

Article

Crashworthiness Performance of Aluminium, GFRP and Hybrid Aluminium/GFRP Circular Tubes under Quasi-Static and Dynamic Axial Loading Conditions: A Comparative Experimental Study

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Abstract: Offshore structures are exposed to risks of vessel collisions and impacts from dropped objects. Tubular members are extensively used in offshore construction, and thus, there is scope to investigate their crashworthiness behaviour. Aluminium, glass fibre reinforced polymer (GFRP) and hybrid aluminium/GFRP circular tube specimens were fabricated and then tested under quasi-static and dynamic axial loading conditions. Two hybrid configurations were examined: external and internal layers from respectively aluminium and GFRP, and vice versa. The material impregnated with epoxy resin woven glass fabric was allowed to cure attached to the aluminium layer to ensure interlayer bonding. The quasi-static and dynamic tests were conducted using respectively a universal testing machine at a prescribed crosshead speed of 10 mm/min, and a 78 kg drop hammer released from 2.5 m. The non-hybrid configurations (aluminium and GFRP specimens) outperformed their hybrid counterparts in terms of crashworthiness characteristics.

Keywords: energy absorption; crashworthiness; impact loading; dynamic loading; axial crushing; thin-walled tube; multi-walled tube; multi-layer tube; hybrid tube; aluminium tube; GFRP tube; composite tube

1. Introduction

The term crashworthiness can be defined as the ability of a structure to absorb kinetic energy in the event of collision [1]. Crashworthiness is important to the construction of any kind of vehicle, from aircraft and cars to trains and ships, as well as road guard rails and offshore structures. Offshore structures are designed to withstand vessel collisions or impacts from dropped objects in order to maintain the integrity and avoid economic loss, environmental pollution, and human injuries or deaths [2].

Tubular members exhibit high specific strength and stiffness compared to their solid section counterparts, and are extensively used in offshore construction for material economy and light weighting where the float-out weight is important [3]. However, their crashworthiness response is complex. Geometrical and material non-linearities may take place at local and global levels, as well as interactions among different deformation patterns which add up to the complexity of the problem. For instance, the steel legs of offshore platforms may undergo indentation (local deformation), bending and stretching (global deformation) at the same time when they are in direct contact with the colliding vessel (Figure 1). In such cases and when the struck member is close to a tubular joint, the supporting braces mostly experience axial compression [2] and absorb energy through different mechanisms depending on the axial length to the cross-sectional perimeter, and the cross-sectional perimeter to wall thickness ratios [4,5]. These mechanisms can broadly

be divided into two categories depending on their crashworthiness ability: the global buckling (Figure 2i,j), and the progressive crushing (Figure 2a–h). Taking the case of metallic tubes, for example, the kinetic energy of the striking object is dissipated in the zones of plastic deformation. Those zones are limited to a small region in the case of global buckling, while in progressive crushing the plastic deformation is spread to a significant part of the tube's wall. As a result, global buckling is characterised by low energy absorption (a non-desirable mechanism), while progressive crushing tends to dissipate significant amounts of energy (a desirable mechanism).

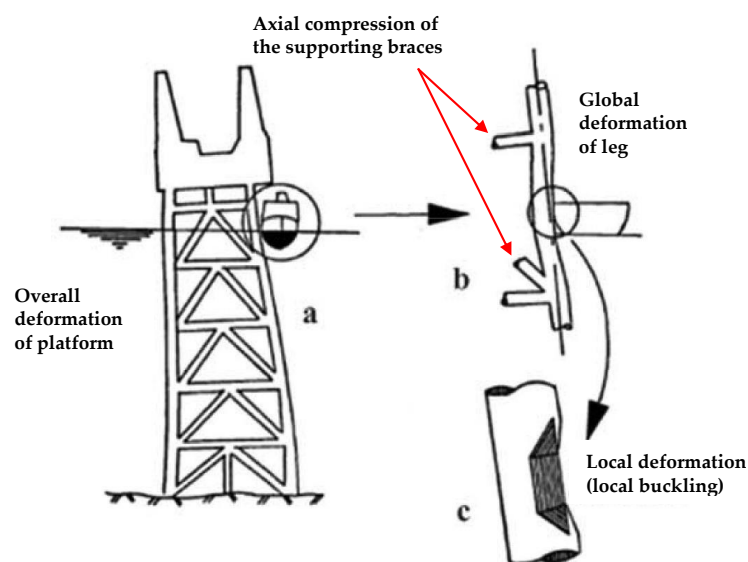


Figure 1. Energy absorption mechanism by a typical offshore structure in the event of vessel collision, Reprinted with permission from Reference [2]. Copyright 2018 Elsevier.

There are various patterns of progressive collapse depending on the tube's material and geometry characteristics, as well as the developed strain rates [6] (Figure 2). However, for low impact speeds the deformation patterns have been found to be roughly the same as those under quasi-static conditions [7,8]. The circular and square cross sections are perhaps the most common tubular shapes for attributes such as ease of fabrication and good crashworthiness characteristics. However, the circular tubes have been found to both crumble under lower loads [9] and absorb larger amounts of energy per unit mass than their square counterparts, regardless of whether the material is ductile (e.g., steel) or brittle (e.g., glass fibre reinforced polymer, GFRP) [7,10–12].

Extensive research has focused on the crashworthiness performance of the axially compressed circular tubes since the early 1960s. At that time Pugsley and Macaulay [13] and Alexander [14] conducted tests on metallic tubes and developed the first analytical expressions for the mean crushing force. Since then, many studies on metallic tubes subjected to both quasi-static and dynamic axial loading conditions followed [15–19]. Three distinctive patterns (modes) of progressive collapse have been identified for metallic tubes: the concertina mode (also reported as extensible or axisymmetric or ring mode), the diamond mode (also reported as inextensible or non-symmetric mode), and the mixed mode which is a combination of the former two, i.e., a combination of axisymmetric and diamond collapse levels (Figure 2a–c). Although in both concertina and diamond modes the tube walls form plastic hinges, in the first case, the perimeter of the crushed tube increases due to wall stretching in the hoop direction (hence the term extensible mode), while in the second, it remains roughly the same at any cross section along the axial length (hence the term inextensible mode). The characteristic of the diamond mode is the formation of peripheral lobes which can vary, from two (2-D) for small perimeter (or diameter) to wall thickness ratios to six (6-D) for larger ratios [20,21].

