Tan, G., Hartley, J. W., Withers, E., Kratz, J., & Ward, C. (2015). Towards the development of an instrumented test bed for tufting visualisation. In Proceedings of the SAMPE Europe Conference 2015 AMIENS.

Peer reviewed version

TOWARDS THE DEVELOPMENT OF AN INSTRUMENTED TEST BED FOR TUFTING VISUALISATION

GEORGE TAN, JAMIE HARTLEY, EMILY WITHERS, JAMES KRATZ, CARWYN WARD

University of Bristol
Advanced Composites Centre for Innovation and Science, University of Bristol, Queens Building, University Walk, Bristol BS8 1TR, UK

SUMMARY

This paper presents the development of a test bed for tufting as Through-Thickness Reinforcement (TTR). The setup provides understanding of quality implications of TTR processing parameters on composite sandwich panels. The main parameters are identified from a commercial TTR machine, then recreated in a test frame with a transparent rig containing the compacted preform, allowing visibility of tuft formation. Initially the needle is observed alone, inserting into and retracting from the preform at controlled rates, and resulting damage is detected with imaging techniques. Thread is then added to observe tuft formation. Damage is found to comprise fragmentation of both the carbon fibre skin and foam core, and non-uniformity of the needle path dimensions. A prototype ‘quality matrix’ is developed, establishing a possible ideal tuft, i.e. uniformity and minimal preform disruption. Results suggest some correlation between improved as-measured tuft quality and insertion rate, potentially allowing greater control of component macro-mechanical properties.

INTRODUCTION

Sandwich assemblies offer very high levels of structural efficiency by delivering increased stiffness and strength for a relatively low increment of weight. A limiting factor of these materials is their resistance to inter-ply delamination, and debonding of the skins, ultimately reducing mechanical performance.

Sandwich panels subjected to in-plane crushing loads can buckle, resulting in separation of the skins from the core (ref. 1). Through-Thickness Reinforcement (TTR) can improve these properties, acting as a mechanical joint between top and bottom skins and altering the failure mechanisms of the component. This can engage the in-plane compression response of the fibres increasing the compressive resistance of the panel. The modified response can result in more efficient energy absorbing structures.

Tufting is one such TTR method. Like stitching it passes loops of thread through the panel to connect the two skins as originally developed by DLR Institute of Structural Mechanics with KSL GmbH (ref. 2). A robotically actuated tufting head by KSL was studied to understand aspects of the tufting process. To form the tufts, thread is inserted without tension by a single hollow needle, much like a standard sewing machine needle. Friction within the panel, between the dry fabric and the tufting thread, prevents the yarn from being pulled out as the needle retracts. A presser foot compacts the preform and holds it in place during the insertion. In order to form a loop on the reverse face the needle must pass a certain distance beyond the back face before retraction and so the preform is placed on top of a backing foam, into which the needle and thread can pass (Figure 1). The robotic head allows control of the insertion rate, as well as the length and spacing of the individual tufts.

