7	11.0	C44-3	10.8
C6-29	10.4	C33-1	10.5	C44-5	10.7
C6-53	10.5	C33-3	9.85	C44-7	10.6
C9-3	11.0	C33-5	9.89	C45-1	12.6
C9-29	9.74	C33-7	10.8	C45-3	12.0
C9-56	10.0	C34-1	10.3	C45-5	12.1
C9-58	10.5	C34-3	10.7	C45-7	12.6
C11-3	10.9	C34-5	10.1	C46-1	12.1
C11-18	10.5	C34-7	11.6	C46-6	13.0
C11-29	10.2	C35-1	10.4	C46-7	13.4
C11-30	10.1	C35-3	9.94	C46-8	12.6
C11-41	9.69	C35-5	10.3	C48-1	12.4
C11-56	9.40	C35-7	10.5	C48-2	13.1
C14-3	10.5	C36-1	10.5	C48-3	12.5
C14-6	12.3	C36-3	10.3	C52-1	12.3
C14-15	12.4	C36-5	10.7	C52-3	10.8
C14-29	11.0	C36-7	10.4	C52-5	10.7
C14-44	10.4	C37-1	10.9	C52-7	10.8
C14-56	10.1	C37-3	10.3	C52-9	11.0
C16-3	11.4	C37-5	10.3	C52-11	11.4
C16-29	10.4	C37-7	10.6	C57-3	12.1
C16-56	9.51	C38-1	10.8	C57-29	11.3
C17-3	11.2	C38-3	10.3	C57-56	11.1
C17-29	10.2	C38-5	10.4		
C17-56	9.17	C38-7	10.0	**Average**	11.3
C20-3	13.8	C39-1	11.4	**SD**	1.44
C20-29	13.2	C39-3	10.4	**COV(%)**	12.7
C20-56	12.1	C39-5	10.1		
C24-3	13.0	C39-7	9.91		
C24-29	12.1	C40-1	11.1		
C24-56	13.0	C40-3	11.0		
C26-3	16.5	C40-5	10.4		
C26-56	15.3	C40-7	10.1		
C27-1	14.1	C41-1	10.6		
C27-6	13.5	C41-3	10.5		
C27-7	14.3	C41-5	10.2		
C27-8	14.3	C41-7	10.5		
C28-6	14.1	C42-1	10.2		
C28-7	14.2	C42-3	9.93		
C28-8	14.3	C42-5	10.1		
C31-1	13.7	C42-7	9.89		
C31-2	13.4	C43-1	10.5		
C31-6	14.3	C43-3	10.2		
C32-1	11.6	C43-5	9.69		
C32-3	11.1	C43-7	9.98		
C32-5	10.8	C44-1	10.8		

Table 3. Summary of room-temperature tensile properties of the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	UTS (MPa)	Failure strain (%)	Specimen number	UTS (MPa)	Failure strain (%)
C1-9	575	1.19	C56-1	369	-
C1-19	462	0.95	C15-15	478	-
C1-36	474	1.01	C15-19	455	0.99
C1-11	552	1.19	C15-27	419	-
C1-15	551	1.17	C15-31	465	-
C1-31	481	1.10	C15-36	494	1.12
C1-21	438	0.98	C18-1	510	1.14
C1-22	471	1.01	C18-9	498	1.00
C1-25	481	1.10	C18-19	404	0.99
C1-27	479	1.14	C18-36	391	0.96
C2-1	433	0.77	C19-1	476	0.99
C2-9	544	1.06	C19-9	470	0.93
C2-19	559	1.07	C19-19	495	0.98
C2-36	522	1.10	C19-36	461	1.09
C3-1	346	0.67	C21-1	394	0.95
C3-9	556	1.14	C21-9	481	1.08
C3-19	529	1.10	C21-19	430	0.80
C3-36	511	1.21	C21-36	470	0.94
C4-1	576	1.19	C22-1	459	0.86
C4-9	450	0.87	C22-9	436	0.85
C4-19	414	0.88	C22-19	469	0.88
C4-36	468	1.07	C22-36	469	0.89
C5-1	410	0.81	C23-1	360	0.84
C5-9	553	1.11	C23-9	446	0.87
C5-19	557	1.16	C23-19	402	0.80
C5-36	463	1.02	C23-36	389	0.73
C5-2	536	1.02	C25-1	435	0.90
C5-3	480	1.00	C25-2	480	0.94
C5-8	485	0.97	C25-3	469	0.92
C12-1	381	0.97	C27-2	458	1.06
C12-19	378	0.90	C27-3	489	0.92
C12-29	449	1.07	C27-4	482	1.14
C12-36	424	1.19	C27-5	477	0.95
C13-1	434	1.01	C28-2	503	1.08
C13-9	492	1.11	C28-3	504	1.06
C13-19	418	1.12	C28-4	504	1.08
C13-36	412	1.18	C28-5	505	0.96
C15-1	446	0.86	C46-2	467	-
C15-9	494	0.99	C46-3	478	-
C15-12	470	-	C46-4	484	-
C48-4	545	-	C46-5	475	-
C48-5	490	-	C56-9	440	-
C52-13	510	-	C56-19	441	-
C52-15	587	-	C56-36	385	-
C52-17	572	-	**Average**	471	1.00
C52-19	483	-	**SD**	52.1	0.12
C52-21	460	-	**COV(%)**	11.1	12.3

Table 4. Summary of room-temperature tensile properties of the crossply carbon-fiber composite, ±45° fiber orientation

Specimen number	UTS (MPa)	Failure strain (%)	Specimen number	UTS (MPa)	Failure strain (%)
C6-6	132	15.0	C33-1	143	6.60
C6-29	132	14.4	C33-3	154	9.92
C6-53	133	10.6	C33-5	148	9.00
C9-3	141	10.0	C33-7	166	9.41
C9-29	148	10.0	C34-1	125	7.45
C9-56	129	10.6	C34-3	142	9.38
C9-58	135	12.0	C34-5	130	13.4
C11-3	124	12.9	C34-7	163	10.4
C11-18	127	14.2	C35-1	149	13.3
C11-29	134	15.0	C35-3	157	8.96
C11-30	132	9.51	C35-5	166	10.8
C11-41	120	15.0	C35-7	159	6.08
C11-56	121	11.0	C36-1	158	11.7
C14-3	131	-	C36-3	154	10.5
C14-6	139	-	C36-5	168	11.7
C14-15	139	-	C36-7	158	8.03
C14-29	139	-	C37-1	148	11.1
C14-44	123	-	C37-3	150	7.73
C14-56	123	-	C37-5	148	12.3
C16-3	117	-	C37-7	150	7.83
C16-29	109	-	C38-1	164	11.1
C16-56	110	-	C38-3	155	10.6
C17-3	116	-	C38-5	147	10.7
C17-29	107	-	C38-7	156	9.32
C17-56	100	-	C39-1	162	9.93
C20-3	127	-	C39-3	153	7.51
C20-29	127	-	C39-5	160	8.76
C20-56	126	-	C39-7	145	8.14
C24-3	162	5.43	C40-1	161	10.6
C24-29	157	6.36	C40-3	172	7.20
C24-56	164	6.33	C40-5	162	11.5
C26-3	171	-	C40-7	157	8.98
C26-56	175	-	C41-1	167	11.1
C27-1	162	-	C41-3	161	11.1
C27-6	157	-	C41-5	158	9.18
C27-7	144	-	C41-7	166	8.36
C27-8	149	-	C42-1	160	11.5
C28-6	154	-	C42-3	155	9.33
C28-7	152	-	C42-5	158	9.48
C28-8	147	-	C42-7	162	8.92
C31-1	150	-	C43-1	160	11.3
C31-2	144	-	C43-3	160	8.87
C31-6	152	-	C43-5	159	9.43
C32-1	172	10.8	C43-7	152	7.59
C32-3	168	9.75	C44-1	164	11.4
C32-5	164	8.12	C44-3	159	10.6
C32-7	156	8.31	C44-5	168	12.2

Table 4. Continued. Summary of room-temperature tensile properties of the crossply carbon-fiber composite, ±45° fiber orientation

Specimen number	UTS (MPa)	Failure strain (%)
C44-7	163	8.92
C45-1	145	5.20
C45-3	149	4.73
C45-5	157	4.56
C45-7	153	5.37
C46-1	150	-
C46-6	156	-
C46-7	164	-
C46-8	152	-
C48-1	152	-
C48-2	161	-
C48-3	161	-
C52-1	156	-
C52-3	163	-
C52-5	170	-
C52-7	170	-
C52-9	168	-
C52-11	165	-
C57-3	161	-
C57-29	155	-
C57-56	162	-
Average	150	9.78
SD	16.2	2.43
COV(%)	10.8	24.8

Table 5. Summary of plaque average tensile properties of the crossply carbon-fiber composite, 0/90° fiber orientation

Plaque number	Number of stiffness tests	E_{avg} (GPa)	Number of tensile tests	UTS_{avg} (MPa)	$\varepsilon_{f\ avg}$ (%)
C1	37	44.7	10	496	1.07
C2	36	46.2	4	514	1.00
C3	36	43.8	4	485	1.03
C4	36	42.4	4	477	1.00
C5	36	43.9	7	498	1.01
C12	4	43.2	4	408	1.03
C13	4	40.3	4	439	1.11
C15	8	48.9	8	465	0.99
C18	4	44.6	4	451	1.02
C19	4	51.9	4	475	1.00
C21	4	50.7	4	444	0.94
C22	4	48.5	4	458	0.87
C23	4	48.4	4	399	0.81
C25	3	50.1	3	461	0.92
C27	4	50.3	4	476	1.02
C28	4	50.8	4	504	1.05
C46	4	49.5	4	476	-
C48	2	49.7	2	518	-
C52	5	47.1	5	522	-
C56	4	47.3	4	409	-
Number of tests	243		91		
Average		45.2		471	1.00
SD		3.76		52.1	0.12
COV %		8.33		11.1	12.3

Table 6. Summary of plaque average tensile properties the crossply carbon-fiber composite, ±45° fiber orientation

Plaque number	Number of stiffness tests	E_{avg} (GPa)	Number of tensile tests	UTS_{avg} (MPa)	$\varepsilon_{f\ avg}$ (%)
C6	3	10.7	3	132	13.3
C9	4	10.3	4	139	10.7
C11	6	10.1	6	126	12.9
C14	6	11.1	6	133	-
C16	3	10.4	3	112	-
C17	3	10.2	3	107	-
C20	3	13.1	3	127	-
C24	3	12.7	3	161	6.04
C26	2	15.9	2	173	-
C27	4	14.1	4	153	-
C28	3	14.2	3	151	-
C31	3	13.8	3	149	-
C32	4	11.1	4	165	9.24
C33	4	10.2	4	153	8.73
C34	4	10.7	4	140	10.2
C35	4	10.3	4	158	9.79
C36	4	10.5	4	160	10.5
C37	4	10.5	4	149	9.73
C38	4	10.4	4	156	10.4
C39	4	10.4	4	155	8.59
C40	4	10.6	4	163	9.57
C41	4	10.4	4	163	9.94
C42	4	10.0	4	159	9.81
C43	4	10.1	4	158	9.30
C44	4	10.7	4	163	10.8
C45	4	12.3	4	151	-
C46	4	12.8	4	155	-
C48	3	12.7	3	158	-
C52	6	11.2	6	165	-
C57	3	11.5	3	159	-
Number of tests	115		115		
Average		11.3		149	9.78
SD		1.49		16.3	2.43
COV %		13.1		10.9	24.8

Table 7. Summary of tensile tests at various strain rates for the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	Stiffness (GPa)	UTS (MPa)
Strain rate = 10^{-6} s^{-1}		
C56-8	43.2	388
C56-13	45.1	416
C56-28	42.6	453
C56-35	49.4	459
Average	45.1	429
SD	3.10	33.1
COV (%)	6.87	7.71
Strain rate = 10^{-4} s^{-1}		
C56-7	41.6	407
C56-12	48.3	426
C56-27	46.4	358
C56-34	50.6	426
Average	46.7	404
SD	3.84	32.3
COV (%)	8.22	7.99
Strain rate = 10^{-2} s^{-1}		
C56-6	47.2	351
C56-11	49.7	441
C56-26	44.9	481
C56-33	50.5	462
Average	48.1	434
SD	2.54	57.9
COV (%)	5.29	13.3
Strain rate = 10 s^{-1}		
C56-5	49.8	355
C56-10	48.7	393
C56-25	47.1	357
C56-32	47.0	412
Average	48.1	379
SD	1.36	28.0
COV (%)	2.83	7.39

Table 8. Summary of tensile tests at various strain rates for the crossply carbon-fiber composite, ±45° fiber orientation