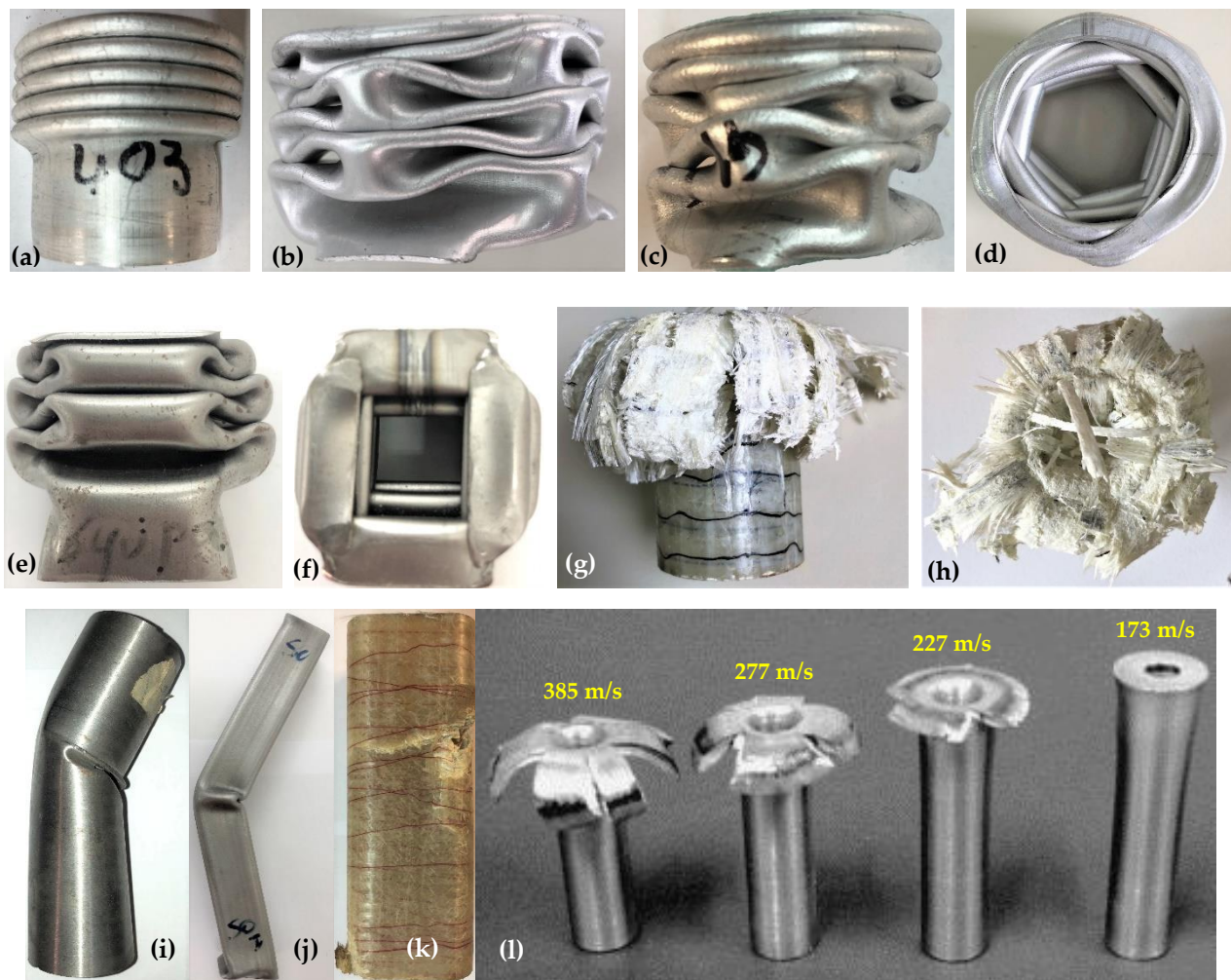


Figure 2. Deformation patterns/modes of tubes under axial loading conditions. Top row: progressive collapse of metallic circular tubes; (a) concertina (or extensible or axisymmetric or ring) mode; (b) diamond (or inextensible or non-symmetric) mode; (c) mixed mode; and (d) diamond mode with three peripheral lobes (3-D). Middle row: (e,f) the characteristic deformation mode of progressive collapse for metallic square tubes; (g,h) progressive collapse for composite tubes (mode Ia or mushrooming). Bottom row: (i,j) global buckling of circular and square metallic tubes; (k) catastrophic failure for a composite square tube (mode III); (l) deformation patterns of aluminium circular tubes under various impact speeds (Reprinted with permission from Reference [6]. Copyright 2002 Elsevier).

The early studies on the crashworthiness behaviour of thin-walled tubes were predominantly focused on metallic and PVC tubes. Composites were not that popular at the time mostly due to high cost and difficulties associated with fabrication. However, in the subsequent years extensive research was conducted seeking a better understanding of the crashworthy ability of composite tubes [22–24]. In contrast to the metallic energy absorbers, which dissipate energy through plastic deformation, the most common composite energy-absorbing devices, such as GFRP and carbon fibre reinforced polymer (CFRP) tubes, are brittle dissipating energy through micromechanisms that include intrawall cracking and axial splitting, fibre breakage or buckling, delamination, splaying and friction. Their energy absorption ability depends on various factors which may include the perimeter to wall thickness ratio, the fibre and matrix materials, the stacking sequence, and the fibre orientation and architecture (unidirectional, woven/braided fabric, random mat etc.). In contrast to the metallic tubes, small defects, such as one or two small holes around the tube's wall, have been found to greatly deteriorate the energy absorption of composite tubes [25].

The macroscopic deformation patterns of composite tubes can be categorised into four modes (I–IV) [26]. In mode I the collapse starts at one end and progresses forming fronds that spread either outwards (mode Ic), inwards (mode Ib) or in both directions (mode Ia, also called ‘mushrooming’ due to its characteristic pattern, Figure 2g,h). Mode II is associated with the formation of cracks in either the axial or hoop directions, which could result in the complete separation of the tube into two parts [27]. Mode III is associated with brittle fracture of long tubes and results in catastrophic failure (Figure 2k). Mode IV is usually observed in tubes with very thin walls. It is characterised by the progressive folding of the walls and the formation of sharp hinges similar to those observed in metallic tubes.

Although there is on-going research on metallic [28,29] and composite [30] tubes, in recent years, the focus has shifted towards foam-filled tubular structures [31] and hybrid metal–composite configurations, in either macroscopic [32,33] or mesoscopic [34] levels, as an attempt to further improve the crashworthy performance of tubular structures at a relatively low cost. The hybridisation of aluminium and CFRP was found to be a promising layout with the potential to be used in applications where lightweighting is important [35]. However, most studies have focused on aluminium/CFRP layouts, while the hybridisation of aluminium and GFRP under both static and dynamic loading conditions has scarcely been investigated. This study attempts to shed some light on this aspect. For this reason, aluminium, GFRP and two kinds of hybrid aluminium/GFRP specimens were fabricated and tested under both quasi-static and dynamic axial loading conditions. The quasi-static and dynamic tests were conducted using a universal testing machine and a drop hammer apparatus, respectively. The obtained experimental results were discussed in detail and useful concluding remarks were drawn.

2. Specimens

Four different configurations were fabricated: the aluminium (AL), the GFRP, the AL–GFRP and the GFRP–AL specimens. The latter two represent the hybrid configurations which are practically two circular tubes of different materials one inside the other. The external and internal tubes/layers were respectively made of aluminium and GFRP (AL–GFRP specimens), and vice versa (GFRP–AL specimens).

The AL specimens were cut from a single extruded AA6063-F (‘F’ stands for ‘as fabricated’) thin-walled circular tube (Figure 3) which was first annealed at 300 °C for 30 min to improve the ductility of the alloy. Additional annealed extrusions of the same dimensions were used as moulds/mandrels for the preparation of the GFRP and hybrid specimens.



Figure 3. Initial views of the four aluminium (AL) specimens.

