THERMOPLASTIC COMPOSITE STRUCTURE FOR MASS TRANSIT VEHICLE: DESIGN, COMPUTATIONAL ENGINEERING AND EXPERIMENTAL VALIDATION.

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Abstract
In the present paper, a thermoplastic composite component of a mass transit vehicle, is designed using a complex mix of computational analyses and experimental testing. Among the currently available composite materials, Eglass fiber/polyetherimide (PEI) thermoplastic composite material is mainly considered for its inherently fire-retardant properties and in life cycle perspective. The thermoplastic composite panel is designed in order to satisfy AnsaldoBreda structural loading and performance requirements. The final configuration of the thermoplastic panel exhibits excellent weight saving of more 50% compared to the conventional aluminum panel.

1 Introduction
As designer in railways industry strive to reduce fuel consumption, environmental pollution and improve safety, composites are becoming an attractive alternative to standard metallic solution for mass transport applications. Lightweight composite materials are primarily specified because they can be used to produce cost-effective, lightweight components of relatively complex geometries that can be easily molded from composite structures to perform the aerodynamic profile demanded by modern high performance vehicles. Examples of composite structures employed in transportation vehicles can be found in [1,2].
Among the currently available composite materials, in the present work, thermoplastic composite material is considered in the design of a side lower panel of the *SIRIO* tram carbody produced by AnsaldoBreda (Figure 1), which is one aspect of a larger effort focused on developing thermoplastic composite materials, processes and designs for mass transit applications. Thermoplastic polymers have several advantages over thermoset polymers. They can be shaped by reheating, are easier to recycle, and have superior impact properties and energy absorption because of their high toughness [3]. The aforementioned benefits make thermoplastics excellent materials for structural component of mass transit vehicles such as body panels [4], floor structure [5] and roof door [6].
The design approach is based upon replacement possibilities of subcomponents of conventional metal-based vehicle with a goal of cost and weight savings, involving both

numerical and experimental activities at various levels of structural complexity. The various aspects covered in the paper include; (a) material and manufacturing details of the body segment; (b) experimental characterizations; (c) design and finite element modeling.

(a) (b)

Figure 1. Case of study: (a) *SIRIO* Tram of AnsaldoBreda; (b) details of side lower panel

2 Material and manufacturing

There are numerous thermoplastic polymers can be used as s a matrix for fiber reinforced composites in structural components in transportation industry. An overview of physical, thermal and mechanical properties of common types of thermoplastic polymers is given in [7].

Since the requirements for mass transportation have become more and more severe especially in the area of fire safety, polyetherimide (PEI) thermoplastic composite material is mainly considered for its inherently fire-retardant properties that evolve low levels of smoke and combustion products during a fire exposition. In particular, E-glass/PEI, supplied as pre-impregnate orthogonal woven fabrics with a nominal ply thickness of 0.24 mm, has been selected to offer outstanding toughness and high heat resistance. The selected material, provided by Tencate Advanced Composites Inc., exceeds 35/35 OSU and is qualified at Airbus and Boeing fire requirements for both structural and interior applications [8].

The thermoplastic laminates have been manufactured using a wood mold designed consistent with the geometry of rounded C-shape frame segment. The wood mold has been placed in a compression molding press of 3 tons capacity. Before molding, the material has been processed at 300°C in an oven equipped with heat lamps and an electronic control system that allow to maintain processing temperature uniform until 500°C. The processing setup is shown in Figure 2.

(a) (b) (c)

Figure 2. The manufacturing setup: (a) compression molding press; (b) wood mold; (c) half component.

3 Material characterization

Since it is well know that structural analysis of composite requires the determination of a large number of independent parameters, generally not provided by manufacture's datasheet,