Specimen number	Stiffness (GPa)	UTS (MPa)
Strain rate = 10^{-6} s^{-1}		
C57-8	9.93	139
C57-20	10.2	135
C57-24	9.38	145
C57-55	9.86	138
Average	9.85	139
SD	0.34	4.23
COV (%)	3.50	3.05
Strain rate = 10^{-4} s^{-1}		
C57-7	10.4	154
C57-19	11.9	149
C57-54	9.52	145
C57-23	9.80	149
Average	10.4	149
SD	1.08	3.46
COV (%)	10.4	2.32
Strain rate = 10^{-2} s^{-1}		
C57-6	12.3	170
C57-18	10.7	165
C57-53	8.83	162
C57-22	10.9	156
Average	10.7	163
SD	1.42	5.89
COV (%)	13.3	3.61
Strain rate = 10 s^{-1}		
C57-5	10.3	191
C57-17	11.4	166
C57-52	10.4	192
C57-21	9.72	173
Average	10.5	177
SD	0.87	13.6
COV (%)	8.24	7.67

Table 9. Summary of tensile tests at various temperatures for the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Failure strain (%)	Stiffness factor	Strength factor
			-40°C			
C1-6	44.3	44.3	521	1.12	1.00	1.05
C1-10	47.0	46.6	549	1.11	0.99	1.11
C1-17	46.3	46.4	544	1.18	1.00	1.10
C1-20	42.3	42.4	477	1.09	1.00	0.96
C1-26	45.2	45.4	472	1.00	1.00	0.95
C1-32	42.8	42.9	483	1.10	1.00	0.97
Average	44.7	44.7	508	1.10	1.00	1.02
SD	1.88	1.77	34.7	0.06		
COV (%)	4.20	3.96	6.84	5.30		
			23°C			
C1-9	49.6	49.6	575	1.19	1.00	1.00
C1-19	42.5	42.5	462	0.95	1.00	1.00
C1-36	42.5	42.5	474	1.01	1.00	1.00
C1-11	46.4	46.4	552	1.19	1.00	1.00
C1-15	43.6	43.6	551	1.17	1.00	1.00
C1-31	42.6	42.6	481	1.10	1.00	1.00
C5-2	49.6	49.6	536	1.02	1.00	1.00
C5-3	46.1	46.1	480	1.00	1.00	1.00
C5-8	47.5	47.5	485	0.97	1.00	1.00
Average	45.6	45.6	511	1.07	1.00	1.00
SD	2.93	2.93	42.3	0.10		
COV (%)	6.43	6.43	8.28	9.08		
			50°C			
C1-3	44.7	44.3	506	1.09	0.99	1.02
C1-8	44.3	43.4	484	1.05	0.98	0.98
C1-13	44.1	43.6	498	1.10	0.99	1.00
C1-16	48.7	48.3	525	1.07	0.99	1.06
C1-24	44.4	43.0	491	1.24	0.97	0.99
C1-30	48.0	47.4	515	1.14	0.99	1.04
C5-4	50.9	50.2	503	0.96	0.99	1.01
C5-5	47.0	47.4	454	0.92	1.01	0.91
C5-10	47.4	47.2	476	0.98	1.00	0.96
Average	46.6	46.1	495	1.06	0.99	1.00
SD	2.39	2.56	21.4	0.10		
COV (%)	5.12	5.57	4.33	9.27		

Table 9. Continued. Summary of tensile tests at various temperatures for the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Failure strain (%)	Stiffness factor	Strength factor
			120°C			
C1-4	47.2	40.7	414	1.00	0.86	0.83
C1-12	47.8	43.5	479	1.08	0.91	0.97
C1-18	44.2	36.4	376	1.07	0.82	0.76
C1-23	45.2	40.1	433	1.13	0.89	0.87
C1-29	46.7	41.3	405	1.00	0.88	0.82
C1-34	39.9	36.9	403	1.08	0.92	0.81
C5-7	50.2	47.1	370	0.76	0.94	0.74
C5-8	48.9	44.3	377	0.82	0.91	0.76
C5-11	51.2	47.5	425	0.88	0.93	0.85
Average	46.8	42.0	409	0.98	0.90	0.82
SD	3.42	3.98	34.4	0.13		
COV (%)	7.30	9.49	8.40	13.3		

Table 10. Summary of tensile tests at various temperatures for the crossply carbon-fiber composite, ±45° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Failure strain (%)	Stiffness factor	Strength factor
			-40°C			
C11-5	11.5	14.5	154	3.34	1.27	1.23
C11-16	10.5	13.9	164	4.05	1.32	1.30
C11-26	10.5	13.5	156	4.00	1.29	1.24
C11-33	10.4	13.7	167	4.95	1.32	1.32
C11-43	9.53	11.7	161	4.43	1.23	1.28
C11-54	10.0	12.5	156	4.41	1.25	1.23
Average	10.4	13.3	160	4.20	1.28	1.27
SD	0.64	1.02	5.12	0.54		
COV (%)	6.14	7.64	3.21	12.9		
			23°C			
C11-3	10.9	10.9	124	12.9	1.00	1.00
C11-18	10.5	10.5	127	14.2	1.00	1.00
C11-29	10.2	10.2	134	15.0	1.00	1.00
C11-30	10.1	10.1	132	9.51	1.00	1.00
C11-41	9.69	9.69	120	15.0	1.00	1.00
C11-56	9.40	9.40	121	11.0	1.00	1.00
Average	10.1	10.1	126	12.9	1.00	1.00
SD	0.56	0.56	5.76	2.28		
COV (%)	5.49	5.49	4.56	17.6		
			70°C			
C11-4	11.1	9.65	102	13.7	0.87	0.81
C11-17	10.7	9.51	104	-	0.89	0.83
C11-28	10.5	8.89	108	-	0.85	0.85
C11-31	10.3	8.96	105	-	0.87	0.83
C11-42	9.30	8.14	107	-	0.87	0.85
C11-55	9.88	8.20	103	-	0.83	0.82
C11-8	11.3	9.9	110	13.9	0.88	0.87
C11-14	10.9	9.65	109	15.4	0.88	0.86
C11-23	10.4	8.87	96.9	18.4	0.85	0.77
C11-36	10.0	8.76	104	15.3	0.87	0.83
C11-45	9.76	8.09	110	14.4	0.83	0.87
C11-52	9.82	8.73	107	14.8	0.89	0.85
Average	10.3	8.95	105	15.1	0.87	0.84
SD	0.60	0.63	3.67	1.57		
COV (%)	5.82	6.99	3.49	10.4		

Table 10. Continued. Summary of tensile tests at various temperatures for the crossply carbon-fiber composite, ±45° fiber orientation

Specimen Number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Failure Strain (%)	Stiffness factor	Strength factor
			120°C			
C11-9	11.5	4.16	82.7	17.0	0.36	0.66
C11-15	11.5	4.07	72.8	17.7	0.36	0.58
C11-24	10.0	3.99	71.3	19.7	0.40	0.57
C11-37	9.99	4.24	71.6	16.5	0.42	0.57
C11-46	9.61	3.85	79.7	20.0	0.40	0.63
C11-53	9.55	3.54	75.3	21.1	0.37	0.60
Average	10.3	3.98	75.5	18.7	0.39	0.60
SD	0.89	0.25	4.67	1.87		
COV (%)	8.56	6.41	6.18	10.0		

Table 11. Temperature multiplication factors for determining at-temperature tensile modulus and strength from room-temperature values for the crossply carbon-fiber composite, 0/90° fiber orientation

Temperature (°C)	Stiffness factor	Strength factor
-40	1.00	1.00
23	1.00	1.00
70	0.98	0.96
120	0.90	0.82

Table 12. Temperature multiplication factors for determining at-temperature tensile modulus and strength from room-temperature values for the crossply carbon-fiber composite, ±45° fiber orientation

Temperature (°C)	Stiffness factor	Strength factor
-40	1.29	1.29
23	1.00	1.00
70	0.79	0.79
120	0.55	0.55

Table 13. Summary of Poisson's ratio measurements at different temperatures for the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	Poisson's ratio			
	-40°C	**23°C**	**70°C**	**120°C**
C12-15	0.06	0.06	0.04	0.04
C12-18	0.03	0.04	0.03	0.05
C12-34	0.05	0.05	0.05	0.03
Average	0.05	0.05	0.04	0.04

Table 14. Summary of Poisson's ratio measurements at different temperatures for the crossply carbon-fiber composite, ±45° fiber orientation

Specimen number	Poisson's ratio			
	-40°C	**23°C**	**70°C**	**120°C**
C11-13	0.68	0.77	0.74	0.84
C11-25	0.71	0.77	0.73	0.90
C11-39	0.70	0.74	0.74	0.86
Average	0.70	0.76	0.74	0.87

Table 15. Effects of prior thermal cycling on mechanical properties of the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	Strength (MPa)	Stiffness factor	Strength factor
		Tension			
C52-14	50.0	46.1	543	0.92	1.02
C52-16	49.4	47.1	570	0.95	1.08
C52-18	46.3	45.6	515	0.98	0.97
C52-20	44.7	43.7	453	0.98	0.86
C52-22	43.6	45.3	518	1.04	0.98
C52-23	49.3	47.3	519	0.96	0.98
Average	47.2	45.8	520	0.97	0.93
SD	2.69	1.31	38.7		
COV (%)	5.70	2.87	7.45		
		Compression			
C25-5	-	64.9	344	1.10	1.04
C25-8	-	56.5	322	0.96	0.98
C25-10	-	55.2	339	0.93	1.03
C25-29	-	60.5	314	1.02	0.95
C25-34		60.8	336	1.03	1.02
C25-38		58.3	343	0.99	1.04
Average	-	59.4	333	1.00	1.01
SD	-	3.48	12.4		
COV (%)	-	5.86	3.72		

Table 16. Effects of prior thermal cycling on mechanical properties of the crossply carbon-fiber composite, ±45° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	Strength (MPa)	Stiffness factor	Strength factor
		Tension			
C52-2	10.5	10.1	161	0.96	0.97
C52-4	11.3	9.31	161	0.82	0.98
C52-6	12.1	10.5	170	0.87	1.03
C52-8	12.4	10.8	184	0.87	1.12
C52-10	11.7	8.48	166	0.72	1.01
C52-12	12.1	9.93	164	0.82	1.00
Average	11.7	9.85	168	0.85	1.02
SD	0.69	0.84	8.69		
COV (%)	5.95	8.58	5.19		
		Compression			
C26-12	-	12.6	172	0.91	1.05
C26-23	-	13.6	171	0.98	1.05
C26-35	-	14.9	173	1.07	1.06
C26-38	-	13.0	174	0.94	1.07
C26-45		14.7	178	1.06	1.09
C26-70		14.1	172	1.02	1.05
Average	-	13.8	173	1.00	1.06
SD	-	0.92	2.50		
COV (%)	-	6.66	1.44		

Table 17. Effects of prior thermal cycling on apparent shear strength in short-beam shear of the crossply carbon-fiber composite, 0/90° fiber orientation*

Specimen number	Apparent shear strength (MPa)	Strength factor
Unexposed specimens		
1	88.9	1.00
4	93.8	1.00
15	86.2	1.00
19	97.9	1.00
28	93.8	1.00
40	95.8	1.00
44	88.9	1.00
49	89.6	1.00
53	92.4	1.00
61	93.1	1.00
Average	92.0	1.00
SD	3.58	
COV (%)	3.89	
Specimens subjected to prior thermal cycling		
21	82.7	0.90
23	81.4	0.88
26	83.4	0.90
51	88.3	0.96
63	88.3	0.96
69	84.1	0.91
Average	84.7	0.92
SD	2.91	
COV (%)	3.43	

*All specimens machined from plaque C23.

Table 18. Effects of prior thermal cycling on apparent shear strength in short-beam shear of the crossply carbon-fiber composite, ±45° fiber orientation*

Specimen number	Apparent shear strength (MPa)	Strength factor
Unexposed specimens		
1	76.5	1.00
4	73.1	1.00
15	77.2	1.00
19	74.5	1.00
28	79.3	1.00
40	75.8	1.00
44	78.6	1.00
49	76.5	1.00
53	82.7	1.00
61	77.2	1.00
Average	77.2	1.00
SD	2.67	
COV (%)	3.46	
Specimens subjected to prior thermal cycling		
21	73.7	0.95
23	75.9	0.98
26	74.1	0.96
51	75.8	0.98
63	74.4	0.96
69	78.4	1.02
Average	75.4	0.98
SD	1.73	
COV (%)	2.29	

*All specimens machined from plaque C23.

Table 19. Effects of fluid environments on apparent shear strength in short-beam shear of the crossply carbon-fiber composite, 0/90° fiber orientation*

Specimen number	Apparent shear strength (MPa)	Strength factor
	Distilled water	
2	85.5	0.93
16	89.6	0.97
30	82.7	0.90
41	89.6	0.97
50	88.3	0.96
60	88.9	0.96
Average	87.4	0.95
SD	2.77	
COV (%)	3.17	
	Saltwater	
3	86.9	0.94
17	82.7	0.90
31	87.6	0.95
42	84.8	0.92
48	84.1	0.91
59	84.1	0.91
Average	85.0	0.92
SD	1.83	
COV (%)	2.16	
	Windshield washer fluid	
18	88.3	0.96
25	91.7	0.99
32	91.0	0.99
43	82.7	0.90
47	95.8	1.04
58	81.4	0.88
Average	88.5	0.96
SD	5.56	
COV (%)	6.29	

*All specimens machined from plaque C23.

