COMPACT TENSION AND COMPRESSION TESTING OF BRAIDED COMPOSITES – CHALLENGES AND LIMITATIONS

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Abstract

The present publication aims to identify challenges and limitations of existing compact tension and compression test procedures applied to braided composites within the scope of extensive experimental programmes performed at Fraunhofer EMI in recent years. Compact tension/compression tests allow the measurement of intralaminar fracture toughness which are of particular interest for energy-based failure criteria in numerical simulations. Following a brief introduction on braided composite meso-structure the observations made during these intra-laminar fracture toughness tests are discussed. Emphasis is given to the impact of braided composite structure and size of inhomogenity on test procedures and failure modes and how these differences affect the validity of the test methods. Some recommendations to address limitations are presented, however main focus of the publication is the identification of challenges in the investigated test methods.

1. Introduction

In recent years fiber reinforced polymers have seen a huge increase in their usage in various fields of application (automotive, aviation, transportation, satellites, sports, etc.). The prevalent type of fiber reinforced polymers is laminated composites. However for some applications other types of fiber architectures such as braided composites may offer advantages in comparison to laminated composites and there has been a steadily increasing interest to introduce them to various fields of application. The main driving factor for using this type of fiber architecture is the ability to produce high volumes of complex shapes at comparatively low costs.

Research addressing performance of components made of braided composites report considerable post-failure behavior which is strongly affected by braid structure [1]. In order to adequately describe this observed post-failure behavior in numerical simulations quantification of the underlying fracture and failure mechanisms is required. However, while experimental characterization of fracture in laminated type composites is well researched and there are well established approaches to determine the fracture toughness [2-4], the know-how specifically regarding braided composites is limited. This applies in particular to test methods used for the determination of intralaminar fracture properties which is not well documented in the literature.

The purpose of this publication is to address these issues and to investigate the adaption of compact tension and compression tests to braided composites. Compact tests have been successfully used to determine intralaminar energy release rates of laminate [2, 5] and woven fabric [6, 7] composites. The presented observations are based on extensive test series on braided composites performed at the Fraunhofer EMI in the recent years.

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2. Compact tests on braided composites – Experimental approach and test setup

In case of material characterization of braided composites, there is a general consensus that the braided meso-structure can affect test results of various test types and should be considered in specimen dimension and test setup [8-12]. A typcal meso-structure and resulting unit cell of a tri-axial braided composite is shown in Figure 1.

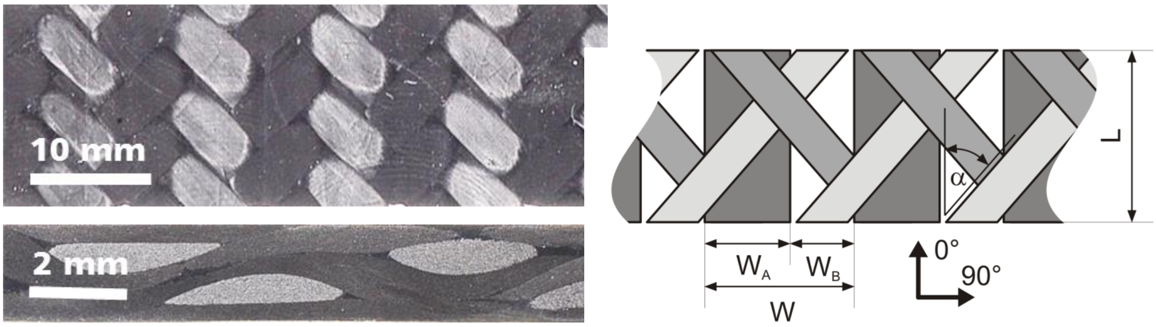

Figure 1. Left hand: Top view and cross-section of tri-axial braided composite / Right hand: Unit cell (LxW) of a tri-axial braided composite.