mechanical characterizations of the selected composite material have been assessed in order to define the basic material properties that can be used as input in structural design and analysis aimed by Finite Element computer code. The experimental activity herein presented was carried out at the Laboratory of the Department of Structural Engineering of the University of Naples Federico II. Test facilities involved in the present activity are: (a) a MTS 500 kN universal test frame controlled by an electronic control unit which allows monitoring the applied load and the stroke of the top cross head; (b) a digital data acquisition system that allows to acquire strain signals .
From the macro-mechanical point of view, a composite material may be characterized by a number of basic stiffness and strength parameters referred to its principal material direction, that in the case of orthogonal woven fabric consists of two set of interlaced yarns: the longitudinal direction of the fabric is called wrap and the transverse direction weft or fill.
In particular, for in-plain loading, a lamina may be fully characterized by: (a) four engineering independent constants - longitudinal (warp) and transverse (weft) Young's moduli E_1 and E_2, shear modulus G_{12}, Poisson's ratio ν_{12}; (b) five strength parameters – longitudinal (warp) tensile and compressive strengths F_{1t} and F_{1c}, transverse (weft) tensile and compressive strengths F_{2t} and F_{2c}, in-plane shear strength F_{12}. Additional lamina strength parameter, relevant in composite structural analysis, is the interlaminar shear strength F_{66}; (c) five strain parameters - ultimate longitudinal (warp) tensile and compressive strains ε_{1t} and ε_{1c}, ultimate transverse (weft) tensile and compressive strains ε_{2t} and ε_{2c}, ultimate in-plane shear strain γ_{12}.

3.1 Tensile Tests

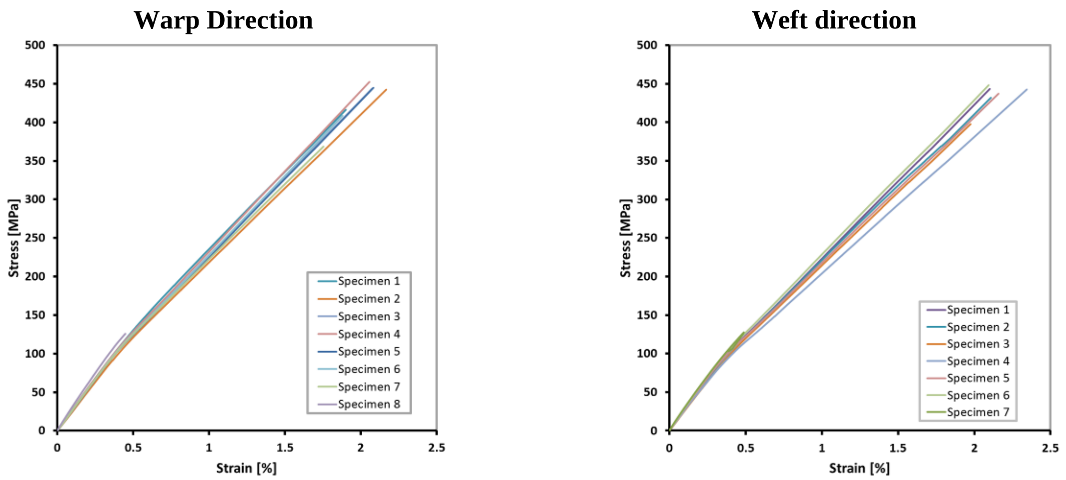
Quasi-static tensile tests were run on fifteen 2.4x25x250 mm coupons, tested in one series with the warp fibers parallel to the load and in a second series with warp fibers perpendicular to the load. These tests were performed in accordance with the ASTM D3039M standard [9]. Three strain gauges were applied to each coupon to monitoring the deformations, two parallel to the load and one perpendicular to the load direction. Tests were conducted at a constant cross head velocity of 2 mm/min.
Ultimate tensile stress and strain, elastic modulus, and Poisson's ratio have been measured for both the warp and weft directions. Figure 3 show the stress-strain curves for both warp and weft direction and the principal failure modes. Generally the failure mode occurred in the gage section, however some specimens failed at the grip/tabs interface, but no relevant differences in results are observed.