Table 19. Continued. Effects of fluid environments on apparent shear strength in short-beam shear of the crossply carbon-fiber composite, 0/90° fiber orientation*

Specimen number	Apparent shear strength (MPa)	Strength factor
	Coolant	
5	93.1	1.01
12	75.8	0.82
29	96.5	1.04
39	88.3	0.96
54	82.0	0.89
57	86.2	0.93
Average	87.0	0.94
SD	7.47	
COV (%)	8.59	
	Motor oil	
6	82.7	0.90
13	91.7	0.99
27	85.5	0.93
38	95.1	1.03
55	91.0	0.99
56	89.6	0.97
Average	89.3	0.97
SD	4.48	
COV (%)	5.02	
	Gasoline	
7	95.1	1.03
10	93.1	1.01
35	90.3	0.98
37	91.0	0.99
52	91.7	0.99
67	95.1	1.03
Average	92.7	1.00
SD	2.08	
COV (%)	2.24	
	Brake fluid	
8	84.1	0.91
11	91.0	0.99
34	86.9	0.94
36	85.5	0.93
62	88.9	0.96
64	72.4	0.78
Average	84.8	0.92
SD	6.56	
COV (%)	7.73	

*All specimens machined from plaque C23.

Table 19. Continued. Effects of fluid environments on apparent shear strength in short-beam shear of the crossply carbon-fiber composite, 0/90° fiber orientation*

Specimen number	Apparent shear strength (MPa)	Strength factor
	Transmission fluid	
9	84.1	0.91
14	80.0	0.87
33	85.5	0.93
45	91.0	0.99
46	93.8	1.01
65	84.1	0.91
Average	86.4	0.94
SD	5.06	
COV (%)	5.86	
	Battery acid	
20	85.5	0.93
22	85.5	0.93
24	91.7	0.99
66	91.0	0.99
68	95.8	1.04
70	95.1	1.03
Average	90.8	0.98
SD	4.50	
COV (%)	4.96	

*All specimens machined from plaque C23.

Table 20. Effects of fluid environments on apparent shear strength in short-beam shear of the crossply carbon-fiber composite, ±45° fiber orientation*

Specimen number	Apparent shear strength (MPa)	Strength factor
	Distilled water	
2	73.8	0.96
16	72.4	0.94
30	73.8	0.96
41	77.9	1.01
50	74.5	0.96
60	69.6	0.90
Average	73.7	0.95
SD	2.70	
COV (%)	3.67	
	Saltwater	
3	78.6	1.02
17	75.2	0.97
31	69.6	0.90
42	71.7	0.93
48	80.0	1.04
59	71.0	0.92
Average	74.3	0.96
SD	4.26	
COV (%)	5.73	
	Windshield washer fluid	
18	71.7	0.93
25	79.3	1.03
32	69.6	0.90
43	71.0	0.92
47	68.9	0.89
58	71.0	0.92
Average	71.9	0.93
SD	3.74	
COV (%)	5.20	
	Coolant	
5	77.9	1.01
12	67.6	0.88
29	73.1	0.95
39	74.5	0.96
54	75.8	0.98
57	69.6	0.90
Average	73.1	0.95
SD	3.88	
COV (%)	5.30	

*All specimens machined from plaque C23.

Table 20. Continued. Effects of fluid environments on apparent shear strength in short-beam shear of the crossply carbon-fiber composite, ±45° fiber orientation*

Specimen number	Apparent shear strength (MPa)	Strength factor
	Motor oil	
6	71.7	0.93
13	75.2	0.97
27	71.7	0.93
38	66.2	0.86
55	68.3	0.88
56	73.8	0.96
Average	71.1	0.92
SD	3.36	
COV (%)	4.73	
	Gasoline	
7	77.9	1.01
10	75.8	0.98
35	73.1	0.95
37	80.0	1.04
52	78.6	1.02
67	73.8	0.96
Average	76.5	0.99
SD	2.76	
COV (%)	3.60	
	Brake fluid	
8	74.5	0.96
11	66.9	0.87
34	68.9	0.89
36	73.1	0.95
62	66.9	0.87
64	73.1	0.95
Average	70.6	0.91
SD	3.40	
COV (%)	4.81	
	Transmission fluid	
9	66.0	0.85
14	68.5	0.89
33	76.5	0.99
45	77.9	1.01
46	71.0	0.92
65	73.1	0.95
Average	72.2	0.93
SD	4.61	
COV (%)	6.39	

*All specimens machined from plaque C23.

Table 20. Continued. Effects of fluid environments on apparent shear strength in short-beam shear of the crossply carbon-fiber composite, ±45° fiber orientation*

Specimen number	Apparent shear strength (MPa)	Strength factor
	Battery acid	
20	71.2	0.92
22	64.9	0.84
24	68.0	0.88
66	69.4	0.90
68	68.1	0.88
70	67.3	0.87
Average	68.1	0.88
SD	2.10	
COV (%)	3.09	

*All specimens machined from plaque C23.

Table 21. Effect of exposure in 23°C distilled water and in 70% RH air on tensile strength and stiffness of the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Change in stiffness (%)	Change in strength (%)
		Distilled water, 1000 h			
C12-2	47.5	45.5	396	-4.21	-2.71
C12-9	41.2	37.0	368	-10.2	-9.64
C12-20	39.4	39.0	384	-1.22	-5.75
C21-2	68.2	62.1	439	-8.90	-1.09
C21-20	64.3	61.0	432	-5.14	-2.49
C21-29	70.3	65.5	434	-6.86	-2.02
Average	55.2	51.7	409	-6.09	-3.95
SD	14.0	12.7	30.0		
COV (%)	25.4	24.5	7.34		
		Distilled water, 4241 h			
C12-4	46.3	43.9	381	-5.36	-6.50
C12-8	44.9	42.1	364	-6.14	-10.7
C12-35	42.4	39.2	384	-7.48	-5.69
C21-8	61.4	56.2	423	-8.53	-4.51
C21-18	70.7	63.6	423	-10.1	-4.53
C21-35	67.8	62.3	415	-8.14	-6.35
Average	55.6	51.2	398	-7.63	-6.38
SD	12.5	10.8	25.4		
COV (%)	22.6	21.0	6.38		
		70% RH, 3968 h			
C12-6	43.6	43.2	436	-1.11	6.94
C12-13	42.0	41.9	447	-0.33	9.81
C12-25	41.9	41.6	444	-0.49	8.97
C21-6	68.3	67.8	405	-0.61	-8.71
C21-13	65.2	64.4	408	-1.3	-7.93
C21-25	61.0	60.5	407	-0.90	-8.24
Average	53.7	53.2	424	-0.78	0.14
SD	12.5	12.3	20.0		
COV (%)	23.2	23.1	4.72		

Table 22. Effect of exposure in 23°C distilled water and in 70% RH air on tensile strength and stiffness of the crossply carbon-fiber composite, ±45° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Change in stiffness (%)	Change in strength (%)
		Distilled water, 1000 h			
C14-4	12.2	11.4	132	-6.21	0.00
C14-14	11.6	11.2	134	-2.98	1.04
C14-28	11.2	11.0	127	-2.45	-4.17
C14-35	10.6	9.79	124	-7.79	-6.25
C14-43	11.4	11.1	125	-2.42	-5.73
C14-55	10.3	10.1	125	-2.67	-5.73
Average	11.2	10.8	128	-4.09	-3.47
SD	0.67	0.67	4.22		
COV (%)	5.98	6.27	3.30		
		Distilled water, 4267 h			
C14-1	12.6	12.1	125	-4.37	-5.21
C14-13	11.8	11.5	132	-2.34	-0.52
C14-25	11.6	11.2	122	-2.98	-7.81
C14-36	10.4	10.0	118	-3.97	-10.9
C14-40	10.2	9.79	111	-4.05	-16.1
C14-53	11.3	10.0	120	-11.6	-9.38
Average	11.3	10.8	121	-4.88	-8.33
SD	0.90	0.96	7.00		
COV (%)	7.95	8.91	5.77		
		70% RH, 4271 h			
C14-10	12.0	11.3	121	-5.75	-8.85
C14-12	11.2	11.3	121	1.23	-8.33
C14-26	11.1	10.6	123	-4.35	-6.77
C14-37	10.3	10.5	122	2.01	-7.81
C14-41	10.5	10.3	127	-1.32	-4.17
C14-51	11.0	10.3	126	-5.7	-4.69
Average	11.0	10.7	123	-2.30	-6.77
SD	0.61	0.46	2.58		
COV (%)	5.51	4.25	2.09		

Table 23. Effect of 1000-h distilled water exposure and 1000-h distilled water exposure followed by freezing on stiffness and strength of the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Change in stiffness (%)	Change in strength (%)
			1000 h in distilled water		
C15-10	49.8	48.5	496	-2.77	5.11
C15-13	51.0	48.0	495	-5.95	4.82
C15-16	53.2	50.3	554	-5.32	17.4
C15-28	46.7	44.1	438	-5.61	-7.30
C15-32	48.6	45.6	433	-6.10	-8.32
C15-35	46.8	44.5	453	-5.01	-4.09
Average	49.4	46.8	478	-5.12	1.27
SD	2.52	2.49	46.3		
COV (%)	5.10	5.31	9.68		
			1000 h in distilled water followed by freezing		
C15-11	52.4	47.7	489	-8.95	3.50
C15-14	52.9	50.5	554	-4.43	17.4
C15-17	50.5	51.9	480	2.73	1.61
C15-30	46.6	44.5	471	-4.44	-0.29
C15-33	45.4	42.7	432	-5.93	-8.61
C15-34	47.2	45.9	455	-2.78	-3.65
Average	49.2	47.2	480	-3.97	1.65
SD	3.20	3.55	41.6		
COV (%)	6.51	7.52	8.66		

Table 24. Effect of 1000-h distilled water exposure and 1000-h distilled water exposure followed by freezing on stiffness and strength of the crossply carbon-fiber composite, ±45° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Change in stiffness (%)	Change in strength (%)
1000 h in distilled water					
C17-18	8.83	9.31	101	5.47	-9.26
C17-21	9.79	8.62	98.6	-12.0	-11.7
C17-24	10.0	9.03	102	-9.66	-8.64
C17-47	8.55	7.86	95.8	-8.06	-14.2
C17-50	11.0	10.7	124	-2.52	11.1
C17-53	11.1	9.93	132	-10.6	18.5
Average	9.87	9.24	109	-6.22	-2.37
SD	1.06	0.99	15.3		
COV (%)	10.7	10.7	14.0		
1000 h in distilled water followed by freezing					
C17-19	9.65	9.24	112	-4.29	0.00
C17-20	9.58	8.96	106	-6.47	-4.94
C17-23	9.72	9.03	108	-7.09	-3.70
C17-46	8.14	7.58	101	-6.78	-9.88
C17-49	8.96	8.48	110	-5.38	-1.23
C17-52	8.62	8.69	112	0.80	0.00
Average	9.11	8.66	108	-4.87	-3.29
SD	0.65	0.59	4.24		
COV (%)	7.12	6.84	3.93		

Table 25. Effect of exposure in windshield washer fluid on tensile strength and stiffness of the crossply carbon-fiber composite, 0/90° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Stiffness factor	Strength factor
		Exposure time = 50 h			
C12-17	45.5	45.0	419	0.99	1.03
C12-27	36.2	36.6	392	1.01	0.96
C21-4	63.8	63.4	454	0.99	1.02
C21-15	62.5	61.9	443	0.99	1.00
C21-27	58.1	57.0	429	0.98	0.97
Average	53.2	52.8	427	0.99	1.00
SD	12.0	11.6	23.8		
COV (%)	22.5	21.9	5.58		
		Exposure time = 100 h			
C12-24	43.2	43.0	416	1.00	1.02
C12-33	39.5	40.4	390	1.02	0.96
C21-17	65.6	61.8	406	0.94	0.92
C21-28	56.4	56.1	461	1.00	1.04
C21-32	63.1	63.6	422	1.01	0.95
Average	53.6	53.0	419	0.99	0.98
SD	11.7	10.7	26.5		
COV (%)	21.9	20.2	6.31		
		Exposure time = 1000 h			
C19-2	51.6	51.2	547	0.99	1.15
C19-4	51.7	50.7	561	0.98	1.18
C19-5	59.1	57.6	589	0.97	1.24
C19-21	49.8	48.1	519	0.97	1.09
C19-22	50.0	48.7	507	0.97	1.07
C19-23	51.8	51.6	540	1.00	1.13
Average	52.3	51.3	544	0.98	1.14
SD	3.43	3.38	29.3		
COV (%)	6.56	6.60	5.38		