In braided composites the material properties depend - beside orientation and characteristics of reinforcements - also on the interaction between the interwoven structure and resulting load paths in the structure for different load cases. Also the scale of material inhomogeneity compared to laminate composites is larger by orders of magnitude (laminates < 0.5 mm / braided composites < 10 mm). These particular characteristics need to be considered for the application of compact tension and compression to braided composites.

The following study is based on approximately two hundert compact tension and compression tests. In these tests braided composites from different manufacturers and of varying composition (braid angle, ratio filler/weft yarn, yarn and matrix material) were examined. In particular, information is given on compact tension/compression tests carried out on a tri-axial braided composite with carbon fiber filler yarns (70% fiber volume content) and glass fiber weft yarns (30% fiber volume content).

The test setup was based on the research work of Pinho [5], although some modifications in order to consider the characteristics of the investigated braided composites were made which are discussed subsequently. Generally, for application to braided composites the compact tension/compression approach needs to overcome several challenges:

- The scale of the inhomogeneity resulting from the braid structure has a similar order of magnitude as as the specimen dimensions and measurement range. This may effect test results and can result in considerable scatter.
- Failure in braided composites is not characterized by crack growth in the classical sense where a discrete crack propagates through the material. Instead, a rather large damage zone exists in front of the cack tip which extends not only in the direction of crack but also transverse to that.
- The load introduction is difficult in case of braided composites with considerable anisotropic material properties where the crack propagates through the dominant reinforcement direction.

Obviously, it is advantageous to realize a preferably large crack length in order to maximize the difference between the size of braid structure and the size of specimen dimensions. However, specimen dimensions are also governed by other constraints such as maximum force, machine size,

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etc. The test apparatus used represents a compromise between these constraints and is shown in Figure 2. Compared to the classical setup (Figure 2, left hand) used in [5] the crack length is larger with 100 mm which represented, depending on load direction, 10 or 20 braid unit cells.

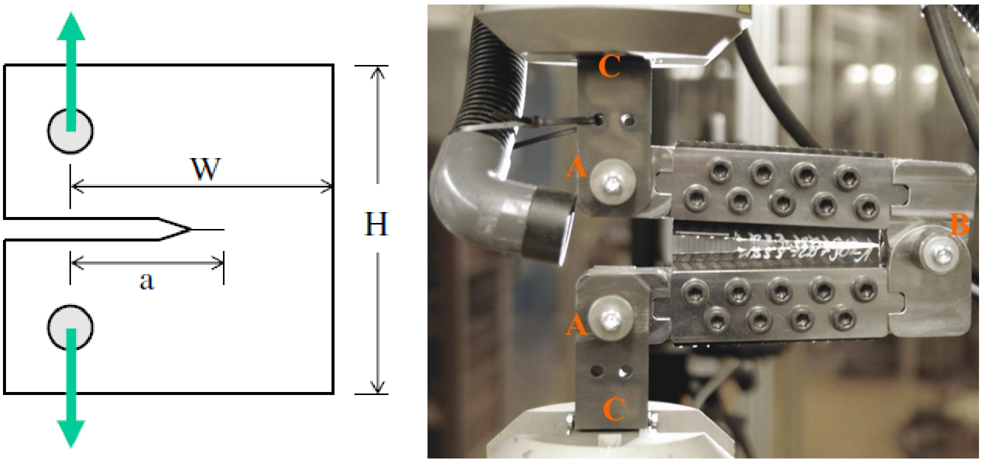

Figure 2. Left hand: Classical compact tension setup [5] / Right hand: Compact test apparatus used in test series (here prepared with a compact tension specimen).

The load introduction was also modified. In the classical compact tension test the load is introduced via two pinholes. In particular in case of considerably anisotropic materials shear-out in the holes of the specimen is a problem [13, 14]. In order to improve introduction of loads into the specimen, the specimen was bolted to metal frames, which allowed rotation via hinges (A) connected to the grips (C). The purpose of this approach was to ensure that critical loads were achieved at the crack tips while in the region of load application the loads remained within the elastic regime (where comparatively low loads could result in damage if acting in weak material direction).