To fabricate the GFRP and GFRP–AL specimens, a single piece of woven E-glass cloth impregnated with epoxy resin was firmly wrapped around the aluminium extrusions (Figure 4). In the case of the GFRP specimens, the aluminium extrusion was previously wrapped with a thin polymer membrane to facilitate its removal at the end of the curing process. The membrane may have remained on the specimens during the tests; however, the results were assumed to be virtually unaffected due to its poor mechanical properties. In the case of the GFRP–AL specimens, the impregnated E-glass fabric was in direct contact with the aluminium extrusions to achieve interface bonding between the two materials at the end of the curing process.

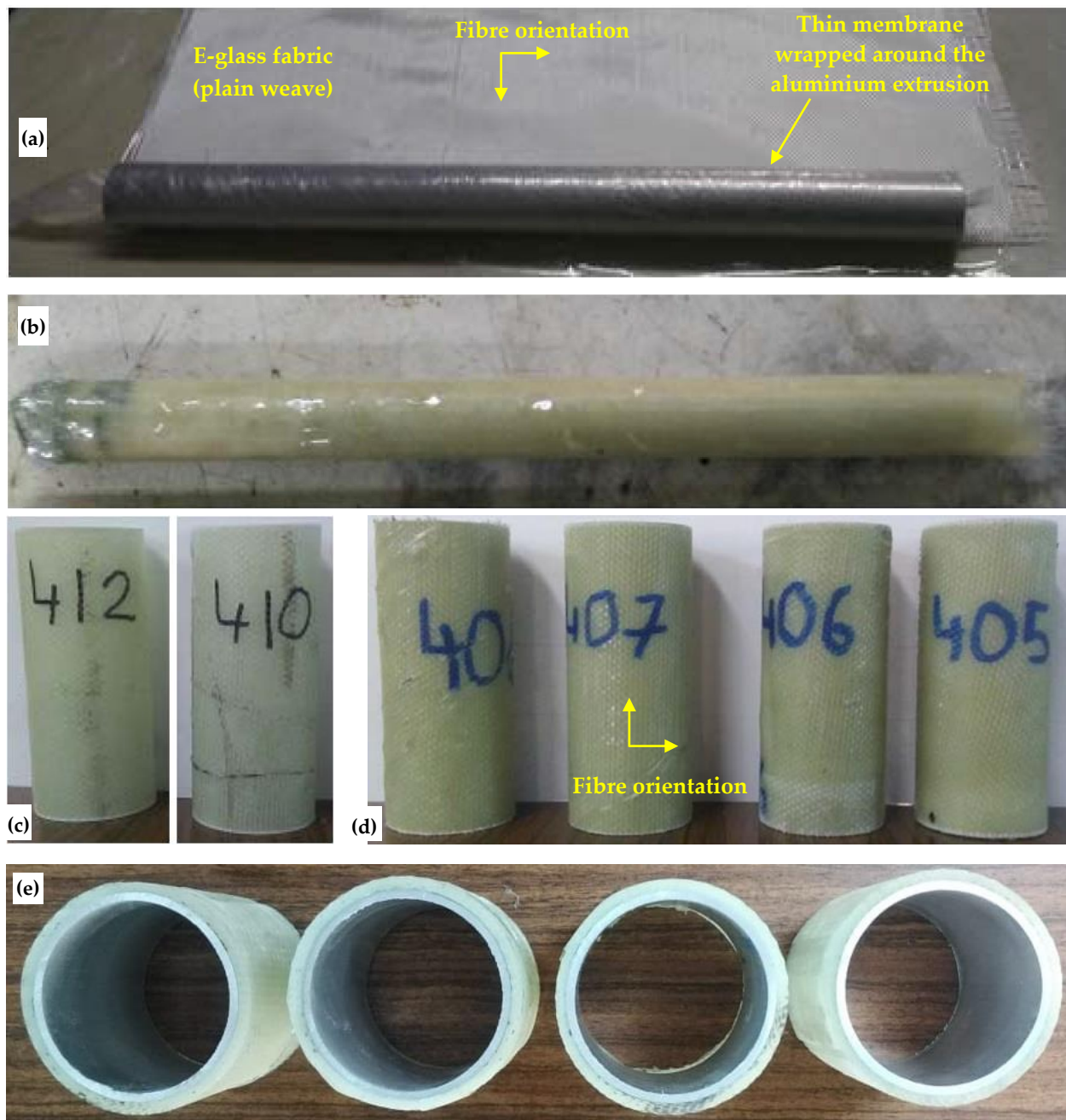


Figure 4. Fabrication steps for the GFRP and GFRP–AL specimens: (a) the E-glass fabric is wrapped around the aluminium extrusion, which, in the case of GFRP specimens only, was wrapped with a thin polymer membrane to facilitate its removal at the end of the curing process; (b) the GFRP–AL tube after curing and before cutting it into specimens; (c) initial views of the GFRP specimens; (d) initial views of the GFRP–AL specimens; and (e) top views of the GFRP–AL specimens.

The internal GFRP layer of the AL–GFRP specimens was prepared by wrapping the E-glass fabric around an inflatable cylindrical mandrel (Figure 5). The mandrel, which was previously wrapped with a thin polymer membrane, was then inserted into the aluminium extrusion and inflated to ensure firm contact between the fabric and the internal wall of the extrusion. After the curing process, the mandrel was deflated and removed.