Table 26. Effect of exposure in windshield washer fluid on tensile strength and stiffness of the crossply carbon-fiber composite, ±45° fiber orientation

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Stiffness factor	Strength factor
		Exposure time = 50 h			
C11-1	12.2	12.3	126	1.01	1.00
C11-35	11.6	11.5	125	0.99	0.99
C11-47	10.3	10.3	125	1.00	0.99
C11-49	10.0	9.72	125	0.97	0.99
C11-50	10.9	10.8	124	0.99	0.98
Average	11.0	10.9	125	0.99	0.99
SD	0.90	1.00	0.79		
COV (%)	8.18	9.10	0.63		
		Exposure time = 100 h			
C11-22	11.7	11.2	122	0.95	0.97
C11-38	11.7	11.1	124	0.95	0.98
C11-44	10.3	10.3	125	0.99	0.99
C11-48	10.6	9.93	119	0.94	0.95
C11-51	10.9	10.2	125	0.94	0.99
C11-58	10.6	10.4	121	0.98	0.96
Average	11.0	10.5	123	0.96	0.97
SD	0.60	0.51	2.47		
COV (%)	5.42	4.81	2.01		
		Exposure time = 1000 h			
C57-4	12.4	10.5	154	0.85	0.97
C57-13	11.1	9.65	157	0.87	0.99
C57-26	10.5	9.58	155	0.91	0.97
C57-34	10.5	10.1	158	0.97	0.99
C57-41	11.2	9.86	149	0.88	0.94
C57-50	10.1	9.79	154	0.97	0.97
Average	11.0	9.93	155	0.91	0.97
SD	0.81	0.36	3.19		
COV (%)	7.37	3.62	2.06		

Table 27. Summary of room-temperature compressive tests for the crossply carbon-fiber composite

Specimen number	Compressive stiffness (GPa)	UCS (MPa)	Failure strain (%)
	0/90° fiber orientation		
C4-C2	50.9	-452	-1.00
C4-C3	51.6	-442	-0.75
C4-C4	56.1	-478	-1.18
C4-C5	57.5	-535	-1.09
C4-C8	43.8	-491	-1.15
C4-C9	43.9	-441	-1.24
C5-C2	50.7	-517	-1.03
C5-C3	48.8	-507	-1.09
C5-C5	53.5	-505	-1.41
C5-C6	44.7	-456	-1.37
C5-C8	53.1	-479	-1.25
C5-C9	50.8	-435	-0.83
C25-2	64.1	-355	[a]
C25-17	58.1	-338	[a]
C25-32	50.8	-324	[a]
C25-36	67.0	-312	[a]
C25-41	59.4	-336	[a]
C25-47	55.1	-313	[a]
Average	53.3	-429	-1.12
SD	6.39	77.4	0.20
COV (%)	12.0	-18.1	-17.7
	±45° fiber orientation		
C26-4	15.6	170	5.42
C26-14	14.0	163	8.01
C26-27	14.2	165	7.41
C26-41	13.4	151	8.37
C26-52	13.2	157	8.74
C26-61	12.9	170	5.57
Average	13.9	163	7.25
SD	0.98	7.47	1.43
COV (%)	7.08	4.59	19.7

[a] No strain measurement

Table 28. Compressive properties of the crossply carbon-fiber composite, 0/90° fiber orientation, at different temperatures

Specimen number	Compressive stiffness (GPa)	UCS (MPa)	Failure strain (%)
	50°C		
C2-C1	50.9	-370	-0.78
C2-C4	48.7	-342	-0.71
C2-C7	49.4	-411	-0.63
C2-C9	46.6	-392	-0.70
C3-C1	51.8	-381	-0.79
C3-C2	42.3	-419	-0.69
C3-C3	39.6	-362	-0.66
C3-C7	47.7	-247	-0.74
Average	47.1	-365	-0.71
SD	4.20	54.4	0.06
COV (%)	8.92	14.9	7.85
	120°C		
C2-C3	45.8	-162	-0.25
C2-C5	51.6	-222	-0.41
C2-C8	37.3	-171	-0.52
C2-C10	40.6	-193	-0.50
C3-C4	33.9	-230	-0.71
C3-C6	41.3	-177	-0.39
C3-C8	49.0	-176	-0.29
C3-C9	38.4	-185	-0.54
Average	42.2	-190	-0.45
SD	6.09	24.6	0.15
COV (%)	14.4	13.0	33.1
	-40°C		
C2-C2	51.9	-515	-0.98
C2-C6	42.5	-474	-1.16
C3-C5	46.4	-472	-0.91
C3-C10	42.1	-475	-1.15
C4-C1	42.5	-484	-1.12
C4-C10	34.7	-468	-1.21
C5-C1	51.6	-500	-0.95
C5-C10	41.0	-483	-1.04
Average	43.5	-480	-1.07
SD	6.21	12.7	0.13
COV (%)	14.3	2.64	12.2

Table 29. Compressive properties of the crossply carbon-fiber composite, ±45° fiber orientation, at different temperatures

Specimen number	Compressive stiffness (GPa)	UCS (MPa)	Failure strain (%)
	70°C		
C26-2	11.8	130	7.41
C26-15	10.6	121	9.68
C26-28	9.79	120	9.09
C26-42	11.2	127	6.23
C26-53	10.3	121	8.58
C26-62	10.9	105	9.48
Average	10.8	121	8.41
SD	0.70	8.61	1.34
COV (%)	6.47	7.12	16.0
	120°C		
C26-6	6.32	78.1	9.41
C26-16	6.76	76.5	8.36
C26-60	6.18	79.1	7.75
C26-43	6.69	76.5	9.55
C26-54	5.67	80.3	7.08
C26-63	5.83	78.0	8.14
Average	6.24	78.1	8.38
SD	0.44	1.47	0.96
COV (%)	7.06	1.88	11.4
	-40°C		
C26-7	16.5	209	2.63
C26-17	17.8	217	2.88
C26-31	17.2	213	3.46
C26-44	16.8	226	2.86
C26-51	17.3	219	3.04
C26-60	18.3	208	3.52
Average	17.3	215	3.07
SD	0.65	6.97	0.35
COV (%)	3.75	3.23	11.6

Table 30. Temperature multiplication factors for determining at-temperature compressive modulus and strength from room-temperature values for the crossply carbon-fiber composite, 0/90° fiber orientation

Temperature (°C)	Stiffness multiplication factor	Strength multiplication factor
-40	1.05	1.10
23	1.00	1.00
70	0.93	0.78
120	0.80	0.41

Table 31. Temperature multiplication factors for determining at-temperature compressive modulus and strength from room-temperature values for the crossply carbon-fiber composite, ±45° fiber orientation

Temperature (°C)	Stiffness multiplication factor	Strength multiplication factor
-40	1.32	1.32
23	1.00	1.00
70	0.76	0.76
120	0.50	0.50

Table 32. Effects of 1000-h exposure in 23°C distilled water on room-temperature compressive properties of the crossply carbon-fiber composite

Specimen number	Compressive stiffness (GPa)	UCS (MPa)	Stiffness factor	Strength factor
		0/90° fiber orientation		
C25-4	54.7	338	0.93	1.02
C25-13	56.7	316	0.96	0.96
C25-20	58.0	320	0.98	0.97
C25-33	54.4	324	0.92	0.98
C25-42	57.4	339	0.97	1.03
C25-48	52.9	311	0.89	0.94
Average	55.7	325	0.94	0.98
SD	1.99	11.4		
COV (%)	3.58	3.52		
		±45° fiber orientation		
C26-1	14.2	164	1.03	1.01
C26-10	13.6	158	0.98	0.97
C26-26	12.8	162	0.92	0.99
C26-32	13.3	150	0.96	0.92
C26-50	12.4	158	0.89	0.97
C26-75	12.3	165	0.89	1.01
Average	13.1	159	0.95	0.98
SD	0.73	5.56		
COV (%)	5.58	3.49		

Table 33. Effect of exposure in windshield washer fluid on compressive strength of the crossply carbon-fiber composite

Specimen Number	UCS (MPa)	Strength factor
0/90° fiber orientation		
Exposure time = 50 h		
C25-3	305	0.92
C252-9	333	1.01
C25-12	313	0.95
C25-19	323	0.98
C25-31	326	0.99
C25-46	329	1.00
Average	321	0.97
SD	10.7	
COV (%)	3.33	
Exposure time = 100 h		
C25-1	308	0.94
C25-11	299	0.91
C25-18	282	0.86
C25-30	308	0.94
C25-43	298	0.90
C25-49	324	0.98
Average	303	0.92
SD	14.0	
COV (%)	4.60	
±45° fiber orientation		
Exposure time = 50 h		
C26-8	170	1.04
C26-25	163	1.00
C26-33	165	1.01
C26-48	151	0.93
C26-55	157	0.96
C26-74	170	1.04
Average	163	1.00
SD	7.47	
COV (%)	4.59	
Exposure time = 100 h		
C26-9	165	1.01
C26-24	158	0.97
C26-34	162	0.99
C26-46	163	1.00
C26-58	164	1.00
C26-71	163	1.00
Average	162	0.99
SD	2.39	
COV (%)	1.47	

Table 34. Summary of room-temperature shear tests for the crossply carbon-fiber composite

Specimen number	Shear modulus (GPa)	Shear strength (MPa)	Failure strain (%)
	0/90° fiber orientation		
C1-20	2.92	81.6	12.8
C1-22	2.74	98.9	11.4
C1-25	3.10	98.8	11.8
C1-30	2.49	100	11.3
C1-32	2.56	86.8	12.4
C2-S3	3.17	89.9	12.1
C2-S4	3.31	91.0	12.1
C2-S5	2.93	87.9	11.4
C2-S8	2.86	80.2	11.1
C2-S9	3.59	103	13.1
C2-S10	3.55	98.9	11.5
C3-2	2.70	107	12.7
C3-6	2.79	95.6	10.8
C3-8	2.68	84.9	11.9
C3-9	2.99	86.4	12.0
C4-3	3.03	90.1	[a]
C4-5	3.33	101	[a]
C4-9	2.71	106	[a]
C5-2	2.90	98.8	[a]
C5-8	3.18	98.0	[a]
C5-10	2.74	109	[a]
Average	2.96	95.0	11.9
SD	0.30	8.45	0.67
COV (%)	10.2	8.90	5.59
	±45° fiber orientation		
C21-S1	23.9	202	1.06
C21-S4	23.3	206	0.94
C21-S10	24.6	168	0.68
C21-S16	24.8	207	0.76
C21-S21	23.8	194	1.12
C21-S27	24.9	167	0.72
Average	24.2	191	0.88
SD	0.64	18.7	0.19
COV (%)	2.65	9.80	21.2

[a] No strain measurement

Table 35. Shear properties of the crossply carbon-fiber composite, 0/90° fiber orientation, at different temperatures

Specimen number	Shear modulus (GPa)	Shear strength (MPa)	Failure strain (%)
		70°C	
C1-2	2.21	69.1	12.7
C1-19	2.25	67.9	11.7
C1-21	2.16	74.0	11.7
C1-27	1.95	65.5	11.9
C1-29	1.92	70.2	12.7
C1-31	2.19	67.8	12.6
Average	2.11	69.1	12.2
SD	0.14	2.87	0.51
COV (%)	6.72	4.15	4.13
		120°C	
C2-1	0.56	23.7	10.6
C2-3	0.58	25.1	11.1
C2-6	0.59	22.0	12.0
C3-1	0.61	25.9	11.3
C3-4	0.65	27.5	12.0
C3-5	0.62	24.9	10.5
Average	0.60	24.9	11.2
SD	0.03	1.87	0.66
COV (%)	5.20	7.52	5.85
		-40°C	
C1-18	3.11	111	8.61
C1-24	3.49	107	12.7
C1-28	3.38	116	12.7
C1-33	3.29	107	11.9
C1-34	3.37	114	9.72
C1-35	3.25	110	9.13
Average	3.31	111	10.8
SD	0.13	3.76	1.86
COV (%)	3.93	3.39	17.2

Table 36. Shear properties of the crossply carbon-fiber composite, ±45° fiber orientation, at different temperatures

Specimen number	Shear modulus (GPa)	Shear strength (MPa)	Failure strain (%)
		70°C	
C21-2	18.1	123	0.76
C21-5	18.7	117	0.53
C21-11	17.8	103	0.64
C21-17	18.7	118	0.59
C21-23	19.5	102	0.62
C21-26	18.0	103	0.47
Average	18.5	111	0.60
SD	0.62	9.33	0.10
COV (%)	3.38	8.42	16.5
		120°C	
C21-6	14.9	87.6	0.05
C21-9	12.4	85.7	0.09
C21-14	13.9	71.0	0.03
C21-19	16.1	88.9	0.04
C21-20	15.8	90.8	0.05
C21-24	13.3	82.0	0.05
Average	14.4	84.3	0.05
SD	1.44	7.18	0.02
COV (%)	10.0	8.51	40.6
		-40°C	
C21-3	29.2	248	1.10
C21-7	28.4	240	1.24
C21-12	29.2	261	1.19
C21-15	34.3	262	1.40
C21-18	31.3	261	1.27
C21-25	29.0	216	0.90
Average	30.2	248	1.18
SD	2.20	18.1	0.17
COV (%)	7.27	7.30	14.4