3.2 Compressive Tests

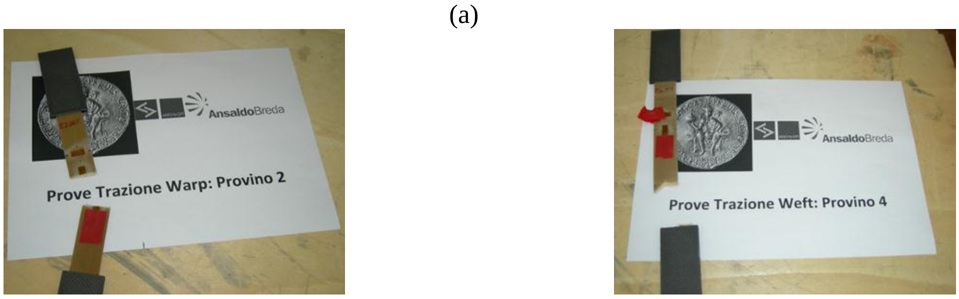
Quasi-static compressive tests were run on sixteen 3.8x20x140 mm coupons, tested in one series with the warp fibers parallel to the load and in a second series with warp fibers perpendicular to the load. These tests were performed in accordance with the ASTM D6641M standard [10] using a Combined Loading Compression (CLC) test fixture (Figure 4) developed at the University of Wyoming. A comparative study of the CLC fixture and ASTM D 3410 [11] procedure, which uses the wedge loading arrangement developed at the Illinois Institute of Technology Research Institute (IITRI), was presented in [12]. Results of the study suggested that the CLC test fixture is preferable to the IITRI test fixture from a practical standpoint. Although the compressive properties measured using these two fixtures are statistically similar, the CLC test fixture is easier to use, less expensive to fabricate, and less massive than the IITRI test fixture, making it easier to install and, as a result, less likely to induce testing errors. Furthermore, because of its simpler design, the CLC test fixture is considerably less prone to machining errors.

In the present case, two strain gauges were applied parallel to the load direction to each coupon to monitoring the deformations. Tests were conducted at a constant cross head velocity of 1.3 mm/min.

Ultimate tensile stress and strain and elastic modulus have been measured for both the warp and weft directions. Figure 5 show the stress-strain curves for both warp and weft direction and the principal failure modes. Failure modes occurred in the gage section for all the specimen, however two different modes were observed: fiber brooming and through the thickness for both the tested series.



(a)



(b)

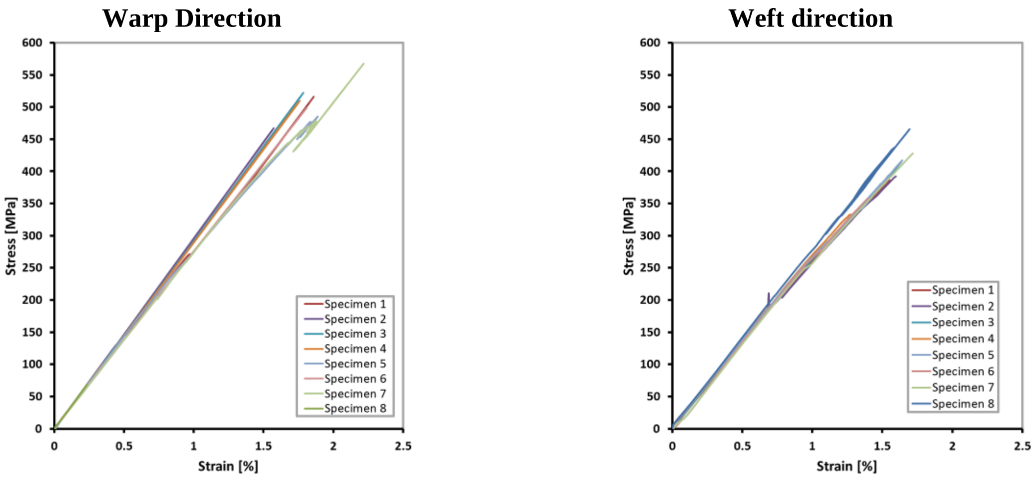
Figure 3. Tensile tests: (a) stress-strain curves; (b) failure modes.

Figure 4. CLC text fixture.

3.3 In-Plane Shear Tests

Quasi-static in-plane shear tests were run on eight 3.8x25x250 mm coupons with a $[+45/-45]_{8s}$ stacking sequence by tensile loading in accordance with the ASTM D3518M standard [13]. Two strain gauges were applied parallel to the load direction to each coupon to monitoring the deformations. Tests were conducted at a constant cross head velocity of 2 mm/min.

Ultimate in-plane shear stress and strain and in-plane shear modulus have been derived. Since the value of the shear strain at maximum shear stress exceed the 5%, according to the standard, the ultimate in-plane shear strain was considered equal to 5%. Figure 6 show the shear stress-crosshead displacement curve and the principal failure mode, that in these case is due to transverse shear for all the specimens.