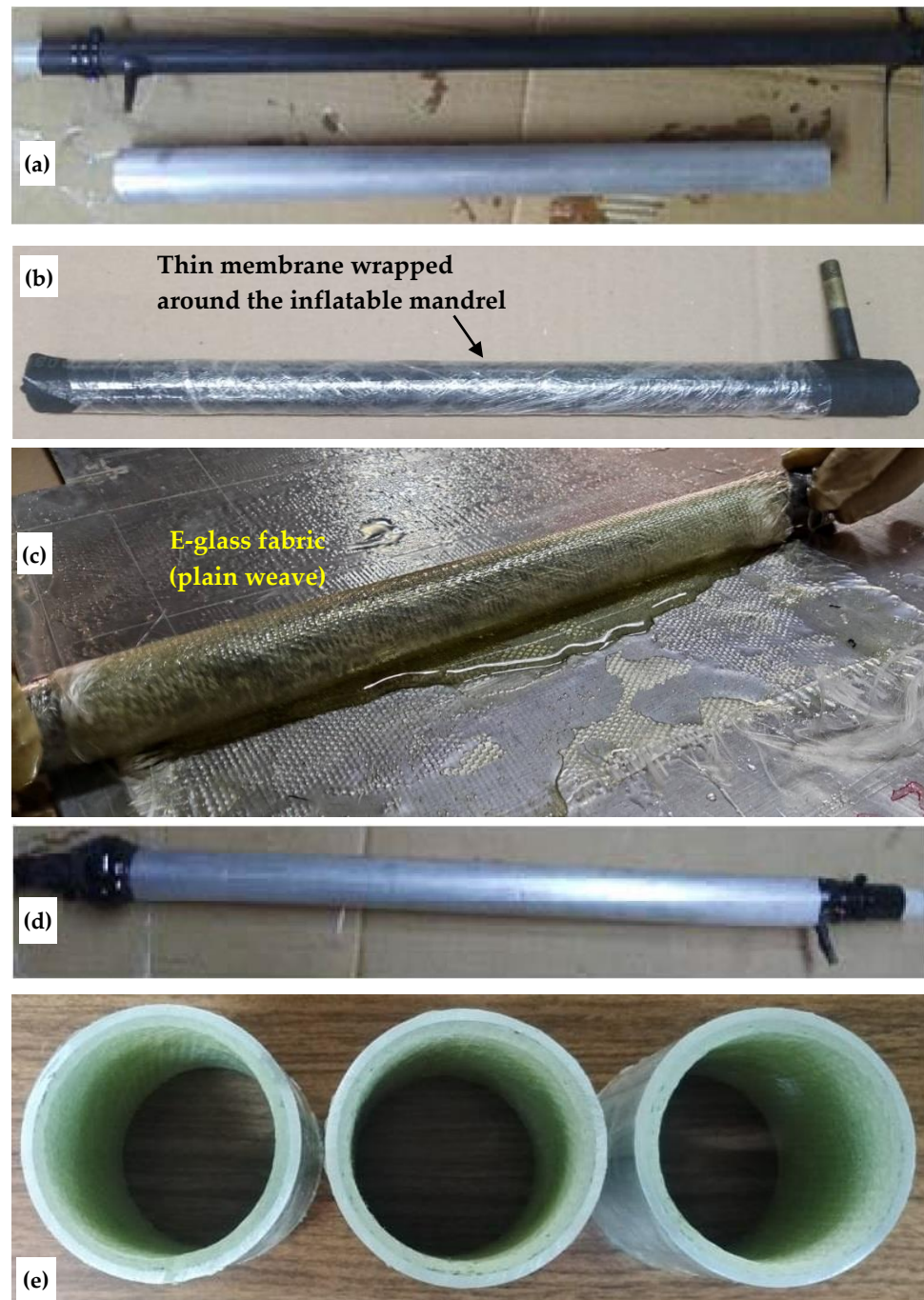


Figure 5. Fabrication steps of the AL–GFRP specimens: (a) the inflatable mandrel and the aluminium extrusion; (b) the inflatable mandrel wrapped with a thin membrane to facilitate its removal at the end of the curing process; (c) wrapping of the impregnated with epoxy resin E-glass fabric around the inflatable mandrel; (d) the mandrel inside the aluminium extrusion being inflated to ensure firm contact between the impregnated fabric and the internal wall of the aluminium extrusion; (e) top views of the AL–GFRP specimens.

The GFRP, GFRP–AL and AL–GFRP specimens were wrapped with the E-glass fabric such that the fibres were oriented at $0^\circ/90^\circ$ specimens and then were allowed to cure for seven days at room temperature under dry conditions. The four tubes that represent the four configurations (i.e., AL, GFRP, GFRP–AL and AL–GFRP) were cut to produce specimens of axial length (L) 100 mm. The specimens were all lathed at their ends to minimise any boundary imperfections and ensure dimensional accuracy. No visual defects were observed in the final specimens. The material properties and the specifications of the specimens are summarised in Tables 1 and 2, respectively.

Table 1. Properties of the materials used to fabricate the specimens. The data were obtained by the manufacturer.

Material	AA6063-F	E-Glass Fibre	Epoxy Resin ¹	Units
Proof stress (0.2%)	50	–	–	MPa
Tensile strength (compressive strength)	120	2700	35 (72)	MPa
Young’s modulus	69.5	72	1.6	GPa
Poisson’s ratio	0.33	0.22	0.34	–
Density	2700	2600	1100	kg/m ³
Viscosity at 20 °C	–	–	420	MPa.s

¹ Allowed to cure for seven days at 23 °C under dry conditions.

Table 2. Specifications and results of the specimens tested. The axial length was common for all specimens ($L = 100$ mm).

Specimen		Mass [g]				GFRP Fibre Vol. Fraction [†]	Diameter [mm]			Loading Condition	Overall Strain Rate (s ⁻¹)	δ_T * [mm]	IPF * [kN]	F_{max} * [kN]	EA [†] [kJ]	MCF [†] [kJ]	SEA [†] [J/g]	CFE [†] [%]
		AL *	E-glass *	Epoxy [†]	Total *		Internal *	Interface [†]	External *									
AL	401	45.2	-	-	45.2	-	35.6	-	38.6	Dynamic	29.1	65.5	25.5	49.5	1.52	23.1	51.2	46.7
	402	45.2	-	-	45.2	-	35.6	-	38.6	Dynamic	28.3	70.5	25.9	48.0	1.61	22.8	50.4	47.5
	403	45.2	-	-	45.2	-	35.6	-	38.6	Quasi-static	1.67×10^{-3}	60.0	43.8	43.8	1.49	24.9	55.0	56.8
	404	45.2	-	-	45.2	-	35.6	-	38.6	Quasi-static	1.67×10^{-3}	60.0	44.1	44.1	1.44	24.1	53.3	54.6
GFRP-AL	405	45.2	25.4	16.1	86.7	0.40	35.6	38.6	43.0	Dynamic	27.0	32.5	43.3	93.4	1.63	50.1	57.8	53.7
	406	45.2	25.4	17.3	87.9	0.38	35.6	38.6	43.7	Dynamic	23.3	36.5	55.0	110.7	1.52	41.6	47.3	37.5
	407	45.2	25.4	16.5	87.1	0.39	35.6	38.6	42.9	Quasi-static	1.67×10^{-3}	60.0	78.3	78.3	2.26	37.6	43.2	48.0
	408	45.2	25.4	17.1	87.5	0.39	35.6	38.6	42.9	Quasi static	1.67×10^{-3}	60.0	79.1	79.1	2.67	44.6	50.1	56.3
GFRP	410	-	25.4	15.8	41.2	0.40	38.6	-	43.0	Quasi-static	1.67×10^{-3}	60.0	22.0	22.0	1.10	18.3	44.5	83.2
	412	-	25.4	16.2	41.6	0.40	38.6	-	42.9	Quasi-static	1.67×10^{-3}	60.0	27.0	27.0	1.13	18.8	45.1	69.5
AL-GFRP	413	45.2	21.1	17.1	91.7	0.34	29.6	35.6	38.6	Dynamic	25.4	35.5	39.2	104.3	1.54	43.3	47.2	41.5
	414	45.2	25.4	22.0	92.6	0.33	29.4	35.6	38.6	Quasi-static	1.67×10^{-3}	60.0	63.9	63.9	2.03	33.9	36.6	53.1
	415	45.2	25.4	21.2	91.8	0.34	29.6	35.6	38.6	Quasi-static	1.67×10^{-3}	60.0	66.8	66.8	2.34	39.0	42.5	58.4

* Measurement (the masses and diameters were the mean values of three measurements); [†] Calculation.

3. Test Set-Up

The specimens were tested under axial quasi-static and dynamic loading conditions. Dynamic tests of the GFRP specimens were not conducted due to difficulties associated with maintaining contact of the tube ends with the striking mass and bottom platen. Two tests were carried out for each specimen configuration and loading conditions, apart from the AL–GFRP configuration which was tested once.