Table 37. Temperature multiplication factors for determining at-temperature shear modulus and strength from room-temperature values for the crossply carbon-fiber composite, 0/90° fiber orientation

Temperature (°C)	Stiffness multiplication factor	Strength multiplication factor
-40	1.18	1.18
23	1.00	1.00
70	0.71	0.71
120	0.26	0.26

Table 38. Temperature multiplication factors for determining at-temperature shear modulus and strength from room-temperature values for the crossply carbon-fiber composite, ±45° fiber orientation

Temperature (°C)	Stiffness multiplication factor	Strength multiplication factor
-40	1.26	1.35
23	1.00	1.00
70	0.79	0.70
120	0.60	0.46

Table 39. Effects of 1000-h exposure in 23°C distilled water on room-temperature shear properties of the crossply carbon-fiber composite

Specimen number	Shear modulus (GPa)	Shear strength (MPa)	Stiffness factor	Strength factor
		0/90° fiber orientation		
C2-7	2.83	87.6	1.03	0.95
C3-3	2.69	88.3	0.98	0.94
C3-7	2.59	95.8	0.94	1.02
C3-10	2.83	88.9	1.03	0.95
C4-1	2.96	95.1	0.98	0.96
C5-1	2.90	104	0.98	1.02
Average	2.80	93.3	0.99	0.97
SD	0.14	6.39		
COV (%)	4.88	6.85		
		±45° fiber orientation		
C22-6	22.5	193	0.89	0.93
C22-7	24.0	197	0.95	0.95
C22-11	24.2	208	0.96	1.00
C22-15	22.7	188	0.90	0.91
C22-17	23.5	207	0.93	1.00
C22-25	24.2	203	0.96	0.98
Average	23.5	199	0.93	0.96
SD	0.77	7.78		
COV (%)	3.29	3.90		

Table 40. Effect of exposure in windshield washer fluid on shear strength of the crossply carbon-fiber composite

Specimen number	Shear strength (MPa)	Strength factor
	0/90° fiber orientation	
	Exposure time = 50 h	
C4-7	99.2	1.00
C4-8	101	1.01
C4-10	97.7	0.98
C5-4	98.6	0.97
C5-6	97.2	0.95
C5-9	98.6	0.97
Average	98.7	0.98
SD	1.21	
COV (%)	1.22	
	Exposure time = 100 h	
C4-2	98.6	0.99
C4-4	96.5	0.97
C4-6	95.8	0.97
C5-3	96.2	0.94
C5-5	101	0.99
C5-7	97.2	0.95
Average	97.5	0.97
SD	1.83	
COV (%)	1.88	
	±45° fiber orientation	
	Exposure time = 50 h	
C22-1	205	0.99
C22-3	192	0.93
C22-12	204	0.98
C22-18	194	0.93
C22-20	192	0.92
C22-26	180	0.87
Average	194	0.94
SD	9.15	
COV (%)	4.71	
	Exposure time = 100 h	
C22-4	184	0.88
C22-8	197	0.95
C22-10	194	0.94
C22-21	192	0.92
C22-23	199	0.96
C22-28	187	0.90
Average	192	0.93
SD	5.99	
COV (%)	3.12	

Table 41. Uniaxial flexural properties of the crossply carbon-fiber composite at different temperatures

Specimen number	Modulus of Elasticity (GPa)	MOR (MPa)
	0/90° fiber orientation	
	23°C	
C27-3	26.4	779
C27-7	21.8	772
C27-11	20.5	738
C27-16	22.2	841
C27-29	25.4	793
C27-36	24.8	855
Average	23.5	796
SD	2.35	44.2
COV (%)	10.0	5.55
	120°C	
C27-15	12.2	477
C27-21	16.0	556
C27-23	14.9	515
C27-24	11.1	422
C27-27	16.0	436
C27-31	14.0	508
Average	14.0	486
SD	2.02	50.8
COV (%)	14.4	10.5
	±45° fiber orientation	
	23°C	
C27-1	2.96	350
C27-6	2.34	279
C27-13	2.69	316
C27-19	2.76	327
C27-24	2.41	288
C27-35	2.62	309
Average	2.63	311
SD	0.23	25.8
COV (%)	8.68	8.29
	120°C	
C27-5	0.76	151
C27-8	0.69	144
C27-16	0.76	155
C27-29	0.69	147
C27-30	0.69	142
C27-34	0.90	181
Average	0.75	153
SD	0.08	14.5
COV (%)	10.8	9.43

Table 42. Effects of 1000-h exposure in 23°C distilled water on room-temperature uniaxial flexural properties of the crossply carbon-fiber composite

Specimen number	MOR (GPa)	MOR design factor
	0/90° fiber orientation	
C27-6	765	0.96
C27-10	724	0.91
C27-14	765	0.96
C27-29	800	1.00
C27-25	696	0.87
C27-33	827	1.04
Average	763	0.96
SD	47.9	
COV (%)	6.28	
	±45° fiber orientation	
C27-4	516	0.91
C27-10	517	0.91
C27-11	598	1.06
C27-18	561	0.99
C27-23	572	1.01
C27-33	576	1.02
Average	557	0.98
SD	33.1	
COV (%)	5.95	

Table 43. Effect of exposure in windshield washer fluid on uniaxial flexural properties of the crossply carbon-fiber composite

Specimen number	MOR (MPa)	MOR design factor
	0/90° fiber orientation	
	Exposure time = 50 h	
C27-4	779	0.97
C27-8	765	0.96
C27-12	765	0.96
C27-17	827	1.03
C27-28	793	0.99
C27-35	786	0.98
Average	786	0.98
SD	23.1	
COV (%)	2.94	
	Exposure time = 100 h	
C27-5	724	0.91
C27-9	807	1.01
C27-13	779	0.97
C27-18	779	0.97
C27-26	752	0.94
C27-34	820	1.03
Average	777	0.97
SD	35.3	
COV (%)	4.55	
	±45° fiber orientation	
	Exposure time = 50 h	
C27-2	592	1.05
C27-7	532	0.94
C27-14	568	1.00
C27-20	560	0.99
C27-25	546	0.96
C27-31	552	0.98
Average	558	0.99
SD	20.5	
COV (%)	3.68	
	Exposure time = 100 h	
C27-3	565	1.00
C27-9	543	0.96
C27-15	552	0.98
C27-17	539	0.95
C27-22	537	0.95
C27-32	574	1.01
Average	552	0.97
SD	14.9	
COV (%)	2.69	

Table 44. Biaxial flexural properties of the crossply carbon-fiber composite at different temperatures: ±45° fiber orientation

Specimen number	Maximum load (N)	Temperature factor
	23°C	
C31-8	12179	1.00
C31-9	13051	1.00
C31-14	12246	1.00
C31-17	12477	1.00
C31-20	12179	1.00
C31-23	12152	1.00
Average	12381	1.00
SD	374.6	
COV (%)	3.03	
	120°C	
C31-6	7033	0.57
C31-7	7362	0.59
C31-16	7277	0.59
C31-19	6530	0.53
C31-22	6183	0.50
C31-25	6214	0.50
Average	6766	0.55
SD	570.6	
COV (%)	8.43	

Table 45. Effects of environment on biaxial flexural properties of the crossply carbon-fiber composite: ±45° fiber orientation

Specimen number	Maximum load (N)	Design factor
1000 h in 23°C distilled water		
C31-1	12104	0.98
C31-5	12419	1.00
C31-11	12446	1.01
C31-13	12250	0.99
C31-21	11939	0.96
C31-24	11863	0.96
Average	12170	0.98
SD	269.9	
COV (%)	2.22	
100 h in windshield washer fluid		
C31-3	11641	0.94
C31-4	12393	1.00
C31-12	12993	1.05
C31-15	12815	1.04
C31-18	12580	1.02
C31-26	11650	0.94
Average	12345	1.00
SD	520.2	
COV (%)	4.21	

Table 46. Summary of room-temperature stiffness values for the quasi-isotropic carbon-fiber composite

Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)
Q9-1	32.1	Q10-43	35.0	Q11-31	34.0	Q12-20	31.4
Q9-2	27.6	Q10-44	33.7	Q11-32	32.8	Q12-21	30.1
Q9-3	26.0	Q10-45	34.3	Q11-33	28.7	Q12-22	34.4
Q9-4	34.4	Q10-46	36.4	Q11-34	29.5	Q12-23	34.0
Q9-5	30.8	Q10-47	30.8	Q11-35	34.8	Q12-24	34.3
Q9-6	32.6	Q10-48	33.8	Q11-36	32.7	Q12-25	35.3
Q10-1	32.8	Q10-49	35.1	Q11-37	32.2	Q12-26	31.0
Q10-2	32.1	Q10-50	33.4	Q11-38	32.8	Q12-27	32.4
Q10-3	31.9	Q10-51	35.3	Q11-39	29.3	Q12-28	31.3
Q10-4	33.1	Q10-52	34.8	Q11-40	31.9	Q12-29	33.5
Q10-5	30.2	Q10-53	33.1	Q11-41	31.6	Q12-30	34.9
Q10-6	30.0	Q10-54	32.6	Q11-42	31.6	Q12-31	30.5
Q10-7	32.4	Q10-55	35.0	Q11-43	34.5	Q12-32	30.7
Q10-8	30.8	Q10-56	33.1	Q11-44	32.0	Q12-33	32.0
Q10-9	31.3	Q10-57	34.8	Q11-45	34.1	Q12-34	33.3
Q10-10	28.7	Q10-58	33.5	Q11-46	34.8	Q12-35	33.5
Q10-11	30.3	Q11-1	31.5	Q11-47	33.1	Q12-36	35.9
Q10-12	31.6	Q11-2	32.9	Q11-48	35.6	Q12-37	32.1
Q10-13	31.1	Q11-3	30.5	Q11-49	32.7	Q12-38	33.5
Q10-14	29.4	Q11-4	28.4	Q11-50	35.3	Q12-39	30.7
Q10-15	30.6	Q11-5	33.8	Q11-51	31.4	Q12-40	34.0
Q10-16	30.0	Q11-6	32.6	Q11-52	29.6	Q12-41	34.1
Q10-17	29.7	Q11-7	31.3	Q11-53	32.5	Q12-42	37.5
Q10-18	28.6	Q11-8	33.0	Q11-54	33.6	Q12-43	34.5
Q10-19	29.4	Q11-9	32.0	Q11-55	36.5	Q12-44	33.3
Q10-20	30.7	Q11-10	33.5	Q11-56	34.5	Q12-45	35.5
Q10-21	30.9	Q11-11	33.4	Q11-57	32.6	Q12-46	32.0
Q10-22	34.9	Q11-12	29.5	Q11-58	35.3	Q12-47	37.0
Q10-23	31.7	Q11-13	26.4	Q12-2	33.0	Q12-48	36.6
Q10-26	32.4	Q11-14	26.9	Q12-3	30.8	Q12-49	33.5
Q10-27	30.8	Q11-15	27.5	Q12-4	35.2	Q12-50	33.6
Q10-28	34.4	Q11-16	31.9	Q12-5	33.1	Q12-51	32.4
Q10-29	31.8	Q11-17	30.4	Q12-6	31.6	Q12-52	34.5
Q10-30	32.2	Q11-18	30.3	Q12-7	32.3	Q12-53	33.2
Q10-31	33.7	Q11-19	35.2	Q12-8	30.6	Q12-54	30.8
Q10-32	30.8	Q11-20	34.7	Q12-9	33.1	Q12-55	34.9
Q10-33	31.3	Q11-21	32.1	Q12-10	28.7	Q12-56	35.7
Q10-34	30.7	Q11-22	31.5	Q12-11	31.1	Q12-57	35.4
Q10-35	31.5	Q11-23	31.2	Q12-12	30.7	Q13-1	33.6
Q10-36	33.4	Q11-24	30.7	Q12-13	32.5	Q13-2	31.0
Q10-37	28.8	Q11-25	33.0	Q12-14	31.9	Q13-3	29.0
Q10-38	31.3	Q11-26	31.8	Q12-15	30.0	Q13-4	31.0
Q10-39	35.0	Q11-27	33.3	Q12-16	30.2	Q13-5	30.6
Q10-40	33.5	Q11-28	32.2	Q12-17	29.7	Q13-6	28.2
Q10-41	36.0	Q11-29	34.3	Q12-18	28.8	Q13-7	30.1
Q10-42	34.6	Q11-30	33.6	Q12-19	30.5	Q13-8	30.3