However, due to the loads induced by the metal frame of above test setup, the bending moments and leverage resulted in a region at the far end of the crack tip loaded in compression. These loads resulted in an irregular failure mode shown in Figure 3, where an unsupported compact tension specimen buckled at the far end side before crack initation. This failure mode was also described by [14] for the classical compact tension setup, who proposed specimen geometry modifications in order to improve the load distribution and avoid irregular failure modes. This approach was not followed, as the additional loads introduced by the metal frame in the critical region were estimated to be too severe as to be avoided by geometry modifications.

Therefore, in case of the presented test setup, a third hinge (B) connecting upper and lower metal frame was introduced. This third hinge (B) supported the far right hand side of the specimen and thus avoided premature failure in compression in the specimen.

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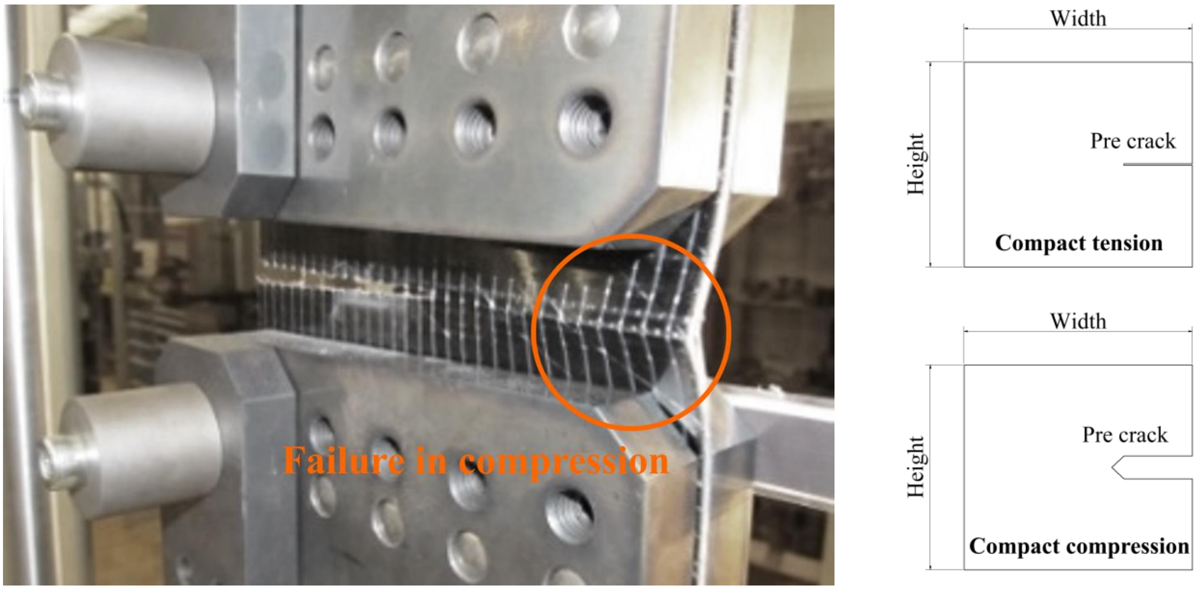

Figure 3. Left hand: Compact tension test, where the specimen failed in compression at the far side of the crack tip before crack tip propagation. / Right hand: Specimen dimensions.

The specimen dimensions were 150 mm x 135 mm x ~3 mm (width, height, thickness). The pre crack was 45 mm in case of compact tension and 53 mm in case of compact compression. The pre crack in the tension specimen was cut with a disk saw of 1 mm thickness. The larger size of the pre crack in compression resulted from a clearance of 15 mm in order to avoid contact of upper and lower crack surfaces. The crack tip was milled with a diameter of 2mm and extended in 45°-direction to both sides until clearance distance was reached. The specimen schematics are shown in Figure 3 (right hand side).