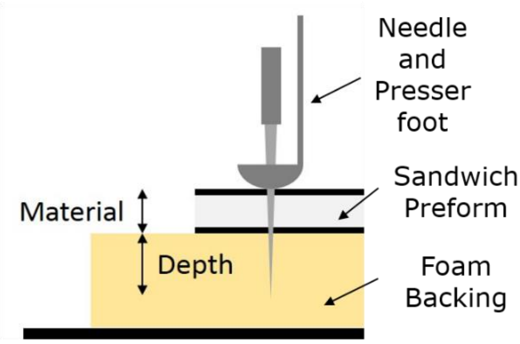

Figure 1: Tufting process control

Other TTR methods include z-pinning, which has been shown to improve delamination resistance compared to composites containing toughened resins, resins with nano-particles or with thermoplastic interleaves (ref. 3). The advantage of tufting is its use for preforming components of dry fibres, rather than more expensive prepreg material. Also access is only required from one side of the component, unlike stitching. The scope for using this technology on prepreg material is unknown, however the tackiness of the prepreg substrates would likely impede the passage of the needle. This would prevent the tufting thread from running freely, requiring greater insertion forces and increased risk of material or needle damage. Even without tension in the tuft thread, insertion of the needle can still cause fibre breakage and in-plane waviness, reducing the in-plane properties (ref. 3), but this should be seen as a trade-off for the improvement in other properties. Cartié *et al.* initially reviewed tufting as reinforcement for composite T-joints (ref. 4). The effect of the tufting was likened to that of a staple, which restricted separation of the laminate. Dell'Anno *et al.* confirmed by C-scanning that tufted panels reduce the delamination within a laminate in compression-after-impact compared to untufted panels (ref. 5) and Henao *et al.* found that tufted sandwich panels have higher failure loads in edgewise compression than untufted ones and fail by delamination and buckling of the skins (ref. 6). While the TTR effects are noted there is no discussion in the literature regarding the quality of the tuft itself. The tufts are difficult to observe given that they are embedded within the preform. The aim of this research is to develop a controllable test bed for tufting that can deliver an understanding of the various parameters available in this processing of composite sandwich panels. This addresses the need to observe and quantify the quality of a tuft in order to better inform the manufacturing process and structural design.

EXPERIMENTAL METHODOLOGY

To simulate the tufting process, a representative sandwich preform and foam backing sheet was contained in a custom-made rectangular box manufactured from transparent acrylic. An overview of the tufting unit geometry is shown in Figure 2.

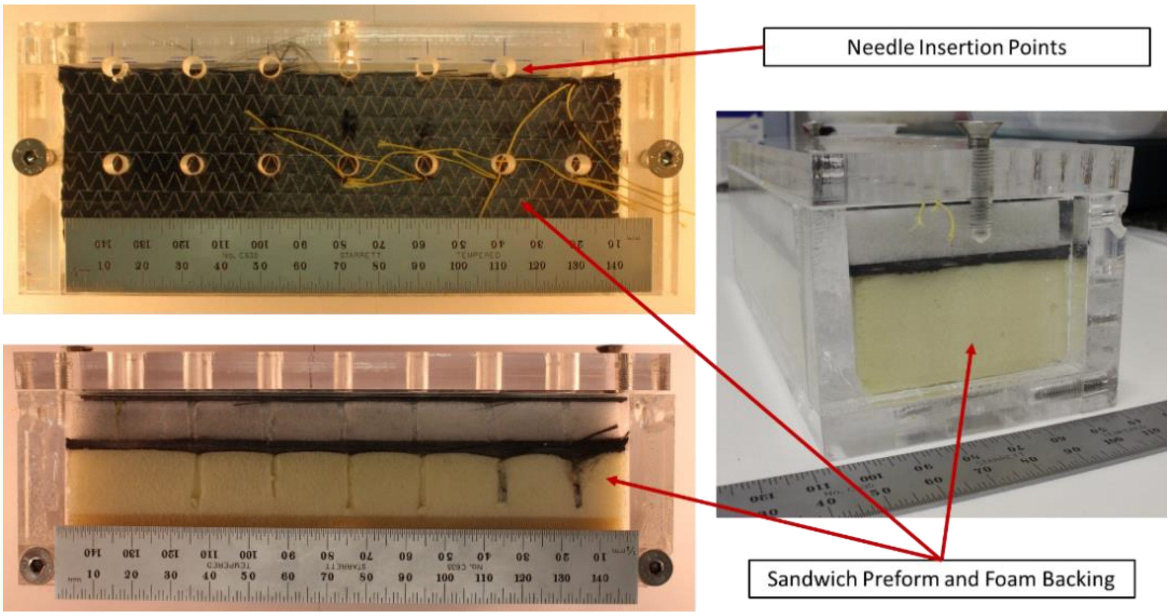

Figure 2: Tufting Unit Design

A series of holes were made in the top of the box along the middle and one edge to allow the tufting needle to pass through. The holes were used rather than an open top to represent the compaction provided by the presser foot during the tuft insertion, and it also allows the needle to retract, holding the panel in place. The transparency of the acrylic allowed real time observation of the needle penetration through each layer of the preform. A tight fit of the preform within the box was necessary to maintain the integrity of the panel when tufting on the edge.

The sandwich preforms were assembled using a uniweave carbon fibre fabric from SGL Automotive (300 gsm), and a Rohacell 110 IG-F closed-cell foam core by Evonik. Each of the skins comprised six plies, formed by hand layup, with a unidirectional ply orientation. The fibre direction was parallel to the long edge of the preform. The total preform thickness was approximately 14 mm with a closed-cell polystyrene backing sheet. To avoid slippage of the plies during needle insertion the preforms were pre-consolidated before being placed in the test rig by being held under vacuum pressure at 1 bar, at 90°C for 2 hours. This activated the binder within the carbon fabric and provided some unification of the core and skins. Tufts were formed of aramid thread (Tkt-40).