Table 46. Continued. Summary of room-temperature stiffness values for the quasi-isotropic carbon-fiber composite

Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)
Q13-9	28.9	Q13-55	33.8	Q14-43	33.9	Q15-31	32.8
Q13-10	31.9	Q13-56	34.4	Q14-44	34.0	Q15-32	29.8
Q13-11	30.6	Q13-57	35.0	Q14-45	33.1	Q15-33	32.8
Q13-12	30.6	Q13-58	32.5	Q14-46	39.0	Q15-34	32.4
Q13-13	27.4	Q14-1	35.4	Q14-47	32.2	Q15-35	31.4
Q13-14	28.6	Q14-2	34.8	Q14-48	36.1	Q15-36	32.3
Q13-15	32.3	Q14-3	31.4	Q14-49	33.4	Q15-37	36.0
Q13-16	30.2	Q14-4	32.3	Q14-50	33.1	Q15-38	31.8
Q13-17	30.5	Q14-5	33.0	Q14-51	35.2	Q15-39	31.6
Q13-18	31.0	Q14-6	33.2	Q14-52	33.6	Q15-40	31.5
Q13-19	28.9	Q14-7	30.9	Q14-53	33.0	Q15-41	32.9
Q13-20	30.5	Q14-8	33.2	Q14-54	32.5	Q15-42	32.6
Q13-21	29.3	Q14-9	32.7	Q14-55	33.7	Q15-43	32.6
Q13-22	30.8	Q14-10	30.0	Q14-56	31.3	Q15-44	32.6
Q13-23	33.0	Q14-11	29.3	Q14-57	33.1	Q15-45	32.3
Q13-24	35.6	Q14-12	31.5	Q14-58	36.1	Q15-46	30.8
Q13-25	30.1	Q14-13	30.6	Q15-1	35.8	Q15-47	30.8
Q13-26	35.9	Q14-14	31.9	Q15-2	32.8	Q15-48	32.4
Q13-27	34.8	Q14-15	33.8	Q15-3	32.9	Q15-49	31.8
Q13-28	30.8	Q14-16	28.4	Q15-4	34.8	Q15-50	31.4
Q13-29	34.7	Q14-17	31.3	Q15-5	33.2	Q15-51	28.8
Q13-30	31.1	Q14-18	32.7	Q15-6	32.6	Q15-52	29.4
Q13-31	30.2	Q14-19	29.0	Q15-7	32.4	Q15-53	31.6
Q13-32	31.1	Q14-20	33.9	Q15-8	33.4	Q15-54	30.7
Q13-33	29.5	Q14-21	34.5	Q15-9	32.6	Q15-55	31.4
Q13-34	34.3	Q14-22	33.2	Q15-10	28.5	Q15-56	32.3
Q13-35	31.3	Q14-23	29.2	Q15-11	32.8	Q15-57	31.0
Q13-36	30.8	Q14-24	32.2	Q15-12	34.0	Q15-58	32.0
Q13-37	33.5	Q14-25	35.8	Q15-13	34.7	Q16-1	31.3
Q13-38	31.7	Q14-26	33.5	Q15-14	33.1	Q16-2	32.8
Q13-39	30.1	Q14-27	32.7	Q15-15	32.7	Q16-3	31.3
Q13-40	33.8	Q14-28	35.3	Q15-16	34.1	Q16-4	32.7
Q13-41	34.1	Q14-29	31.6	Q15-17	32.4	Q16-5	32.4
Q13-42	31.5	Q14-30	32.3	Q15-18	32.9	Q16-6	33.3
Q13-43	32.0	Q14-31	32.7	Q15-19	33.0	Q16-7	33.1
Q13-44	34.0	Q14-32	34.4	Q15-20	33.5	Q16-8	33.6
Q13-45	32.5	Q14-33	33.2	Q15-21	34.6	Q16-9	32.4
Q13-46	33.3	Q14-34	29.9	Q15-22	29.8	Q16-10	30.9
Q13-47	34.0	Q14-35	31.3	Q15-23	29.5	Q16-11	31.9
Q13-48	29.5	Q14-36	30.1	Q15-24	32.2	Q16-12	32.8
Q13-49	34.1	Q14-37	31.7	Q15-25	31.1	Q16-13	31.1
Q13-50	33.5	Q14-38	34.0	Q15-26	30.9	Q16-14	29.6
Q13-51	33.4	Q14-39	36.2	Q15-27	33.2	Q16-15	31.1
Q13-52	34.3	Q14-40	32.9	Q15-28	32.6	Q16-16	31.3
Q13-53	35.0	Q14-41	33.6	Q15-29	32.9	Q16-17	33.1
Q13-54	33.8	Q14-42	34.6	Q15-30	31.7	Q16-18	32.9

Table 46. Continued. Summary of room-temperature stiffness values for the quasi-isotropic carbon-fiber composite

Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)	Specimen number	Stiffness (GPa)
Q16-19	35.5	Q16-42	34.0	Q19-1L	30.7	Q24-4	32.1
Q16-20	31.8	Q16-43	29.1	Q19-2L	35.2	Q25-1	33.3
Q16-21	32.7	Q16-44	31.5	Q19-1T	34.4	Q25-2	35.0
Q16-22	31.4	Q16-45	33.0	Q19-2T	38.9	Q25-3	33.0
Q16-23	34.1	Q16-46	30.7	Q20A	32.0	Q25-4	33.2
Q16-24	30.6	Q16-47	31.4	Q20B	33.0	Q26-1	32.3
Q16-25	33.8	Q16-48	29.1	Q20C	35.3	Q26-2	34.9
Q16-26	32.4	Q16-49	31.6	Q20D	36.1	Q26-3	35.4
Q16-27	31.8	Q16-50	29.6	Q21-1	34.0	Q26-4	33.4
Q16-28	31.7	Q16-51	30.7	Q21-2	30.7	Q27-1	31.6
Q16-29	29.8	Q16-52	31.0	Q21-3	34.2	Q27-2	30.4
Q16-30	32.4	Q16-53	32.0	Q21-4	34.5	Q27-3	32.3
Q16-31	32.7	Q16-54	32.8	Q22-1	33.2	Q27-4	31.6
Q16-32	30.4	Q16-55	33.0	Q22-2	34.4	Q28-1	34.5
Q16-33	32.2	Q16-56	31.1	Q22-3	39.0	Q28-2	33.9
Q16-34	28.6	Q16-57	31.9	Q22-4	38.1	Q28-3	34.3
Q16-35	33.8	Q16-58	30.5	Q23-1	33.0	Q28-4	29.9
Q16-36	30.5	Q18-1	33.2	Q23-2	31.5		
Q16-37	34.9	Q18-2	31.5	Q23-3	33.8	**Average**	32.4
Q16-38	32.0	Q18-3	34.8	Q23-4	34.7	**SD**	2.04
Q16-39	37.1	Q18-4	35.5	Q24-1	32.3	**COV(%)**	6.28
Q16-40	32.0	Q18-5	35.0	Q24-2	31.4		
Q16-41	30.4	Q18-6	35.3	Q24-3	31.0		

Table 47. Summary of room-temperature tensile properties for the quasi-isotropic carbon-fiber composite

Specimen number	UTS (MPa)	Failure strain (%)	Specimen number	UTS (MPa)	Failure strain (%)
Q9-1	261	0.90	Q19-1L	328	1.07
Q9-2	298	1.06	Q19-2L	340	0.92
Q9-3	286	1.11	Q19-1T	362	1.07
Q9-4	335	0.99	Q19-2T	354	0.89
Q9-5	308	1.01	Q20A	346	1.11
Q9-6	308	0.95	Q20B	322	0.98
Q10-5	331	1.12	Q20C	379	1.08
Q10-16	346	1.02	Q20D	372	1.04
Q10-43	295	0.91	Q21-1	339	0.98
Q10-54	328	1.00	Q21-2	351	1.14
Q11-5	403	1.05	Q21-3	366	1.05
Q11-16	362	1.07	Q21-4	380	1.09
Q11-22	362	1.00	Q22-1	341	1.03
Q11-36	362	0.99	Q22-2	306	0.88
Q11-43	317	1.05	Q22-3	380	0.95
Q11-54	341	0.99	Q22-4	397	1.04
Q12-5	411	1.20	Q23-1	299	0.90
Q12-16	312	0.99	Q23-2	351	1.13
Q12-22	338	0.99	Q23-3	331	0.97
Q12-36	407	1.13	Q23-4	296	0.84
Q12-43	281	0.96	Q24-1	341	1.04
Q12-54	337	0.99	Q24-2	346	1.13
Q13-5	310	0.98	Q24-3	314	0.99
Q13-16	333	1.09	Q24-4	350	1.07
Q13-22	327	0.96	Q25-1	292	0.88
Q13-36	341	1.04	Q25-2	336	0.97
Q13-43	306	1.10	Q25-3	351	1.07
Q13-54	358	1.05	Q25-4	337	1.02
Q14-5	372	1.06	Q26-1	326	1.05
Q14-16	281	-	Q26-2	332	0.94
Q14-43	332	0.99	Q26-3	336	0.97
Q14-54	325	0.98	Q26-4	324	0.97
Q15-5	317	1.00	Q27-1	323	1.02
Q15-16	354	1.04	Q27-2	307	0.99
Q15-43	371	1.14	Q27-3	318	0.97
Q15-54	334	1.07	Q27-4	320	1.00
Q16-5	344	1.07	Q28-1	340	0.98
Q16-16	332	1.07	Q28-2	334	1.00
Q16-43	313	1.05	Q28-3	367	1.04
Q16-54	343	0.98	Q28-4	276	0.92
Q18-1	330	1.00			
Q18-2	340	1.07	**Average**	336	1.02
Q18-3	314	0.88	**SD**	29.1	0.07
Q18-4	353	0.98	**COV(%)**	8.66	6.80
Q18-5	365	1.04			
Q18-6	352	1.03			

Table 48. Summary of plaque average tensile properties for the quasi-isotropic carbon-fiber composite

Plaque number	Number of stiffness tests	E_{avg} (GPa)	E_{max} (GPa)	E_{min} (GPa)	Number of tensile tests	UTS_{avg} (MPa)	UTS_{max} (MPa)	UTS_{min} (MPa)	$\varepsilon_{f\ avg}$ (%)
Q9	6	30.6	34.4	27.6	6	299	335	261	1.00
Q10	58	32.3	36.4	28.6	4	325	346	295	1.01
Q11	58	32.2	36.5	26.4	6	358	403	317	1.02
Q12	56	32.8	37.5	28.7	6	348	411	281	1.04
Q13	58	31.9	35.9	27.4	6	329	358	306	1.04
Q14	58	32.9	39.0	28.4	4	328	372	281	1.01
Q15	58	32.2	36.0	28.5	4	344	354	317	1.06
Q16	58	31.9	37.1	28.6	4	333	344	313	1.04
Q18	6	34.2	35.5	31.5	6	342	365	314	1.00
Q19	4	34.8	38.9	30.7	4	346	362	328	0.99
Q20	4	34.1	36.1	32.0	4	355	379	322	1.05
Q21	4	33.3	34.5	30.7	4	359	380	339	1.07
Q22	4	36.2	39.0	33.2	4	356	397	306	0.98
Q23	4	33.2	34.7	31.5	4	319	351	296	0.96
Q24	4	31.7	32.3	31.0	4	338	350	314	1.06
Q25	4	33.6	35.0	33.0	4	329	351	292	0.99
Q26	4	34.0	35.4	32.3	4	330	336	324	0.98
Q27	4	31.5	32.3	30.4	4	317	323	307	1.00
Q28	4	33.2	34.5	29.9	4	329	367	276	0.99
Number of tests	456				86				
Average		32.4				336			
SD		2.04				29.1			
COV %		6.28				8.66			
MAX		39.0				411			
MIN		26.0				261			

Table 49. Summary of tensile tests at various strain rates for the quasi-isotropic carbon-fiber composite

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Failure strain (%)
		Strain rate = 10^{-6} s^{-1}		
Q13-3	29.0	27.4	307	1.15
Q13-14	28.6	28.3	309	1.10
Q13-28	30.8	29.6	318	1.06
Q13-49	34.1	32.8	343	1.03
Average	30.6	29.5	319	1.09
SD	2.51	2.36	16.5	0.05
COV (%)	8.18	8.00	5.18	4.79
		Strain rate = 10^{-4} s^{-1}		
Q13-2	31.0	32.3	312	1.01
Q13-13	27.4	28.4	300	1.07
Q13-27	34.8	33.9	305	0.89
Q13-51	33.4	33.3	358	1.07
Average	31.7	32.0	319	1.01
SD	3.24	2.47	26.6	0.08
COV (%)	10.2	7.73	8.35	8.40
		Strain rate = 10^{-2} s^{-1}		
Q13-1	33.6	30.9	322	1.07
Q13-12	30.6	31.1	296	0.93
Q13-26	35.9	35.9	308	0.87
Q13-50	33.5	31.9	317	0.99
Average	33.4	32.5	311	0.97
SD	2.17	2.34	11.4	0.09
COV (%)	6.50	7.21	3.67	8.85
		Strain rate = 10 s^{-1}		
Q13-4	31.0	22.6	292	0.96
Q13-15	32.3	25.2	259	0.83
Q13-29	34.7	24.7	319	0.95
Q13-53	35.0	25.9	294	0.83
Average	33.3	24.6	291	0.89
SD	1.93	1.42	24.6	0.07
COV (%)	5.79	5.78	8.46	8.10