When fixed to the to the metal frame, the distance between hinges and crack tip was 85 mm (tension) and 93 (compression) respectively. Depending on grip movement, the specimen could either be loaded in compression or in tension. Five tests were performed for each type of load (Transverse and longitudional tension / Transverse and longitudinal compression). The test velocity was 1 mm/s. Force measurement was performed with an Instron 500 kN load cell. The crack propagation was followed with video recording of the specimen side view (Photron Fastcam APX TS). A test was considered valid if damage/failure exclusively occurred in the region of crack propagation.

Several data reduction methods in compact tension/compression tests (compliance calibration method, area method, or modified compliance calibration) were compared in [2, 15]. Although modified compliance calibration was recommended, the other two methods were reported to give consistent results. Good agreement was also reported for data reduction using finite element analysis [16]. In the presented case the area method was used for data reduction due to the good agreement with crack propagation properties and the method's simplicity.

3. Results and discussion

Typically in case of braided composites damage is initiated in the matrix in location of yarn junctures and spreads from there. If the matrix is considerably damaged the mechanical response of a braided composite can exhibit a "textile-like" post-failure behavior. Finally, total failure occurs when the fiber/yarn reinforcement fractures.

Similar behavior was also observed in the compact tension tests. At the crack tip a rather large damage zone exists which spreaded in direction of the crack as well as transverse to it. Within this damage

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zone a sequence of failure mechanisms occurred: Initially rather large zone with matrix damage spreads in front of the crack tip which was mainly governed by the straightening the undulated fiber yarns. Subseqently the crack advances when the yarns rupture. The matrix damage zone typically advanced several cms before yarn rupture was observed at the crack tip. In Figure 4 a picture sequence shows the advancement of matrix damage zone and crack tip (yarn fracture).

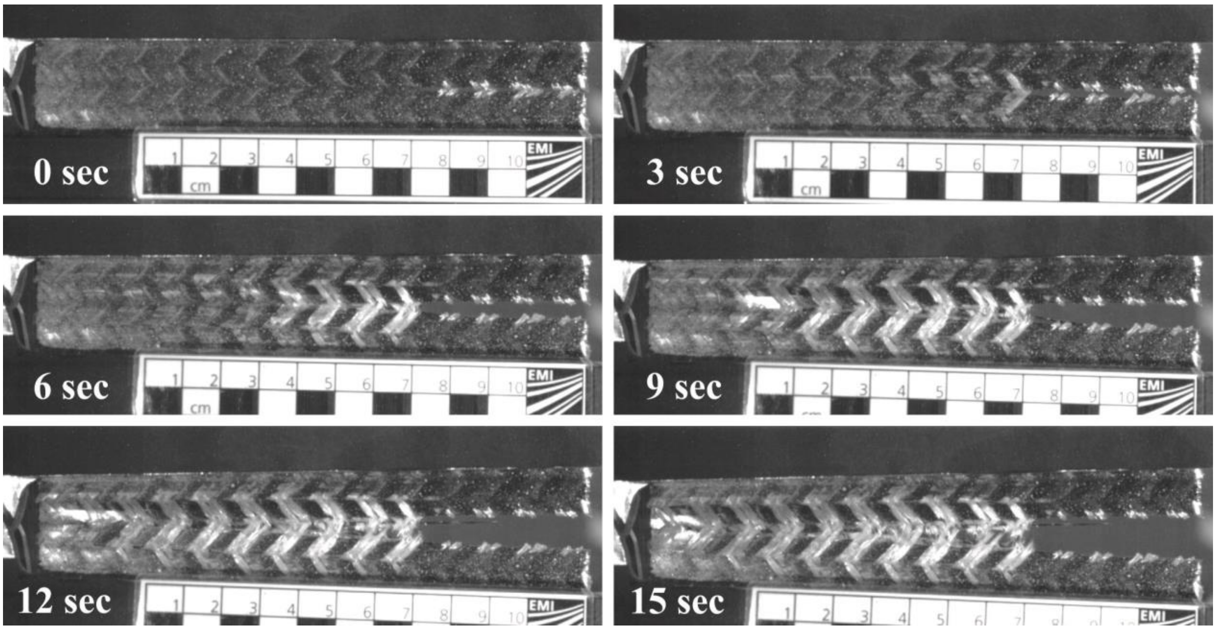

Figure 4. Picture sequence of crack advancement in a compact tension test.

