RESIDUAL TORSIONAL STRENGTH AFTER IMPACT OF CFRP TUBES

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1. Introduction

Impact on composite laminates has been widely examined by various researchers, both through experiments and by analyses. Many researchers have reported that low-velocity impacts (LVI) cause matrix cracking, delamination, and fiber breakage. Such damage can be very difficult to detect by the naked eye and may significantly reduce the strength and stiffness of the material [1]. Other studies investigated the compression-after impact behavior of laminate panels.

This study addresses the LVI problem on laminated composite tubes under torsional preload. First, the torsional strength of four different lamination sequences is studied. Later it is compared with the residual torsional strength (RTS) of tubes impacted under different torsional preloads. The Acoustic Emission (AE) technique is used to study the damage propagation during the torsional loading.

2. Materials and Methods

A total of 24 cylindrical specimens (200 mm long, 50 mm internal diameter, 2.56 mm thick) were tested. Four different stacking sequences were manufactured:

Q.ty	Name - Symmetry	Stacking sequence
6	AP_S	$[+45/-45]_{4s}$
6	AP_{NS}	$[+45/-45]_8$
6	QI_S	$[0_2/(+45,-45)_2/90_2]_s$
6	QI_{NS}	$[0_2/(+45,-45)_2/90_4/(+45,-45)_2/0_2]$

Each lamina is assumed to be 0.16 mm thick, and the material properties are: $E_1 = 105GPa$, $E_2 = E_3 = 6.5GPa$, $G_{12} = G_{13} = 5.5GPa$, $G_{23} = 2.0GPa$, $\nu_{12} = \nu_{13} = 0.27$, $\nu_{23} = 0.625$.

The experiments plan consisted of three stages:

1) Measurement of the torsional strength of 2 undamaged specimen for each lamination sequence.

2) Measurement of the RTS of 8 tubes[1] previously subjected to a $7J$ impact without preload.

3) Measurement of the RTS of tubes previously impacted under torsional preload. Four specimens (one for each lamination sequence) were first loaded by a nominal torque equal to 65% of the RTS found in stage 2, then damaged by a 7J transversal impact, and later loaded in torsion up to failure. For the last four specimens, the initial preload was 130% of the RTS found in stage 2.

To clamp the specimens in the testing machine, tubes were bonded to semi-cylindrical steel ends by a high-strength bicomponent epoxy cement. All specimens were also equipped with an AE sensor. More details about the torsional experiments setup and the design of the clamping system can be found in [2].

3. Experimental Results

3.1. Torsional strength (undamaged tubes)

Name	Stress external (±)45° lamina	M_t
AP_S	(+) Traction	$4.17\ kNm$
AP_{NS}	(-) Compression	$3.73\ kNm$
QI_S	(+) Traction	$3.00\ kNm$
QI_{NS}	(-) Compression	$3.00\ kNm$

Table 1: Experimental torsional strength of the undamaged tubes.

Table 1 shows that no differences were found between the torsional strength M_t of symmetric and non-symmetric QI laminated tubes, while AP_S tubes show higher torsional strength than the non-symmetric ones (AP_{NS}).

Notice that: (1) the torque direction is the same; (2) in the AP_S specimens the outside ply is oriented at $-45°$ and the fibers are in tension; (3) in the AP_{NS} specimens the outside ply is oriented at 45° and the fibers are compressed.

3.2. Torsional strength (damaged tubes)

This section will firstly focus on the effect of preload on the impact behavior, to later analyze its effects on the residual torsional strength.

The low-velocity impact was produced by an instrumented pendulum striking the middle of the tube in the transverse direction. The impact energy was set to approximately 7J for all tests. During experiments, the contact force histories reach a sharp initial spike, followed by a significant drop. Table 2 indicates that the peak force F is not dependent on the torsional preload M_p, but is only affected by the lamination sequence. On the other hand, a higher torsional preload induces a steeper drop in force immediately after the peak, as well as a longer contact time t and wider maximum beam deflection δ. These results suggest that, although the torsional preloads do not affect the delamination initiation, it significantly plays a role in delamination propagation. Even if the internal damage increases with the preload, the absorbed energy E_{abs} remains constant.

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[1] Two specimens for each lamination sequence.

Name (Stress)[a]	M_p [kNm]	E_{abs} [J]	F [N]	t [ms]	δ [mm]	RTS [kNm]	$RTS_{\%}$ %
1) $AP1_{NS}$ **(+)**	0	6.334	2.15	4.5	4.5	1.696	45.4
2) $AP2_S$ **(+)**	0	6.317	2.11	4.1	4.5	1.919	46.0
3) $AP3_{NS}$ **(-)**	0	– – –	– – –	– – –	– – –	1.747	46.8
4) $AP4_S$ **(-)**	0	6.709	2.04	4.5	4.5	2.056	49.3
5) $QI1_{NS}$ **(+)**	0	6.201	1.90	4.0	4.0	1.561	52.0
6) $QI2_S$ **(+)**	0	6.288	1.87	3.9	4.0	1.522	50.7
7) $QI3_{NS}$ **(-)**	0	6.438	1.80	3.8	4.0	1.599	53.3
8) $QI4_S$ **(-)**	0	6.176	1.78	4.0	4.0	1.576	52.5
9) $AP5_{NS}$ **(+)**	1.12	6.885	2.15	4.3	4.85	0.890	24.0
10)$AP6_S$ **(-)**	1.25	6.609	2.10	4.7	4.85	0.900	21.5
11)$AP7_{NS}$ **(+)**	2.24	6.377	1.80	5.5	5.80	– – –	– – –
12)$AP8_S$ **(-)**	2.58	6.377	2.08	7.0	7.00	– – –	– – –
13)$QI5_{NS}$ **(+)**	1.00	6.727	1.80	3.8	4.00	1.241	41.3
14)$QI6_S$ **(-)**	0.98	6.165	1.80	3.7	4.00	1.375	45.8
15)$QI7_{NS}$ **(+)**	1.99	6.675	1.80	5.5	5.50	– – –	– – –
16)$QI8_S$ **(-)**	2.00	6.471	1.80	5.5	5.70	– – –	– – –

Table 2: Experimental results

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[a] Stress along the fiber in the external (±)45° lamina.