The quasi-static tests were carried out in an Instron 4482 universal testing machine equipped with a standard PC to acquire the test data (Figure 6 top). The total crushing displacement (δ_T) was chosen to be 60% of the specimens' axial length (i.e., $\delta_T = 60$ mm). This displacement was considered to be sufficient for drawing conclusions and prevent crushing bulk material during the final stages of the test. The crosshead speed was chosen to be 10 mm/min, which corresponds to quasi-static test conditions with an overall strain rate of $1.7 \times 10^{-3} \text{ s}^{-1}$.

The dynamic tests were carried out in a conventional drop hammer with a 78 kg striking mass (Figure 6 bottom). To acquire the test data, the load cell was connected to an oscilloscope which transmitted the signal to a standard PC. To avoid crushing bulk material during the final collapse stages of AL specimens, the release height of the drop hammer was chosen to be 2.5 m, which corresponded to a $\delta_T \approx 2/3 L$. For consistency, the same release height was chosen for all specimens. The developed overall strain rates ranged from 23.3 to 29.1 s^{-1} (Table 1), which classify the tests in the low dynamic band according to Mayers [36].

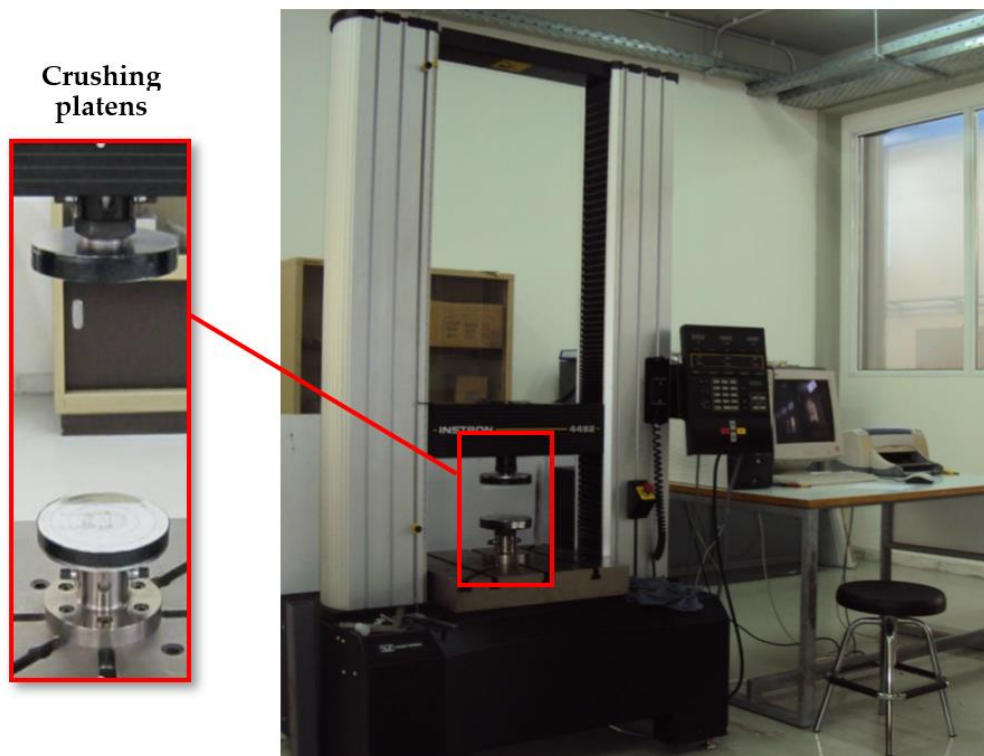


Figure 6. Cont.

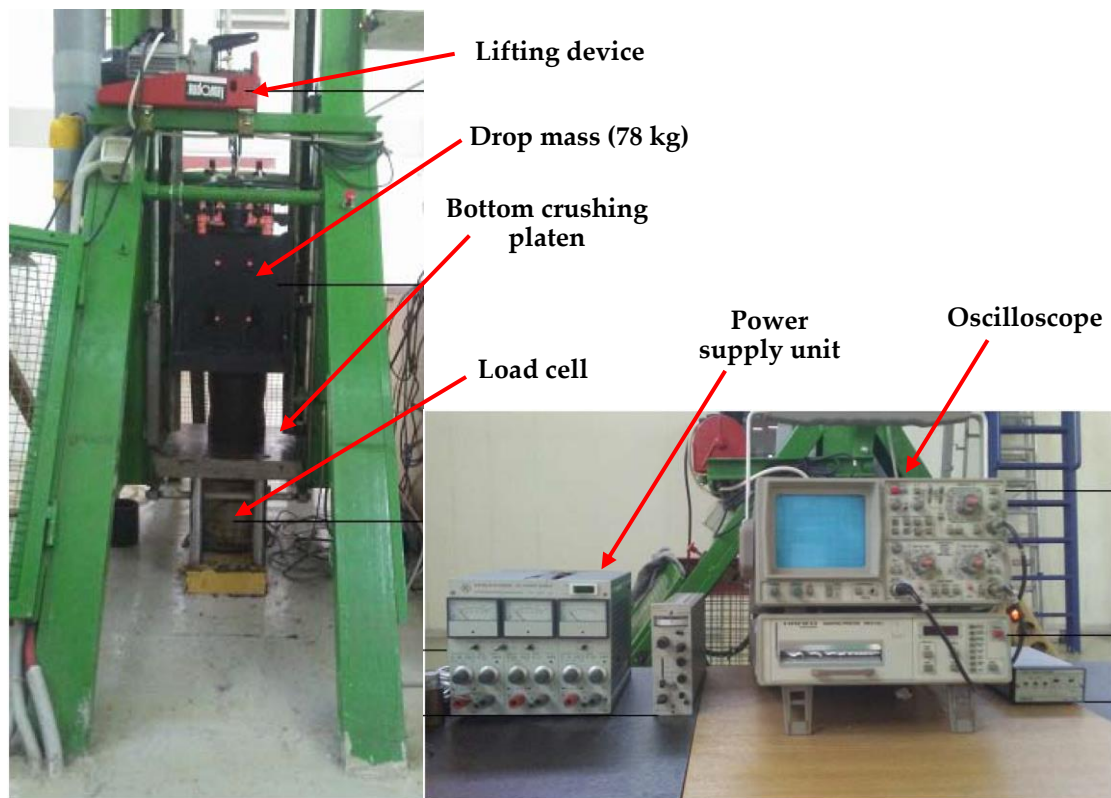


Figure 6. Experimental equipment for the quasi-static tests (**top**, Instron 4482 universal testing machine) and the dynamic tests (**bottom**, conventional 78 kg drop-hammer).

4. Crashworthiness Parameters

To evaluate the crashworthiness performance of a structure, crushing tests on specimens are conducted and force–displacement curves are produced. Useful parameters (i.e., crashworthiness parameters), that further aid evaluation and facilitate comparisons, can be extracted by processing the data obtained from the tests and curves. Two representative force–displacement curves for metallic (ductile material) and composite (brittle material) thin-walled tubes under quasi-static axial loading conditions along with the most common crashworthiness parameters are shown in Figure 7. The crashworthiness parameters are detailed as follows.