In order to quantify crack growth damage propagation was associated with yarn rupture per unit cell. The reasoning behind this approach was that the majority of energy is absorbed by yarn fracture. This method of quantification had the benefit that it could be directly connected to the measured force curve where each individual load drop is linked to yarn rupture in the load direction (see Figure 5).

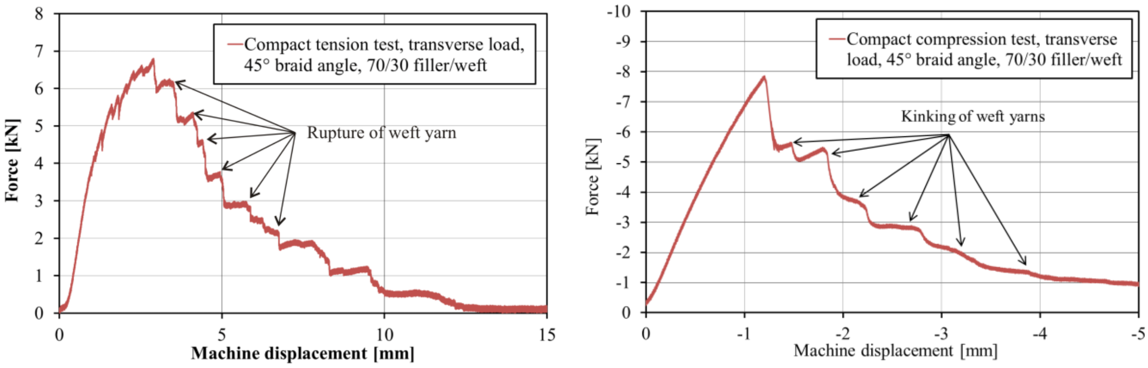

Figure 5. Left hand: Force vs. displacement of compact tension test / Right hand: Force vs. displacement of compact compression test (the filler yarn was orientated transverse to load direction).

Generally, good test results were achieved if major parts of reinforcement were orientated parallel to the direction of crack propagation (see Figure 6). The magnitudes of measured energy release rates could vary considerably and mainly depended on the structure of their fiber/yarn reinforcement. The braided composite type exhibited an energy release rate of roughly 110 kJ/mm² (COV ~10%) if loaded transverse to filler yarn orientation in tension and 50 kJ/mm² (COV ~15%) if loaded in compression.

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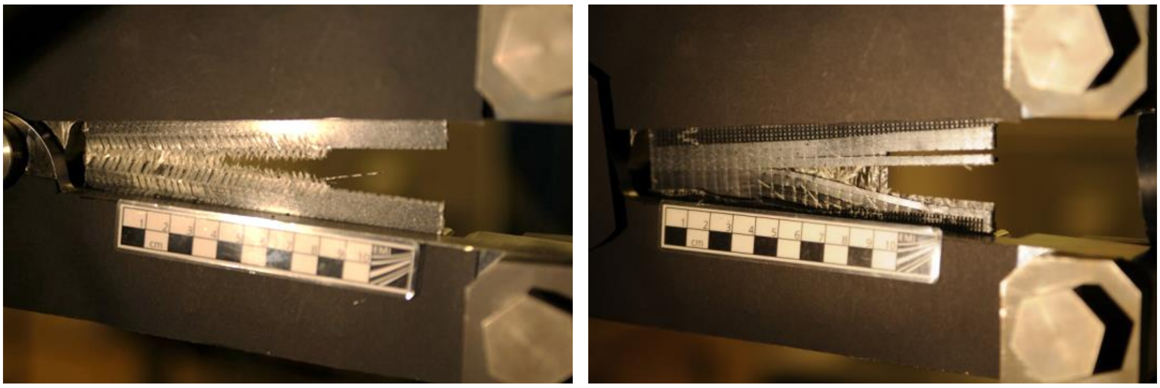