An Instron 3343 electromechanical test machine was used to control the needle insertion. The tufting needle was fixed onto the test machine, with a 1 kN load cell, and the acrylic box was positioned below. A temporary frame was assembled around the box to prevent it from slipping under the force of the needle and to hold it in place as the needle was retracted. The test set-up is shown in Figure 3.

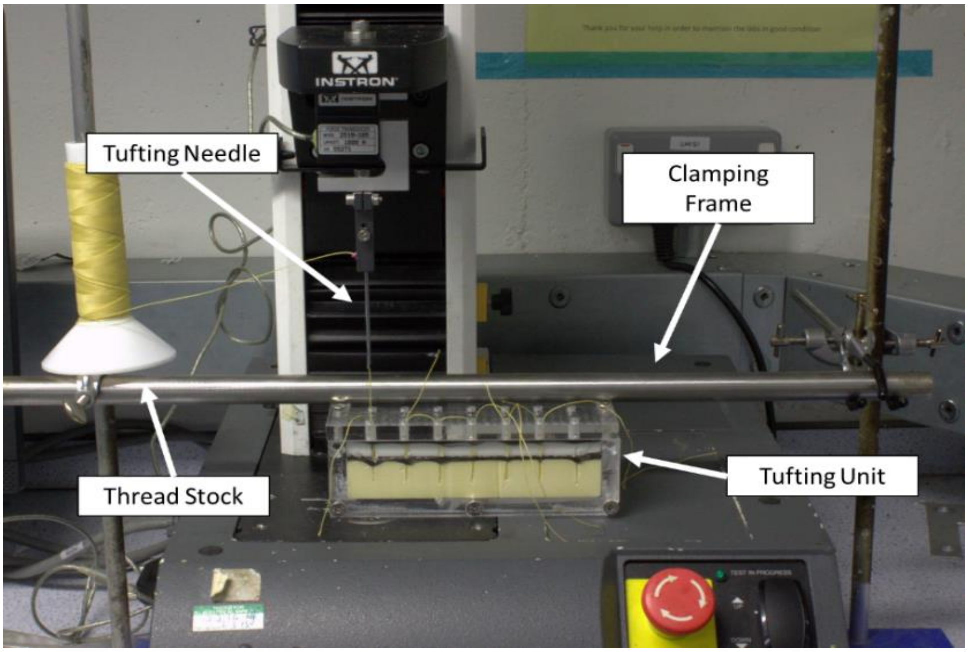

Figure 3: Experimental Set-up

The tufting test consisted of a compressive motion to a total distance of 30 mm through the preform and into the backing foam. This was then followed by the equivalent tensile displacement rate to withdraw the needle. The progression and associated damage by the needle as it passed through the preform was recorded by video through the side panel. This process was repeated for a range of tufting speeds, from 100 mm/min to 1,000 mm/min, both at the edge of the preform and in the centre. Inserting at the edge of the preform allowed visibility of any damage created. Inserting at the centre of the preform more accurately represented the boundary conditions of a large panel and was therefore used to record the loading on the needle.

RESULTS

The measured load-displacement data at the maximum tested rate is shown in Figure 4 for insertions in the middle of the panel. The results between inserting at the edge of the preform and at the centre showed similar trends with a reduction in load at the edge due to the smaller contact area of needle and preform.