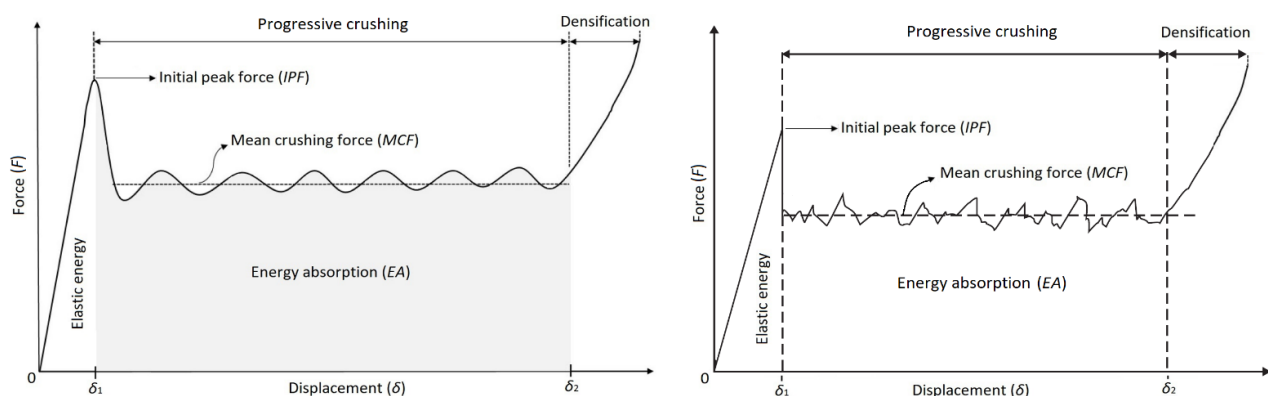


Figure 7. Typical force–displacement curves for uniform metallic (**left**) and composite (**right**) thin-walled tubes crushed progressively under quasi-static axial loading.

- Initial peak force (*IPF*) is defined as the first force peak in the force–displacement curve. The displacement δ_1 corresponds to *IPF* and marks the initial wall buckling of the tube and the beginning of the energy dissipation process.
- $F_{\max}$ is the maximum force achieved during the test. In the case of uniform non-triggered thin-walled tubes (i.e., non-tapered tubes with constant wall thickness) under quasi-static axial crushing conditions, $F_{\max}$ usually coincides with *IPF*.
- Energy absorption (*EA*) is the non-recoverable energy during the test and corresponds to the area under the force–displacement curve, from δ_1 until the displacement that marks the beginning of the densification region (δ_2):

$$EA = \int_{\delta_1}^{\delta_2} F(\delta) d\delta, \quad (1)$$

where F is the reaction force of the structure at any δ . The elastic energy is usually negligible compared to *EA*, therefore, the lower limit of the integral is very often replaced with zero in such cases.

- Mean crushing force (*MCF*) is defined as the ratio of the *EA* and the displacement from δ_1 until δ_2 :

$$MCF = \frac{EA}{\delta_2 - \delta_1}, \quad (2)$$

in the cases where there is no densification region and $\delta_1 \rightarrow 0$, the denominator $\delta_2 - \delta_1$ can be replaced with the total crushing displacement (δ_T). *MCF* is a crashworthiness parameter that allows comparisons among the energy absorption ability of structures that have been crushed at different δ_T s.

- Specific energy absorption (*SEA*) is defined as the *EA* over the specimen mass swept by the crushing platen (i.e., δ_T). The expression for uniform tubes of multiple layers from different materials is given below:

$$SEA = \frac{EA}{\delta_T \times \sum \rho_i A_i}, \quad (3)$$

where ρ_i and A_i are the material density and the cross-sectional area of each layer, respectively. *SEA* is an important design parameter in applications where the weight of the structure is essential.

- Crush force efficiency (*CFE*) is defined as the percentage ratio of *MCF* over $F_{\max}$:

$$CFE = \frac{MCF}{F_{\max}} \times 100\%, \quad (4)$$

If *CFE* reaches 100% the curve between δ_1 and δ_2 becomes a straight line parallel to the displacement axis (Figure 7) and the structure demonstrates ideal crashworthiness behaviour.

5. Results and Discussion

5.1. Collapse Patterns

For all the specimens apart from GFRP–AL 407, which first formed a horizontal crack at approximately $L/3$ from the bottom end, the collapse front formed at one end (Figures 8–11). Collapse initiation at one end is quite common irrespective of the material when the tube ends are simply supported [33,37,38]. This is usually attributed to unavoidable boundary imperfections, such as the non-uniform contact of the tube ends with the crushing platens. Manufacturing imperfections can be anywhere in the specimen; however, those at the boundaries seem to affect collapse initiation the most.