Table 50. Summary of tensile tests at various temperatures for the quasi-isotropic carbon-fiber composite

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Failure strain (%)	Stiffness factor	Strength factor
			-40°C			
Q11-4	28.4	29.4	270	0.92	1.04	0.78
Q11-15	27.5	28.3	280	0.98	1.03	0.81
Q11-21	32.1	35.1	307	0.87	1.09	0.89
Q11-35	34.8	34.9	337	0.97	1.00	0.97
Q11-42	31.6	34.5	281	0.83	1.09	0.81
Q11-53	32.5	33.4	303	0.91	1.03	0.88
Average	31.2	32.6	296	0.91	1.05	0.86
SD	2.73	2.98	24.5	0.06		
COV (%)	8.85	9.15	8.28	6.30		
			-10°C			
Q11-10	33.5	34.3	370	1.05	1.02	1.07
Q11-14	26.9	27.5	266	0.98	1.02	0.77
Q11-26	31.8	32.8	309	0.92	1.03	0.89
Q11-34	29.5	29.9	293	0.97	1.01	0.85
Q11-40	31.9	32.3	329	1.01	1.01	0.95
Average	30.7	31.4	313	0.99	1.02	0.91
SD	2.57	2.68	39.1	0.05		
COV (%)	8.36	8.53	12.5	4.90		
			23°C			
Q11-5	33.8	33.8	403	1.05	1.00	1.00
Q11-16	31.9	31.9	362	1.07	1.00	1.00
Q11-22	33.2	33.2	362	1.00	1.00	1.00
Q11-36	30.1	30.1	362	0.99	1.00	1.00
Q11-43	34.5	34.5	317	1.05	1.00	1.00
Q11-54	33.6	33.6	341	0.99	1.00	1.00
Average	32.9	32.9	358	1.03	1.00	1.00
SD	1.60	1.60	28.4	0.04		
COV (%)	4.87	4.87	7.95	3.48		
			50°C			
Q11-9	32.0	32.0	301	0.93	1.00	0.87
Q11-13	26.4	27.2	277	1.00	1.03	0.80
Q11-25	33.0	34.0	336	0.99	1.03	0.97
Q11-33	28.7	28.5	231	0.81	0.99	0.67
Q11-39	29.3	30.3	326	1.06	1.03	0.94
Q11-49	32.7	33.5	336	1.01	1.02	0.97
Average	30.4	30.9	301	0.97	1.02	0.87
SD	2.63	2.73	41.4	0.09		
COV (%)	8.68	8.84	13.7	9.03		

Table 50. Continued. Summary of tensile tests at various temperatures for the quasi-isotropic carbon-fiber composite

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Failure strain (%)	Stiffness factor	Strength factor
			70°C			
Q11-6	32.6	31.9	331	1.04	0.98	0.96
Q11-17	30.4	29.4	318	1.08	0.97	0.92
Q11-23	31.2	30.5	307	0.97	0.98	0.89
Q11-37	32.2	30.8	332	1.07	0.96	0.96
Q11-44	32.0	31.2	308	1.03	0.97	0.89
Q11-55	36.5	33.2	364	1.10	0.91	1.05
Average	32.5	31.2	327	1.05	0.96	0.95
SD	2.12	1.29	21.2	0.05		
COV (%)	6.52	4.15	6.50	4.41		
			120°C			
Q11-7	31.3	28.5	304	1.00	0.91	0.88
Q11-18	30.3	28.3	260	0.98	0.93	0.75
Q11-24	30.7	27.7	263	0.97	0.90	0.76
Q11-38	32.8	29.1	302	1.03	0.89	0.87
Q11-45	34.1	31.0	290	0.98	0.91	0.84
Q11-56	34.5	31.8	309	1.04	0.92	0.89
Average	32.3	29.4	288	1.00	0.91	0.83
SD	1.78	1.63	21.5	0.03		
COV (%)	5.52	5.55	7.46	2.90		

Table 51. Temperature multiplication factors for determining at-temperature tensile modulus and strength from room-temperature values for the quasi-isotropic carbon-fiber composite

Temperature (°C)	Stiffness multiplication factor	Strength multiplication factor
-40	1.04	0.87
-10	1.02	0.96
23	1.00	1.00
50	0.98	0.99
70	0.96	0.97
120	0.92	0.81

Table 52. Summary of Poisson's ratio measurements at different temperatures for the quasi-isotropic carbon-fiber composite

Specimen number	Poisson's ratio			
	-40°C	23°C	70°C	120°C
Q13-8	0.28	0.28	0.29	0.31
Q13-24	0.33	0.33	0.32	0.33
Q13-32	0.31	0.32	0.31	0.35
Q13-45	0.33	0.33	0.34	0.35
Q13-57	0.31	0.32	0.31	0.35
Average	0.31	0.32	0.31	0.34
SD	0.02	0.02	0.02	0.02
COV (%)	6.57	6.56	5.79	5.29

Table 53. Effects of prior thermal cycling on mechanical properties of the quasi-isotropic carbon-fiber composite

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	Strength (MPa)	Stiffness factor	Strength factor
		Tension			
Q13-7	30.1	30.1	284	1.00	0.86
Q13-18	31.0	30.2	306	0.97	0.93
Q13-21	29.3	29.4	305	1.00	0.93
Q13-33	29.5	29.6	308	1.00	0.94
Q13-42	31.5	31.4	306	1.00	0.93
Q13-56	34.4	34.7	334	1.01	1.01
Average	31.0	30.9	307	1.00	0.93
SD	1.88	1.99	15.9		
COV (%)	6.08	6.43	5.18		
		Compression			
Q18-7	-	29.2	246	0.93	1.11
Q18-18	-	28.0	281	0.89	1.27
Q18-21	-	29.7	279	0.95	1.26
Q18-51	-	34.7	254	1.11	1.15
Average	-	30.4	265	0.97	1.20
SD	-	2.95	17.6		
COV (%)	-	9.72	6.66		
		Shear			
Q18-7	-	9.38	224	0.77	0.99
Q18-20	-	9.10	229	0.75	1.01
Q18-21	-	8.89	212	0.73	0.94
Q18-34	-	9.38	210	0.77	0.93
Average	-	9.19	219	0.76	0.97
SD	-	0.24	9.22		
COV (%)	-	2.59	4.21		

Table 54. Effect of exposure in 23°C distilled water on tensile strength and stiffness of the quasi-isotropic carbon-fiber composite

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Change in stiffness (%)	Change in strength (%)
		Exposure Time = 500 h			
Q12-4	35.2	36.4	374	1.03	7.54
Q12-17	29.7	29.0	303	0.98	-12.9
Q12-21	30.1	33.0	330	1.10	-4.96
Q12-33	32.0	32.2	292	1.01	-16.1
Q12-42	37.5	38.5	355	1.03	2.18
Q12-48	36.6	37.2	414	1.02	19.2
Average	33.5	34.4	345	1.03	-0.84
SD	3.37	3.59	45.8		
COV (%)	10.1	10.5	13.3		
		Exposure Time = 1000 h			
Q12-12	30.7	32.3	346	1.05	-0.34
Q12-23	34.0	35.2	373	1.04	7.36
Q12-34	33.3	32.6	352	0.98	1.39
Q12-44	33.3	32.5	341	0.98	-1.83
Q12-50	33.5	33.6	327	1.00	-6.02
Average	33.0	33.2	348	1.01	0.11
SD	1.30	1.21	16.8		
COV (%)	3.93	3.63	4.84		
		Exposure Time = 1506 h			
Q12-7	32.3	32.4	305	1.00	-12.1
Q12-13	32.5	33.0	359	1.02	3.37
Q12-24	34.3	33.8	346	0.99	-0.40
Q12-35	33.5	34.3	365	1.02	4.96
Q12-51	33.6	34.1	354	1.01	1.79
Average	33.2	33.5	346	1.01	-0.48
SD	0.83	0.80	23.8		
COV (%)	2.50	2.38	6.90		
		Exposure Time = 1990 h			
Q12-8	30.6	31.5	354	1.03	1.79
Q12-14	31.9	32.4	321	1.02	-7.54
Q12-25	35.3	36.0	364	1.02	4.76
Q12-37	32.1	33.0	354	1.03	1.79
Q12-46	32.0	34.1	325	1.07	-6.35
Q12-52	32.4	33.6	350	1.04	0.60
Average	32.4	33.4	345	1.03	-0.83
SD	1.56	1.55	17.5		
COV (%)	4.81	4.64	5.06		

Table 54. Continued. Effect of exposure in 23°C distilled water on tensile strength and stiffness of the quasi-isotropic carbon-fiber composite

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Change in stiffness (%)	Change in strength (%)
			Exposure Time = 4818 h		
Q12-9	33.1	31.2	321	0.94	-7.74
Q12-15	30.0	30.4	300	1.01	-13.7
Q12-26	31.0	31.6	330	1.02	-4.96
Q12-38	33.5	34.6	361	1.03	3.77
Q12-47	37.0	37.0	360	1.00	3.57
Q12-53	34.5	34.1	345	0.99	-0.79
Average	33.2	33.2	336	1.00	-3.31
SD	2.50	2.51	23.8		
COV (%)	7.54	7.58	7.09		

Table 55. Effect of exposure in 70% relative humidity air on tensile strength and stiffness of the quasi-isotropic carbon-fiber composite

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Failure strain (%)	Change in stiffness (%)	Change in strength (%)
			Exposure Time = 1000 h			
Q12-10	28.7	28.6	266	0.93	1.00	-23.4
Q12-18	32.6	33.0	330	1.01	1.01	-4.97
Q12-27	32.4	32.9	345	1.11	1.02	-0.78
Q12-30	34.9	35.0	378	1.10	1.00	8.69
Q12-39	33.3	33.4	343	1.05	1.00	-1.21
Q12-55	30.8	31.3	341	1.09	1.02	-2.00
Average	32.1	32.4	334	1.05	1.01	-3.95
SD	2.14	2.19	37.0	0.07		
COV (%)	6.66	6.77	11.1	6.57		
			Exposure Time = 1990 h			
Q12-2	33.0	32.5	326	0.99	0.98	-6.15
Q12-19	30.5	30.3	338	1.12	0.99	-2.78
Q12-28	31.3	31.9	326	1.01	1.02	-6.15
Q12-31	30.5	29.6	312	1.15	0.97	-10.1
Q12-40	34.0	34.3	303	0.88	1.01	-12.9
Q12-56	34.9	34.5	361	1.05	0.99	3.77
Average	32.4	32.2	328	1.03	0.99	-5.72
SD	1.88	2.01	20.4	0.10		
COV (%)	5.80	6.25	6.2	9.42		
			Exposure Time = 4818 h			
Q12-11	31.1	32.3	365	1.12	1.04	5.16
Q12-20	31.4	31.6	309	0.97	1.01	-11.1
Q12-29	33.5	34.3	327	0.94	1.02	-5.95
Q12-32	30.7	30.3	316	1.06	0.99	-9.13
Q12-41	34.1	34.9	370	1.08	1.02	6.55
Q12-57	35.7	35.3	361	1.02	0.99	3.77
Average	32.8	33.1	341	1.03	1.01	-1.79
SD	1.99	2.01	27.1	0.07		
COV (%)	6.08	6.08	7.9	6.61		

Table 56. Effects of 100-h exposure in windshield washer fluid on tensile stiffness and strength of the quasi-isotropic carbon-fiber composite

Specimen number	Virgin stiffness (GPa)	Stiffness (GPa)	UTS (MPa)	Stiffness factor	Strength factor
Q13-6	28.2	29.2	299	1.04	0.91
Q13-17	30.5	29.7	319	0.97	0.97
Q13-23	33.0	33.6	329	1.02	1.00
Q13-37	33.5	32.3	365	0.96	1.11
Q13-44	34.0	34.7	347	1.02	1.05
Q13-55	33.8	34.9	325	1.03	0.99
Average	32.2	32.4	331	1.01	1.01
SD	2.32	2.47	22.9		
COV (%)	7.23	7.63	6.92		

Table 57. Summary of room-temperature compressive tests for the quasi-isotropic carbon-fiber composite