Figure 6. Tested compact tension specimen, Left hand: Major reinforcement oriented parallel to crack propagation / Right hand: Major reinforcement oriented transverse to crack propagation.

If major parts of the reinforcement were oriented transversely to the direction of crack propagation it was not possible to drive the failure into the desired direction. Considerable failure appeared around the bolt holes and filler yarn was pulled out before crack propagation was occurring (see Figure 6, right hand).

In compact compression a different fracture behavior was observed compared to compact tension: Instead of an initial matrix crack the fiber yarn reinforcement kinked in the region of the crack tip. With the kinking matrix failure was associated. The kink zone propagated through the whole specimen before the fiber yarn reinforcement begun to fracture along the kinked fibers starting from the initial crack tip. Failed compact compression specimen are shown in Figure 6.

Similarly to the compact tension tests damage growth was associated with the failure of individual unit cells. It is noted that the damage growth signified the propagation of the kink zone and not the final rupture of the fiber yarns. The reason is that the major drops in load were associated with the propagation of the kink zone (see Figure 5).

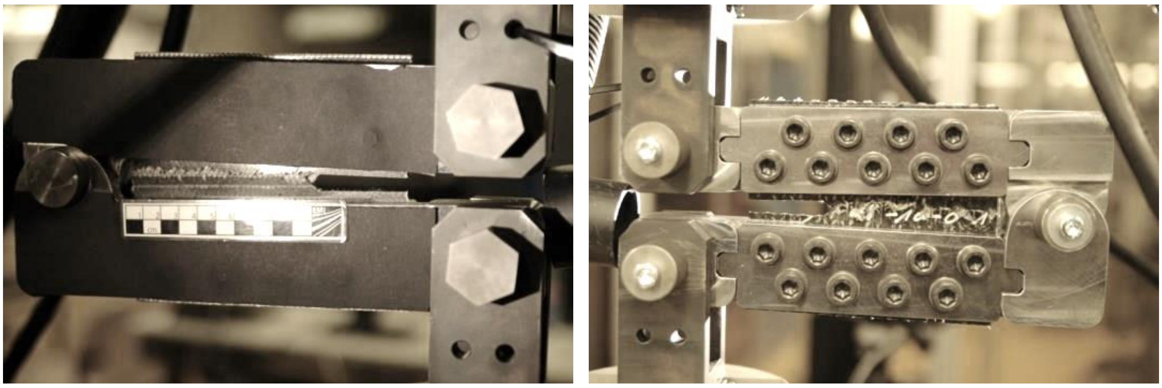

Figure 6. Tested compact compression specimen, Left hand: Major reinforcement oriented parallel to crack propagation / Right hand: Major reinforcement oriented transverse to crack propagation.

In Table 1 mean values and coefficient of variation (COV) for the energy release rates of one of the investigated tri-axial braided composites are summarized.

Table 1. Mean values and COVs of compact tension and compact compression tests.

Energy release rate	*Compact tension*	*Compact compression*

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Load direction	Parallel to filler yarn	Transverse to filler yarn	Parallel to filler yarn	Transverse to filler yarn
Mean value	-	115 kJ/m²	180 kJ/m²	52 kJ/m²
COV	-	11 %	3 %	5 %

5. Conclusions

This paper summarized the observations made during test series for compact tension and compact compression of tri-axial braided composites. Compact tension test gave good results for the determination of the intralaminar energy release rate transverse to filler yarn direction. The intralaminar energy release rate could not be determined in direction of the filler yarn as failure in the specimen also appeared around the bolt holes and filler yarn was pulled out before crack propagation was occurring. Intralaminar energy release rates in compression were determined under the assumption that the crack propagation could be associated with kinking of the fiber yarn reinforcement.