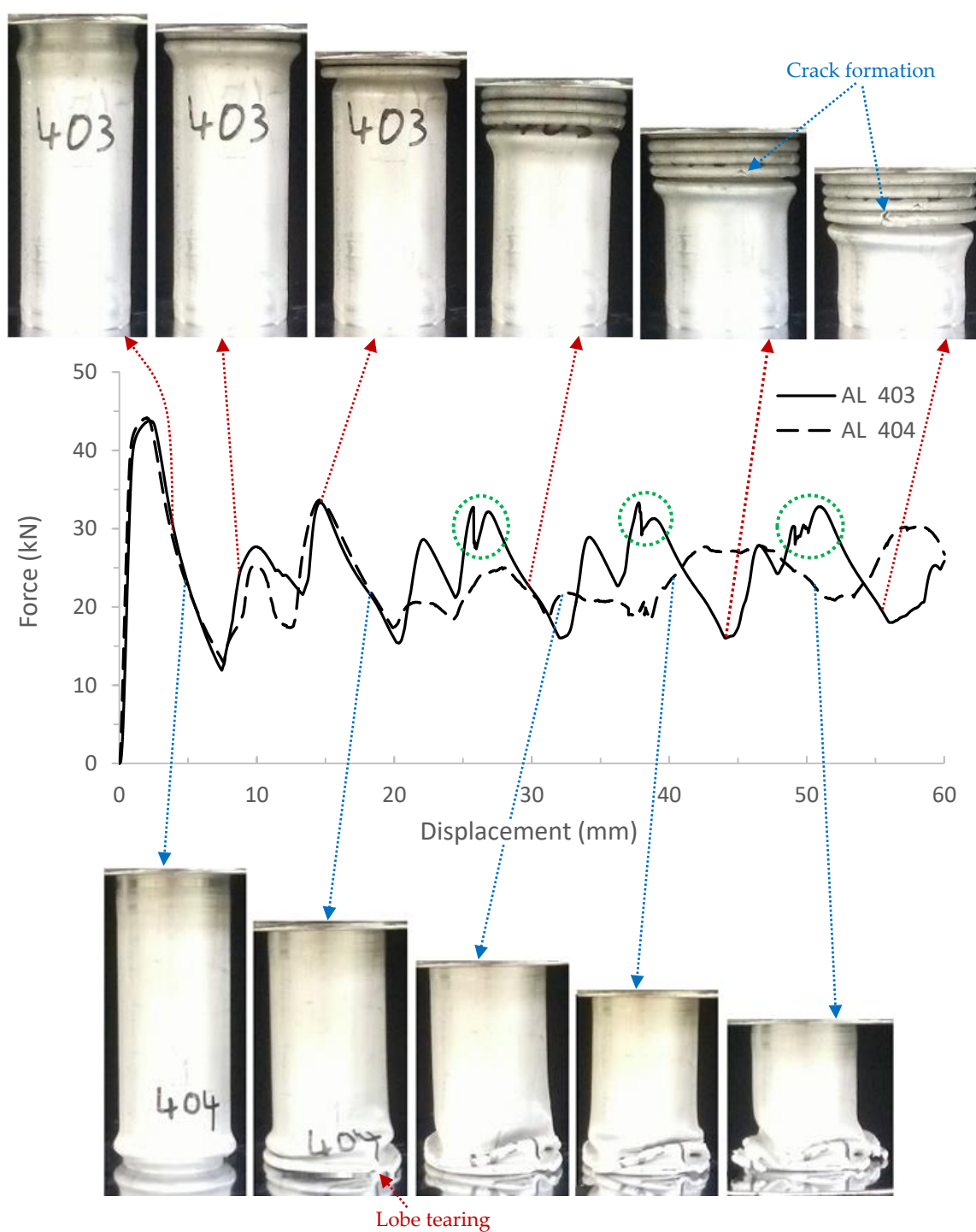


Figure 8. Views of progressive collapse and force–displacement curves of the aluminium (AL) specimens. The green dotted circles correspond to microcrack formation of the specimen wall.

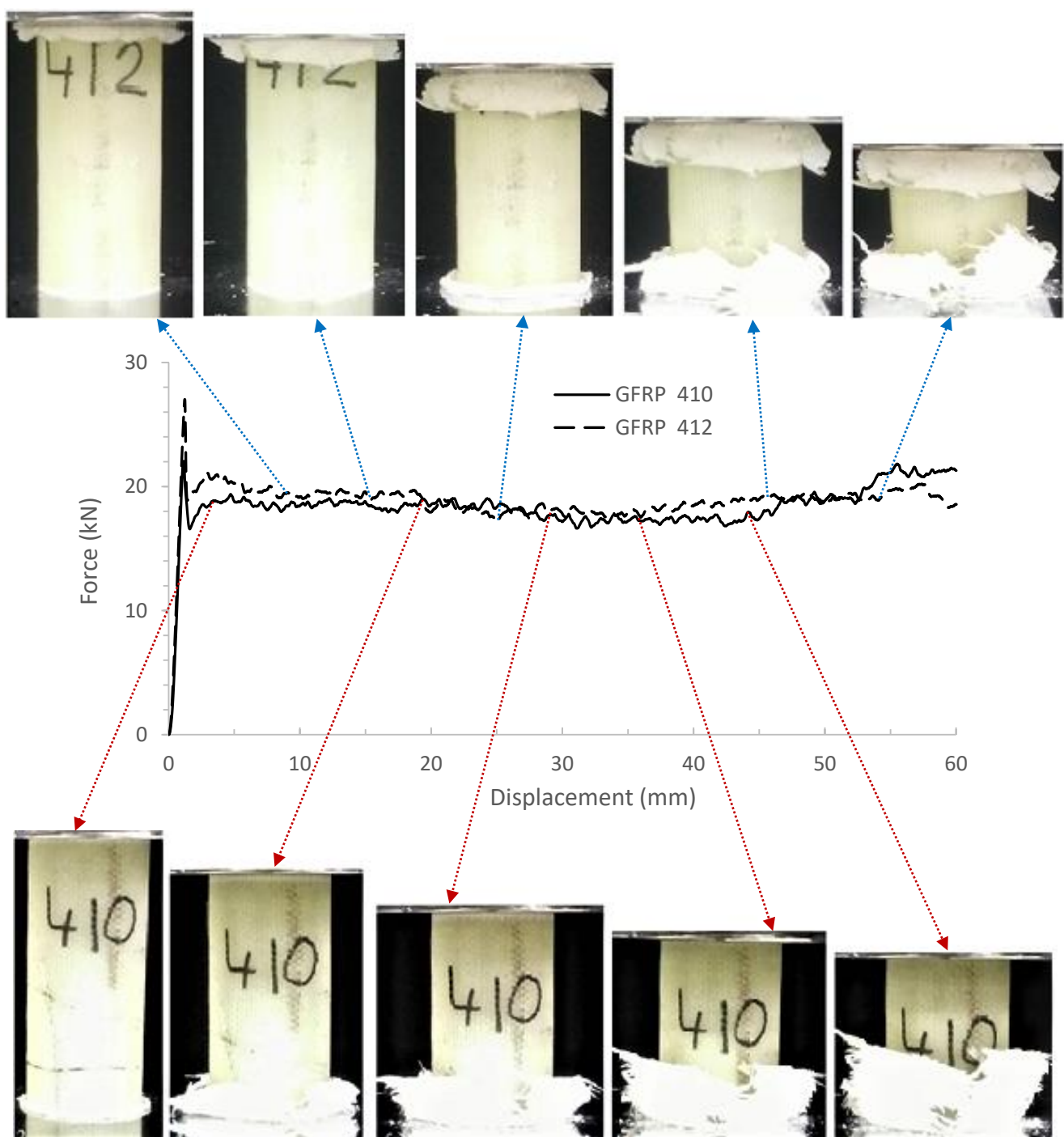


Figure 9. Views of progressive collapse and force-displacement curves of the GFRP specimens.