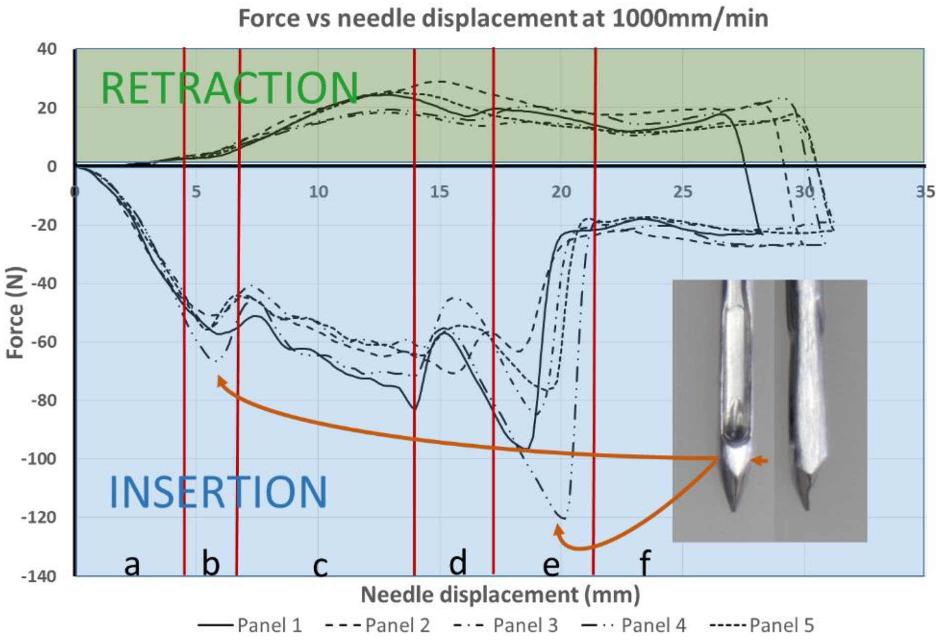

Figure 4: Load-displacement behavior of the tufting needle path

The graph shows two distinct regions, where negative force indicates insertion and positive force is that which is required for retraction. Some deflection of the panel is seen as the needle contacts the top skin and tip penetrates (4.a). The widest part of the needle (indicated in the figure) passes through the top skin, concurrent with the tip contacting the core foam and there is peak localised force (4.b). The widest part of the needle then passes through the core foam and friction increases approximately linearly as contact length increases (4.c). The widest part of the needle then exits the core with some separation of the lower skin from the core occurring as the needle tip contacts the carbon fibre, causing a reduction in insertion force (4.d). The force increases again as the needle begins to penetrate the lower skin and peaks as the widest point passes through it (4.e). The needle then penetrates the backing foam and the force increases slightly with contact length. The needle then retracts with a reversal of forces (4.f).

For the needle insertions carried out at the edge of the preform, any interesting features observed were recorded. Examples of these are shown in Figure 5.

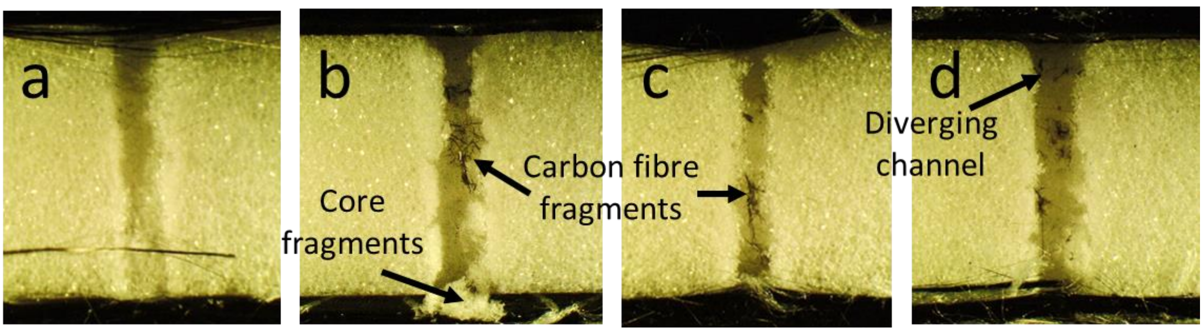

Figure 5: Needle channel features; a: near ideal tuft, b: carbon fibre and core fragments, c: carbon fibre fragments, d: divergence of the needle channel