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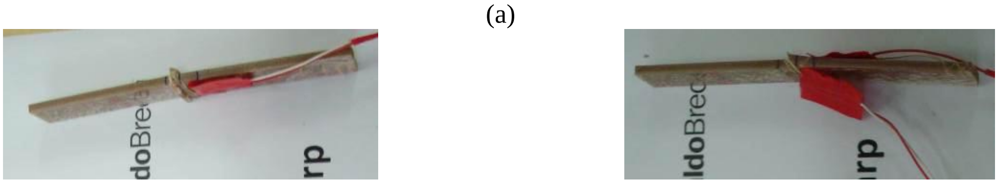
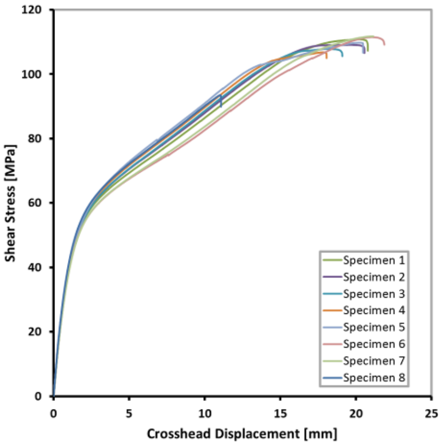


(b)

Figure 5. Compressive tests: (a) stress-strain curves; (b) failure modes.



(a) (b)

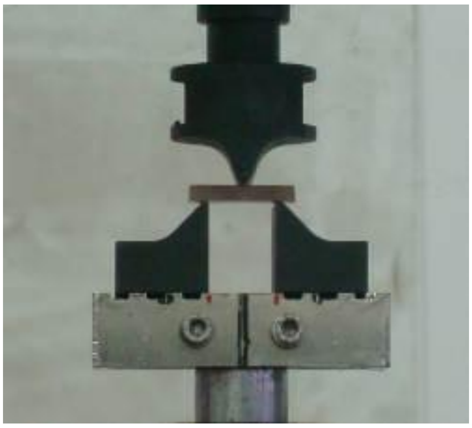
Figure 6. In-plane shear tests: (a) shear stress- displacement curves; (b) failure modes.

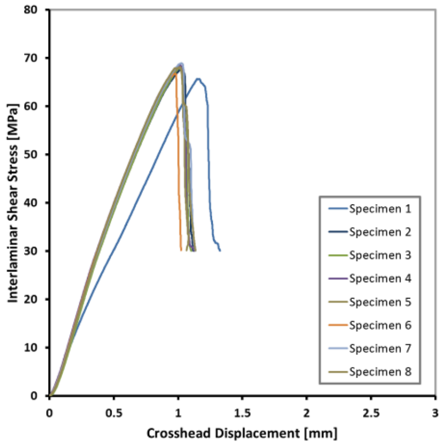
3.4 Short-Beam Tests

Short-beam tests were run on eight 6x12x36 mm coupons, made by parallel laminating of prepreg, using a three-point bending set-up (Figure 7a) in accordance with the ASTM D2344M standard [14]. Tests were conducted at a constant cross head velocity of 1 mm/min. Interlaminar shear strength have been derived as function of ultimate applied load. Figure 7b show the interlaminar shear stress-crosshead displacement curve.

3.5 Summary of Test Results

Table 1 reports elastic properties and strength values obtained in static tests of thermoplastic material. These values are the implemented in the laminate composite material card of the Finite Element software as described in the next section. Due to the nearly balanced nature of the fabrics, laminates with the warp fibers perpendicular to the load are characterized by values close to those with warp fibers perpendicular to the load





(a) (b)

Figure 7. Short beam tests: (a) test set-up; (b) interlaminar shear stress- displacement curves.

Tensile Young Modulus	Warp	E_1 [GPa]	26.90	(3.28%)
	Weft	E_2 [GPa]	25.93	(3.80%)
Poisson's Modulus	Warp	ν_{12} [-]	0.13	(6.07%)
	Weft	ν_{21} [-]	0.14	(7.20%)
Ultimate Tensile Strength	Warp	F_{1t} [MPa]	434.72	(4.09%)
	Weft	F_{2t} [MPa]	433.48	(4.24%)
Ultimate tensile Strain	Warp	ε_{1u} [%]	2.00	(6.10%)
	Weft	ε_{2u} [%]	2.15	(6.32%)
Compressive Young Modulus	Warp	E_1 [GPa]	29.12	(2.84%)
	Weft	E_2 [GPa]	27.64	(3.16%)
Ultimate Compressive Strength	Warp	F_{1c} [MPa]	511.74	(5.87%)
	Weft	F_{2c} [MPa]	399.41	(10.41%)
Ultimate Compressive Strain	Warp	ε_{1u} [%]	1.87	(9.57%)
	Weft	ε_{2u} [%]	1.53	(10.33%)
In-plane Shear Modulus		G_{12} [GPa]	4.25	(0.67%)
Ultimate In-plane Shear Strength		F_{12} [MPa]	109.66	(1.70%)
Ultimate In-plane Shear Strain		γ_{12} [%]	5.00	(-)
Interlaminar shear strength		F_{66} [MPa]	67.76	(1.55%)