Table 2 shows that the stress state in the outside (±)45° lamina of the *AP* specimens did not affect the RTS. However the Symmetric *AP* specimens revealed higher RTS in these cases.

Impacts on unloaded specimens (*Tests 1 to 8*) produced barely visible damage, and the RTS was reduced to about 50% of its original value for the *QI* tubes, and even less (46%) for the *AP* tubes.

Impacts on tubes preloaded at 65% of the RTS (*Tests 9-10,13-14*) produced visible damages: matrix cracks, extensive delaminations, and fiber failure clearly appeared. RTS dropped down to $\approx$ 42% of its original value for the *QI* tubes, and only to $\approx$ 22% for the *AP* tubes. The introduction of a torsional preload clearly lowered the residual torsional strength. However it is reasonable to suppose that at this preload level, specimens were still undamaged before impact, because no *AE* were produced during preloading.

Tubes preloaded at M_p =130% of the RTS (*Tests 11-12,15-16*) collapsed under the impact with complete loss of strength and stiffness. By the AE technique is possible to say that at this preload level, specimens contained an internal damage before the impact.

3.3. Damage evolution

The Sentry[2] function was used to determine the important damage events occurring during the torsional loading [3]. Figure 1 shows an example of this function. For each relevant drop in the sentry function, a mark is plotted on the experimental torque-rotation curve. In correspondence with these events, a damage function based on the reduction of the torsional stiffness in respect to the initial one was calculated[3]. Figure 2 shows the results. *QI* specimens curve is basically divided into three parts: an initial steady increase (that can be related to the collapse due to local buckling in the compressed plies), followed by a slump (related to the damage in the 0° and 90° plies, which gives limited changes of the stiffness) and a final rise (due to the fiber breakage in traction). *AP* specimens showed only two phases: an initial steady increase, related to the local buckling of the compressed plies, followed by the final rise, representing the final failure of the plies in tension.

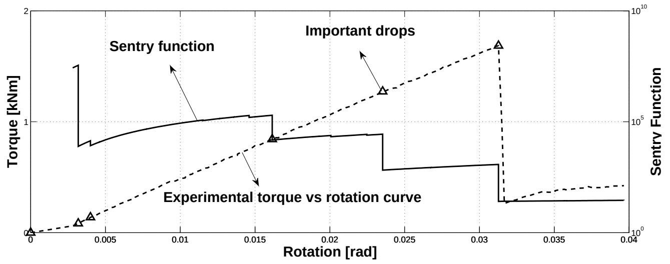

Figure 1: Sentry function and torque vs. rotation.

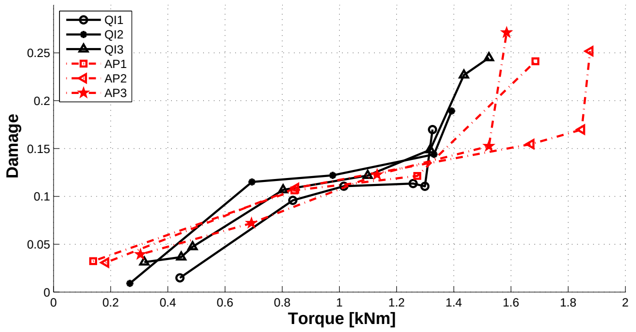

Figure 2: Damage evolution in QI and AP specimens

4. Conclusion

The present study is perhaps the first one to deal with the RTS of composite tubes damaged while under different torsional preloads. It is shown that impacts induce localized delamination, with a subsequent reduction of the plies buckling critical load. As a consequence, impacts lower the RTS at least by a factor of two respect to the undamaged tubes. The RTS decreases as the preload increases, even if it is lower than the torque necessary to produce the first matrix crack. In conclusion, we found an interaction between torsional preload and delaminations propagation: the higher the preload, the more delaminations propagate, the lower the plies critical buckling load and the residual torsional strength. When delaminations are too large, the specimens collapse under the torsional preload, with complete loss of strength and stiffness.

References

[1] Serge Abrate. *Impact on Composite structures*. Cambridge University Press, 1998.

[2] G Minak, D Ghelli, and A Zucchelli. Torsion testing of cfrp laminate tubes. *5th ESIS TC4 International Conference on Fracture of Polymers, Composites and Adhesives, Les Diablerets*, (2008).

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[2] Defined as $f(\theta) = ln(E_s(\theta)/AE_a(\theta))$, where E_s is the strain energy and AE_a is the cumulated acoustic energy.

[3] Damage=$1 - \frac{GJ_p(\theta)}{GJ_p(0)}$, where $GJ_P(0)$ is the initial torsional stiffness of the tube, and $GJ_P(\theta)$ is the torsional stiffness calculated between two marks.