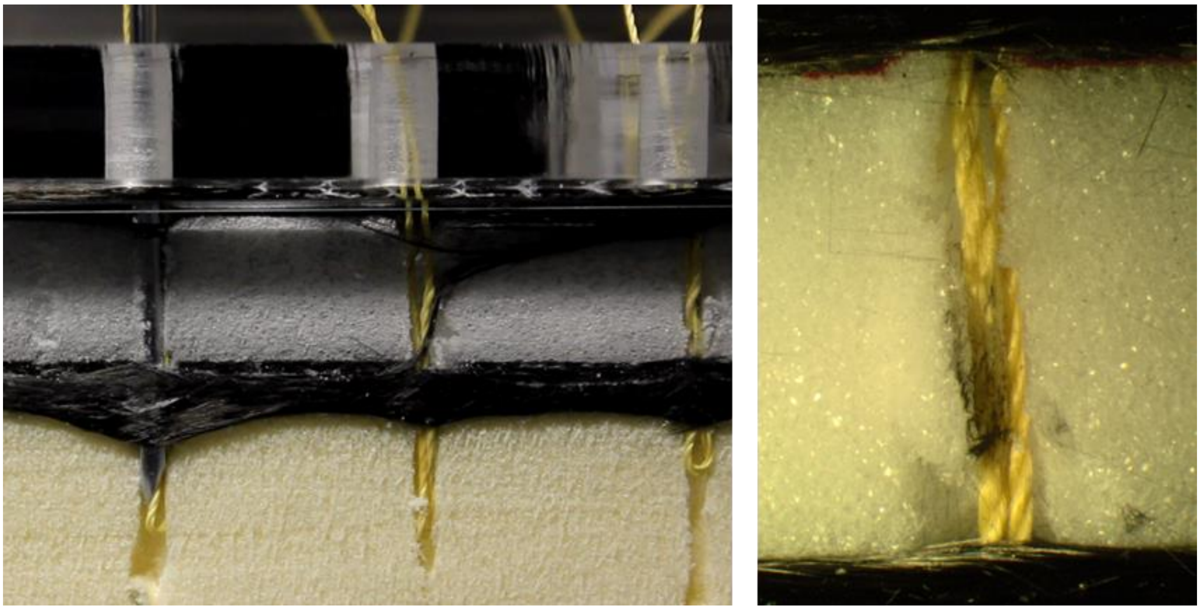

Figure 6: Tufting process with thread (L); thread in needle channel (R)

There are three common features observed, carbon fibre fragments, foam core pieces and the diverging opening of the column (Figure 5). In order to rate these features the relative area covered by the carbon and core pieces were measured as was the width of the channel opening. All image processing was carried out in ImageJ software. This can distinguish between different regions in the image and calculate the area covered. It also permits measurements of image dimensions.

When the thread was inserted to form a tuft similar features were noted (Figure 6). The behaviour of the thread within the channel could also be observed.

DISCUSSION

A quality matrix was developed based around the three main features observed as shown in Table 1 and Table 2. A rating of 1 represents the best tufting quality possible while 0 represents what could be considered a worst case scenario. The percentage area of the carbon fibre and core debris was calculated relative to the total area of a perfect column (2mm x 10mm).

The ideal tufting column rating at 1 is a clean channel without any carbon fibre fragments or core pieces with the opening of the column is exactly the diameter of the needle (2 mm). The upper limit on the channel opening diameter was selected based on the maximum measurement in the sample population. Debris within the resin column is considered a negative feature as it potentially disrupts resin flow through the tuft increasing the chance of voids forming. It may also negatively affect the bonding of skin and core and is a potential crack initiator.

Sample ID	Insertion rate	Fibre fragment area (%)	Opening diameter (mm)	Core fragment area (%)
S1_100	100	0.7	3.1	54.4
S1_100_2	100	0.1	2.7	83.2
S2_100	100	2.6	2.8	0.0
S1_200	200	1.8	2.3	0.0
S2_200	200	0.8	2.6	2.5
S4_200	200	2.7	3.6	13.2
S1_300	300	0.1	2.7	0.0
S2_300	300	0.7	2.5	8.7
S4_300	300	4.6	3.8	16.4
S2_400	400	0.3	2.8	5.1
S4_400	400	5.7	3.7	2.2
S2_500	500	0.5	2.5	0.0
S4_500	500	1.4	3.4	10.2
S5_600	600	0.3	2.6	0.0
S5_700	700	3.4	2.4	13.8
S5_800	800	0.5	2.6	0.0
S5_900	900	3.0	3.1	5.6
S5_1000	1000	0.6	2.4	0.0

Table 1: Image processing results

Criteria			Rating
Fibre fragments (%)	Opening diameter (mm)	Core fragments (%)	
Total blockage	>3.8	Total blockage	0
<90	<3.8	<90	0.1
<80	<3.6	<80	0.2
<70	<3.4	<70	0.3
<60	<3.2	<60	0.4
<50	<3.0	<50	0.5
<40	<2.8	<40	0.6
<30	<2.6	<30	0.7
<20	<2.4	<20	0.8
<10	<2.2	<10	0.9
0	2.0	0	1

Table 2: Criteria rating method

The diverging opening seen in the columns was a result of the needle breaking through the surface of the core. During infusion, this increased volume would result in a resin-rich region at the interface of the foam core and the skin, which due to its brittle nature, could increase the risk of fracture.