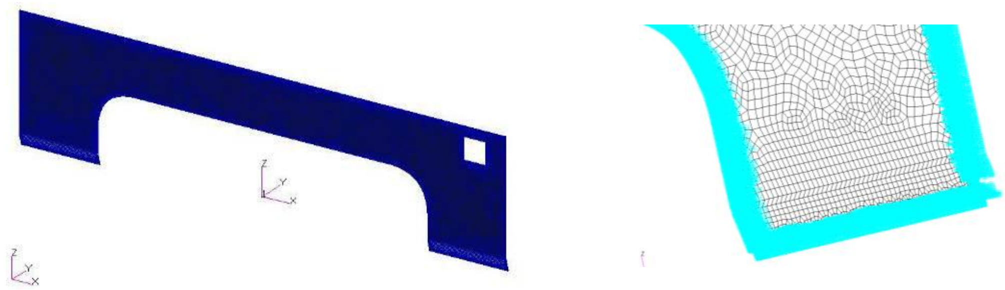
Table 1. Mechanical properties of thermoplastic materials investigated in these study.

4 Design and Computational Analysis

In the present section design and computational analysis of the thermoplastic composite component is presented. The activity herein presented was carried out by Aerosoft department. Starting from geometrical information, a FE model was developed using MSC Nastran® code. The component was meshed using 4-node shell elements; a 2D-orthotropic material was used to define the thermoplastic prepreg, whereas PCOMP function was used to create the stacking sequence of the panel (Figure 8a).

Since the final side body panel will be adhesively joined to the frame of the vehicle along all the edges for a depth of 20mm, the external nodes of the model were restrained against all the rotation and translation (Figure 8b).

According to the AnsaldoBreda requirements and the European standard [15], the following two static loading conditions were defined into the model as suggested for a vehicle of class P-IV: Case 1 - Inertial Load Condition, combining inertial load equal to 3g of the component mass along the *x*-direction, inertial load equal to 1g component mass along the *y*-direction and inertial load equal to 3g of the component mass along the gravity direction; Case 1A - Lateral Wind Condition, combining a lateral wind equal to 160 km/h and a inertial load equal to 1g of the component mass along the gravity direction. The lateral wind was simulated applying a dynamic pressure of 1185 N/m^2 distributed on the surface of the panel.



(a) (b)

Figure 8. FE model: (a) view of meshed panel; (b) detailed view of boundary conditions.

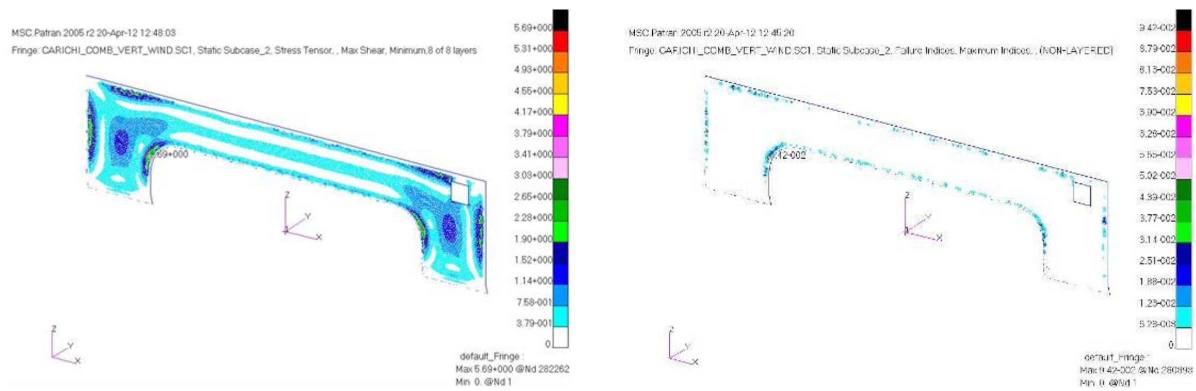
The described FE model allows to optimize the component, in term of the stacking sequence and the total number of plies, and to verify the structural requirements.