Acknowledgments

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References

[1] R. Sturm, F. Heieck. Energy absorption capacity of braided frames under bending loads. *Composite Structures*, 134:957–965, 2015.

[2] M. J. Laffan, S. T. Pinho, P. Robinson, A.J. McMillan. Translaminar fracture toughness testing of composites: A review. *Polymer Testing*, 31:481-489, 2012.

[3] P. Davies, B.R.K. Blackman, A.J. Brunner. Standard Test Methods for Delamination Resistance of Composite Materials: Current Status. *Applied Composite Materials*, 5(6):345-364, 1999.

[4] M. May. Measuring the rate-dependent mode I fracture toughness of composites - A review. *Composites Part A; Applied Science and Manufacturing*, 81:1-12, 2016.

[5] S. T. Pinho, Modelling failure of laminated composites using physically-based failure models. *PhD thesis*, 94, Imperial College London, U.K., 2005.

[6] N. Blanco, D. Trias, S. T. Pinho, P. Robinson. Intralaminar fracture toughness characterization of woven composite laminates. Part II: Experimental characterization. *Engineering Fracture Mechanics*, 131:361-370, 2014.

[7] T. Bru, P. Hellström, R. Gutkin, D. Ramantani, G. Peterson. Characterisation oft he mechanical and fracture properties of a uni-weave carbon fibre/epoxy non-crimp fabric composite. *Data in Brief*, 6:680-695, 2016.

[8] A. K. Pickett, M. R. C. Fouinneteau, Material characterization and calibration of a meso-mechanical damage model for braid reinforced composites, *Composites Part A*, 37:368-377, 2006.

[9] S. V. Lomov, D. S. Ivanov, T. C. Truong, I. Verpoest, F. Baudry, K. Vanden Bosche, H. Xie, Experimental methodology of study of damage initiation and development in textile composites in uni-axial tests, *Composites Science and Technology*, 68:2340-2349, 2008.

[10] D. S. Ivanov, F. Baudry, B. Van den Broucke, S. V. Lomov, H. Xie, I. Verpoest, Failure analysis of triaxial braided composite, *Composites Science and Technology*, 69:1372-1380, 2009.

[11] J. D. Littell, W. K. Binienda, W. A. Arnold, G. D. Roberts, R. K. Goldberg, Effect of microscopic damage events on static and ballistic impact strength of triaxial braid composites, *Composites Part A*, 40:1846-1862, 2009.

[12] S. Kilchert, M. Nossek, M. May, Challenges and limitations in measuring the mechanical properties of braided composites. *Proceedings of the 5th Thematic Conference on Mechanical Response of Composites ECCOMAS, Bristol, U.K.*,7th-9th September, 2015.

Excerpt from ISBN 978-3-00-053387-7

[13] A. Ortega, P. Maimí, E. V. González, L. Ripoll. Compact tension specimen for orthotropic materials. *Composites: Part A*. 63:85-93, 2014.

[14] N. Blanco, D. Trias, S. T. Pinho, P. Robinson. Intralaminar fracture toughness characterization of woven composite laminates. Part I: Design and analysis of a compact tension (CT) specimen. *Engineering Fracture Mechanics*, 131:349-360, 2014.

[15] M.J. Laffan, S. T. Pinho, P. Robinson, L. Iannucci. Measurement of the in situ ply fracture toughness associated with mode I fibre tensile failure in FRP. Part I: Data reduction. *Composites Science and Technology*. 70:606-613, 2010.

[16] S. T. Pinho, P. Robinson, L. Iannucci. Fracture toughness of the tensile and compressive fibre failure modes in laminated composites. *Composites Science and Technology*, 66:2069-2079, 2006.

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