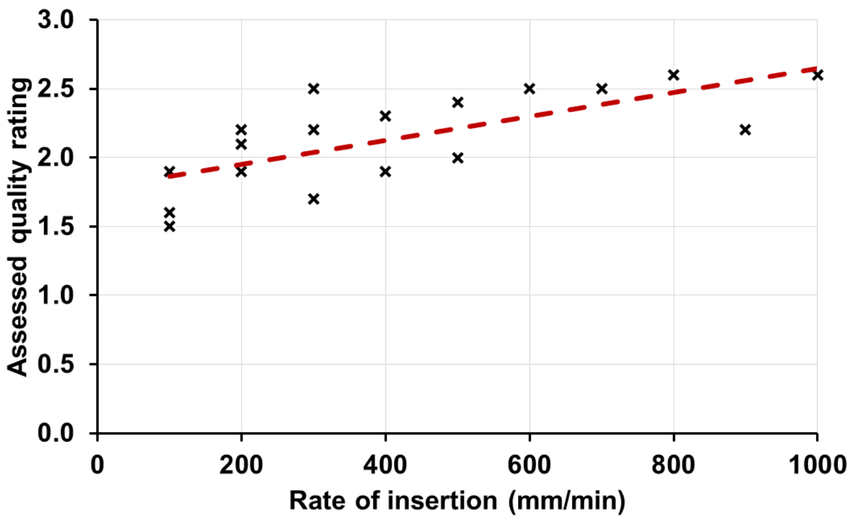

Figure 7: Graph showing trend of quality vs insertion rate

Initial results (Figure 7) of the quality analysis show some correlation between increasing the tufting speed and an improvement in tuft quality. The variation in the column opening dimension has the greatest effect on the assessed quality. Debris from carbon fragments and broken core did not vary significantly between insertion rates.

The test rig allows insertion of thread loops but there was difficulty in keeping the edge tufts intact when extracting them for analysis. The presence of the thread also obscures the detail of the criteria developed in the outlined matrix. An extended quality matrix is therefore required, where the 3D nature of the tuft and needle channel are evaluated.

While the test bed has successfully provided insight into the structure of tufts there are still a number of improvements to be made. Due to the fixed nature of the test bed, the edge of any preform samples that are slightly smaller than the dimensions of the box will not sit flush against the front panel. This can cause difficulties in aligning the needle and may result in the needle actually missing part of the preform. The current maximum insertion rate of 1000 mm/min is also relatively low when compared to current commercial models which can tuft at a rate of 5000 mm/min. There are also some issues with the current post-processing method. Because of the depth of the columns, it is difficult to capture all detail in the channels debris may not be picked up by the image processing software. The added complexity of thread inclusion showed that the metrics developed for needle insertion alone are not easily measurable in this case.

CONCLUSIONS

The initial testing and results of the tufting test bed show a promising method for characterizing the formation of tufts within sandwich preforms. The test bed allowed for visualisation of the insertion process, as well as recording of the loads exerted on the needle along its path. Current image analysis suggests a possible trend between increasing insertion speed and an increased quality of the column within the preform however more improved analysis methods are required to validate this. This is because the current imaging methods can only see two dimensional information and cannot capture the entire column.

ACKNOWLEDGMENTS

This work was supported by the Engineering and Physical Sciences Research Council through the EPSRC Centre for Doctoral Training in Advanced Composites for Innovation and Science [grant number EP/G036772/1] and the EPSRC Centre for Innovative Manufacturing in Composites (CIMComp) (Grant: EP/IO33513/1).

REFERENCES

1) A. G. Mamalis, D. E. Manolakos, M. B. Ioannidis and D. P. Papapostolou, Compos. Struct., 71 (2005) 246.
2) C. Sickinger and A. Herrmann, in Proc. Techtextil Symp. Conf., 2001.
3) A. P. Mouritz, P. Chang and M. D. Isa, J. Aerosp. Eng., 24 (2011) 425.
4) D. D. R. Cartié, G. Dell'Anno, E. Poulin and I. K. Partridge, Eng. Fract. Mech., 73 (2006) 2532.
5) G. Dell'Anno, D. D. R. Cartié, I. K. Partridge and A. Rezai, Composites Part A, 38 (2007) 2366.
6) A. Henao, M. Carrera, A. Miravete and L. Castejón, Compos. Struct., 92 (2010) 2052.