Specimen number	Compressive stiffness (GPa)	UCS (MPa)	Failure strain (%)
Q18-4	29.6	197	0.63
Q18-7	30.3	252	0.81
Q18-10	32.1	197	0.63
Q18-17	33.0	236	0.74
Q18-29	33.4	220	0.63
Q18-32	38.0	223	0.65
Q18-39	27.0	243	1.13
Q18-46	28.8	230	[a]
Q18-48	31.0	214	0.79
Q21-1	32.2	196	0.64
Q21-2	29.1	232	0.78
Q21-3	37.2	183	0.79
Q22-1	29.5	239	0.81
Q22-2	31.2	234	0.77
Q22-3	34.5	190	0.62
Q22-4	33.1	252	0.70
Q23-1	32.2	225	0.70
Q23-2	30.5	215	0.66
Q23-3	29.6	208	0.71
Q23-4	29.5	[a]	[a]
Q24-1	29.8	237	0.84
Q24-2	32.5	257	0.83
Q24-3	27.4	182	0.79
Q24-4	38.0	244	0.69
Q25-1	31.7	253	0.76
Q25-2	30.0	225	0.73
Q25-3	35.1	252	0.63
Q25-4	32.7	183	0.54
Q26-1	[a]	231	[a]
Q26-2	[a]	230	[a]
Q26-3	39.0	252	0.69
Q26-4	41.0	243	0.56
Q27-1	31.1	246	0.62
Q27-2	32.5	237	0.63
Q27-3	[a]	223	[a]
Q27-4	33.4	241	0.71
Q28-1	27.0	227	1.04
Q28-2	32.6	197	0.59
Q28-3	29.2	219	0.71
Q28-4	[a]	212	[a]
Average	32.1	225	0.72
SD	3.34	21.6	0.12
COV (%)	10.4	9.62	16.9

[a] No strain measurement

Table 58. Compressive properties of the quasi-isotropic carbon-fiber composite at different temperatures

Specimen number	Compressive stiffness (GPa)	UCS (MPa)	Failure strain (%)
	70°C		
Q18-2	30.5	203	0.64
Q18-5	29.9	160	0.64
Q18-12	[a]	203	
Q18-28	30.2	203	0.65
Q18-41	29.5	215	0.60
Average	30.0	192	0.63
SD	0.43	21.2	0.02
COV (%)	1.40	11.0	3.51
	120°C		
Q18-3	28.4	136	0.49
Q18-13	22.8	106	0.55
Q18-30	[a]	124	[a]
Q18-34	27.4	130	0.55
Q18-42	28.5	128	0.46
Average	26.8	124	0.51
SD	2.70	11.4	0.04
COV (%)	10.1	9.17	8.78
	-40°C		
Q18-8	28.1	226	0.89
Q18-11	32.0	252	0.88
Q18-27	32.3	237	0.64
Q18-31	30.7	203	0.71
Q18-45	33.9	238	0.52
Average	30.8	230	0.78
SD	2.17	18.3	0.16
COV (%)	7.04	7.96	20.3

[a] No strain measurement

Table 59. Temperature multiplication factors for determining at-temperature compressive stiffness and strength from room-temperature values for the quasi-isotropic carbon-fiber composite

Temperature (°C)	Stiffness multiplication factor	Strength multiplication factor
-40	1.02	1.02
23	1.00	1.00
70	0.95	0.86
120	0.85	0.58

Table 60. Effects of 1000-h exposure in 23°C distilled water on room-temperature compressive properties of the quasi-isotropic carbon-fiber composite

Specimen number	Compressive stiffness (GPa)	UCS (MPa)	Stiffness factor	Strength factor
Q18-6	31.3	206	1.00	0.93
Q18-16	28.8	212	0.92	0.96
Q18-20	35.8	180	1.14	0.82
Q18-37	[a]	219	[a]	0.99
Q18-44	26.1	216	0.83	0.98
Q18-50	28.6	211	0.91	0.96
Average	30.1	207	0.96	0.94
SD	3.67	14.1		
COV (%)	12.2	6.81		

[a] No strain measurement

Table 61. Effects of 100-h exposure in windshield washer fluid on room-temperature compressive strength of the quasi-isotropic carbon-fiber composite

Specimen number	UCS (MPa)	Strength design factor
Q18-15	228	1.03
Q18-19	226	1.02
Q18-33	223	1.01
Q18-38	207	0.94
Q18-43	211	0.95
Q18-49	210	0.95
Average	218	0.98
SD	9.18	
COV (%)	4.20	

Table 62. Summary of in-air room-temperature shear properties of the quasi-isotropic carbon-fiber composite

Specimen number	Shear modulus (GPa)	Shear strength (MPa)	Failure strain (%)
Q18-1	10.9	217	2.48
Q18-3	12.2	235	2.51
Q18-26	13.0	238	2.01
Q18-29	12.2	212	2.33
Q18-30	13.9	244	2.13
Q18-39	11.2	238	2.43
Q18-11	[a]	211	[a]
Q18-14	[a]	212	[a]
Average	12.2	226	2.32
SD	1.11	14.1	0.20
COV (%)	9.11	6.24	8.77

[a] No strain measurement

Table 63. Shear properties of the quasi-isotropic carbon-fiber composite at different temperatures

Specimen number	Shear Modulus (GPa)	Shear strength (MPa)	Failure strain (%)
		70°C	
Q18-13	11.9	178	1.75
Q18-16	11.5	200	2.18
Q18-25	11.9	182	2.04
Q18-28	11.9	197	1.97
Q18-40	12.1	202	2.32
Average	11.9	192	2.05
SD	0.22	11.0	0.22
COV (%)	1.85	5.74	10.5
		120°C	
Q18-10	10.7	138	1.65
Q18-17	11.3	125	1.82
Q18-24	10.8	133	1.43
Q18-31	11.2	136	1.24
Q18-37	10.8	127	1.30
Average	11.0	132	1.49
SD	0.27	5.63	0.24
COV (%)	2.47	4.27	16.3
		-40°C	
Q18-2	12.4	235	2.22
Q18-15	12.1	271	2.61
Q18-27	11.9	232	2.16
Q18-38	12.5	249	2.31
Average	12.2	247	2.33
SD	0.28	17.8	0.20
COV (%)	2.25	7.21	8.59

Table 64. Temperature multiplication factors for determining at-temperature shear modulus and strength from room-temperature values for the quasi-isotropic carbon-fiber composite

Temperature (°C)	Stiffness multiplication factor	Strength multiplication factor
-40	0.99	1.06
23	1.00	1.00
70	0.97	0.85
120	0.89	0.59

Table 65. Effects of 1000-h exposure in 23°C distilled water on room-temperature shear properties of the quasi-isotropic carbon-fiber composite

Specimen number	Shear modulus (GPa)	Shear strength (MPa)	Stiffness factor	Strength factor
Q18-5	13.1	226	1.07	1.00
Q18-8	13.1	244	1.07	1.08
Q18-18	10.3	190	0.84	0.84
Q18-22	13.0	238	1.06	1.05
Q18-33	11.0	209	0.90	0.93
Q18-35	[a]	227	[a]	1.00
Average	12.1	223	0.99	0.98
SD	1.34	19.9		
COV (%)	11.1	8.92		

[a] No strain measurement

Table 66. Effects of 100-h exposure in windshield washer fluid on room-temperature shear strength of the quasi-isotropic carbon-fiber composite

Specimen number	Shear strength (MPa)	Strength design factor
Q18-6	237	1.05
Q18-9	231	1.02
Q18-19	218	0.97
Q18-23	224	0.99
Q18-32	221	0.98
Q18-36	197	0.87
Average	222	1.01
SD	13.7	
COV (%)	6.19	

Table 67. Uniaxial flexural properties of the quasi-isotropic carbon-fiber composite at different temperatures

T beams			L beams		
Specimen number	**MOR (MPa)**	**Temperature factor**	**Specimen number**	**MOR (MPa)**	**Temperature factor**
	-40°C			**-40°C**	
Q19-5T	531	0.85	Q19-1L	601	1.02
Q19-7T	669	1.08	Q19-8L	548	0.93
Q19-16T	585	0.94	Q19-14L	565	0.96
Q19-19T	497	0.80	Q19-19L	628	1.06
Q19-26T	717	1.15	Q19-25L	612	1.04
Q19-34T	692	1.11	Q19-32L	627	1.06
Average	615	0.99	**Average**	597	1.01
SD	90.7		**SD**	33.2	
COV (%)	14.7		**COV (%)**	5.57	
	23°C			**23°C**	
Q19-3T	571	1.00	Q19-3L	567	1.00
Q19-9T	610	1.00	Q19-10L	590	1.00
Q19-15T	643	1.00	Q19-16L	614	1.00
Q19-20T	620	1.00	Q19-21L	576	1.00
Q19-29T	681	1.00	Q19-27L	500	1.00
Q19-31T	609	1.00	Q19-34L	699	1.00
Average	622	1.00	**Average**	591	1.00
SD	37.0		**SD**	65.2	
COV (%)	5.94		**COV (%)**	11.0	
	70°C			**70°C**	
Q19-6T	500	0.80	Q19-2L	426	0.72
Q19-10T	534	0.86	Q19-9L	410	0.69
Q19-13T	593	0.95	Q19-15L	379	0.64
Q19-21T	526	0.85	Q19-20L	427	0.72
Q19-30T	538	0.86	Q19-26L	475	0.80
Q19-32T	505	0.81	Q19-33L	485	0.82
Average	533	0.86	**Average**	434	0.73
SD	33.3		**SD**	40.0	
COV (%)	6.25		**COV (%)**	9.22	
	120°C			**120°C**	
Q19-4T	245	0.39	Q19-4L	278	0.47
Q19-8T	265	0.43	Q19-11L	255	0.43
Q19-14T	338	0.54	Q19-17L	257	0.43
Q19-22T	372	0.60	Q19-22L	265	0.45
Q19-25T	399	0.64	Q19-28L	271	0.46
Q19-33T	281	0.45	Q19-35L	237	0.40
Average	317	0.51	**Average**	261	0.44
SD	62.2		**SD**	14.4	
COV (%)	19.7		**COV (%)**	5.51	

Table 68. Effects of 1000-h exposure in 23°C distilled water on uniaxial flexural properties of the quasi-isotropic carbon-fiber composite

Specimen number	MOR (MPa)	Strength factor
	T beams	
Q19-1T	589	0.95
Q19-12T	592	0.95
Q19-17T	637	1.02
Q19-24T	541	0.87
Q19-27T	546	0.88
Q19-35T	647	1.04
Average	592	0.95
SD	44.2	
COV (%)	7.47	
	L beams	
Q19-5L	537	0.91
Q19-7L	497	0.84
Q19-12L	560	0.95
Q19-23L	523	0.88
Q19-29L	576	0.97
Q19-31L	621	1.05
Average	552	0.93
SD	43.6	
COV (%)	7.89	

Table 69. Effects of 100-h exposure in windshield washer fluid on uniaxial flexural properties of the quasi-isotropic carbon-fiber composite

Specimen number	MOR (MPa)	Strength factor
	T beams	
Q19-2T	607	0.98
Q19-11T	614	0.99
Q19-18T	672	1.08
Q19-23T	632	1.02
Q19-28T	664	1.07
Q19-36T	597	0.96
Average	631	1.01
SD	31.0	
COV (%)	4.91	
	L beams	
Q19-6L	589	1.00
Q19-13L	558	0.94
Q19-18L	502	0.85
Q19-24L	608	1.03
Q19-30L	491	0.83
Q19-36L	566	0.96
Average	552	0.93
SD	46.8	
COV (%)	8.48	

Table 70. Biaxial flexural properties of the quasi-isotropic carbon-fiber composite at different temperatures

Specimen number	Maximum load (N)	Temperature factor
	23°C	
Q19-1	9643	1.00
Q19-3	10267	1.00
Q19-6	9390	1.00
Q19-7	10211	1.00
Q19-17	9329	1.00
Q19-23	9599	1.00
Average	9740	1.00
SD	405	
COV (%)	4.16	
	120°C	
Q19-9	3739	0.38
Q19-11	4126	0.42
Q19-13	4370	0.45
Q19-18	4421	0.45
Q19-19	5051	0.52
Q19-24	4196	0.43
Average	4317	0.44
SD	433	
COV (%)	10.0	

Table 71. Effects of environment on biaxial flexural properties of the quasi-isotropic carbon-fiber composite

Specimen number	Maximum load (N)	Design factor
	1000 h in 23°C distilled water	
Q19-5	9831	1.01
Q19-10	8856	0.91
Q19-12	8732	0.90
Q19-14	8687	0.89
Q19-16	8972	0.92
Average	9016	0.93
SD	469	
COV (%)	5.20	
	100 h in windshield washer fluid	
Q19-2	10113	1.04
Q19-4	9117	0.94
Q19-8	9956	1.02
Q19-15	9656	0.99
Q19-20	9168	0.94
Q19-22	9521	0.98
Average	9588	0.98
SD	404	
COV (%)	4.22	

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