The optimization is achieved by changing the values of certain design variables in order to minimize the objective function while at the same time satisfying certain behavioral constraints. In this study, in order to optimize simultaneously the stacking sequence and the total number of plies, discrete ply angles, 0°, ±45°and 90° were considered as design parameters, whereas the objective function is the structural weight and the design constraint is the Hill Maximum Indices that in each ply must be lower than 1.

The design procedure provided that the $[0,90]_{4S}$ lay-up configuration allows the optimize the structural weight of the component. Table 2 reports the numerical results of the critical ply for the designed composite panel, where *RF* is the reserve factor calculated as ratio between the derived experimental strength and the numerical stress values. Figure 9 shows the contour plots of the maximum shear stress and Hill Maximum Indices for the optimal layup configuration for the wind loading combinations.

ID	Load Case	Hill Maximum Indices	Max Shear Value [MPa]	Max Displacement [mm]	RF Shear Stress	RF Max Principal Stress	RF Min Principal Stress
1	Inertial Load	2.69E-03	0.65	0.46	167.93	330.90	312.04
1A	Lateral Wind	9.42E-02	22.60	16.20	4.85	9.61	8.82

Table 2. Mechanical properties of thermoplastic materials investigated in these study.



(a) (b)

Figure 9. FE model: (a) view of meshed panel; (b) detail of boundary conditions.

Conclusion

In the present paper the design procedure, involving both experimental and computational studies, have been presented for the case of study of a thermoplastic lower side panel of a tram vehicle. The experimental activities allow to characterize the basic stiffness and strength parameters of the selected thermoplastic composite material. Whereas, FE analysis have been used both to optimize the layup configuration of the composite component and to assess the structural requirements. The final configuration of the thermoplastic panel exhibits excellent weight saving of more 50% compared to the conventional aluminum panel.

Ongoing work, final validation of the design procedure will be performed testing the final component, such as, in order to reliably predict the structural safety of thermoplastic composite structure, the adverse effects of environmental degradations and in-service impact events will be assessed.

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References

[1] Kim J.S., Lee S.J., Shin K.B. Manufacturing and structural safety evaluation of a composite train carbody. *Composite Structures*, **78**, pp. 468–76 (2007).
[2] Zinno A., Fusco E., Prota A., Manfredi G. Multiscale approach for the design of composite sandwich structures for train application. *Composite Structures*, **92**, pp. 2208–2219 (2010).
[3] D'Hooghe E.L., Edwards C. Thermoplastic composite technology; tougher than you think. *Advanced Materials*, **12**, pp. 1865–8 (2000).
[4] Ning H., Janowski G.M., Vaidya U.K., Husman G. Thermoplastic sandwich structure design and manufacturing for the body panel of mass transit vehicle. *Composite Structures*, **80**, pp. 82–91 (2007).
[5] Vaidya U.K., Samalot F., Pillay S., Janowski G.M., Husman G., Gleich K. Design and Manufacture of Woven Reinforced Glass/Polypropylene Composites for Mass Transit Floor Structure. *Journal of Composite Materials*, **38**, pp. 1949–1972 (2004).
[6] Ning H., Pillay S., Vaidya U.K. Design and development of thermoplastic composite roof door for mass transit bus. *Materials and Design*, **30**, pp. 983–991 (2009).
[7] Van de Velde K., Kiekens P. Thermoplastic polymers: overview of several properties and their consequences in flax fiber reinforced composites. *Polymer Testing*, **20**, pp. 885–893 (2001).
[8] Tencate Advanced Composites. *Cetex® PEI Technical Data*.
[9] ASTM D 3039. *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials* (2008).
[10] ASTM D 6641. *Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture* (2009).
[11] ASTM D 3410. *Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading* (2008).
[12] U.S. Department of Transportation. *Verification of the Combined Load Compression (CLC) Test Method*. National Technical Information Service (NTIS), Springfield, Virginia, U.S. (2000).
[13] ASTM D 3518. *Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a ±45° Laminate* (2007).
[14] ASTM D 2344. *Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates* (2000).
[15] EN 12663. *Railway Applications. Structural Requirements of Railway Vehicle Body* (2002).