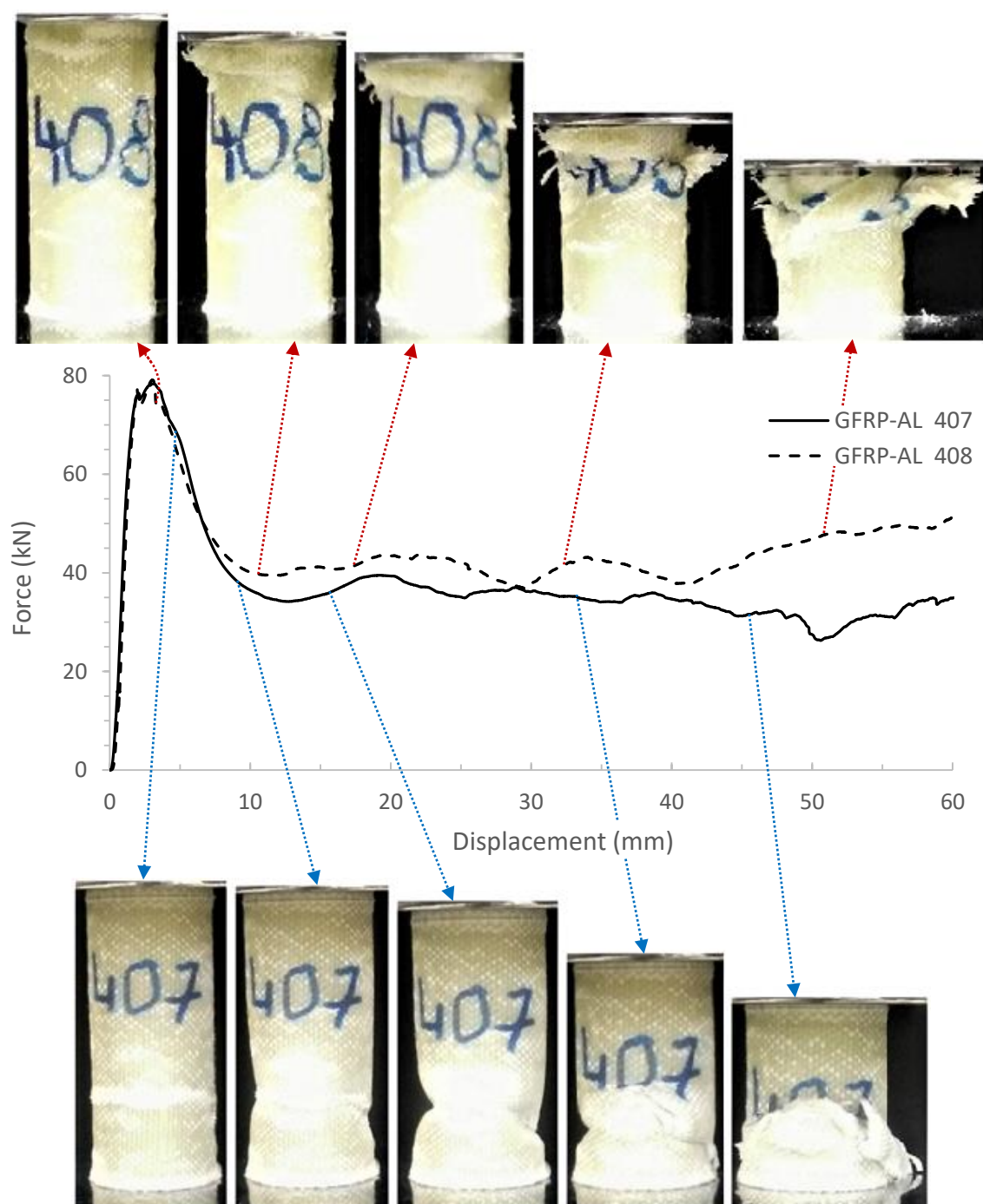


Figure 10. Views of progressive collapse and force–displacement curves of the GFRP–AL specimens.

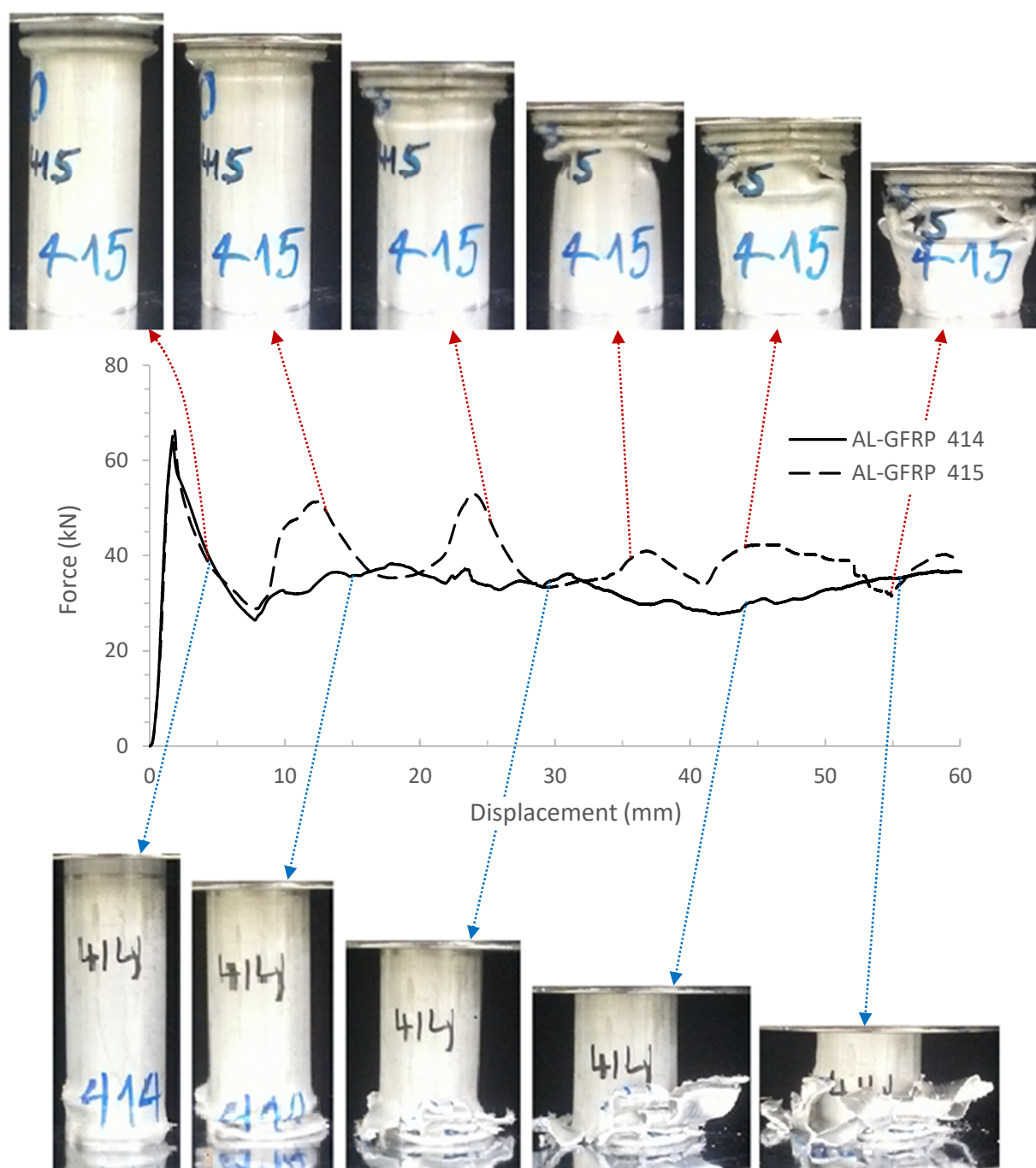


Figure 11. Views of progressive collapse and force–displacement curves of the AL–GFRP specimens.

As discussed in Section 1, metallic thin-walled tubes under low speed axial compression can either collapse in concertina, diamond, or mixed modes. According to both Andrews et al. [21] and Guillow et al. [22] mode classification charts (Figure 12) all four specimens should have collapsed in concertina mode, but only three of them did so (AL 401–403, Figure 13). AL 404 initially formed an axisymmetric ‘ring’ (1st axial lobe) but very soon the pattern switched to 2-D (2nd axial lobe), see Figure 8 bottom. This transition was attributed to the tearing of the first lobe during the formation of the second, which weakened the lobes’ common boundary and thus, aided the transition to 2-D. At greater crushing displacements multiple wall cracks formed and spread over the crushed zone, which resulted in the amorphous collapse pattern shown in Figure 13. Wall cracks were also observed in AL 403 (Figure 8 top), but not developed in wall tearing as in AL 404.

The cracks in AL 403 formed at intermediate lobes where the preceding lobe kept them from tearing, and thus, from affecting the pattern of the subsequent lobe. Such cracks, however, were not observed in dynamic tests (AL 401 and AL 402, Figure 13), which indicates that AA6063-F at moderately elevated strain rates may depict some improved ductility characteristics.

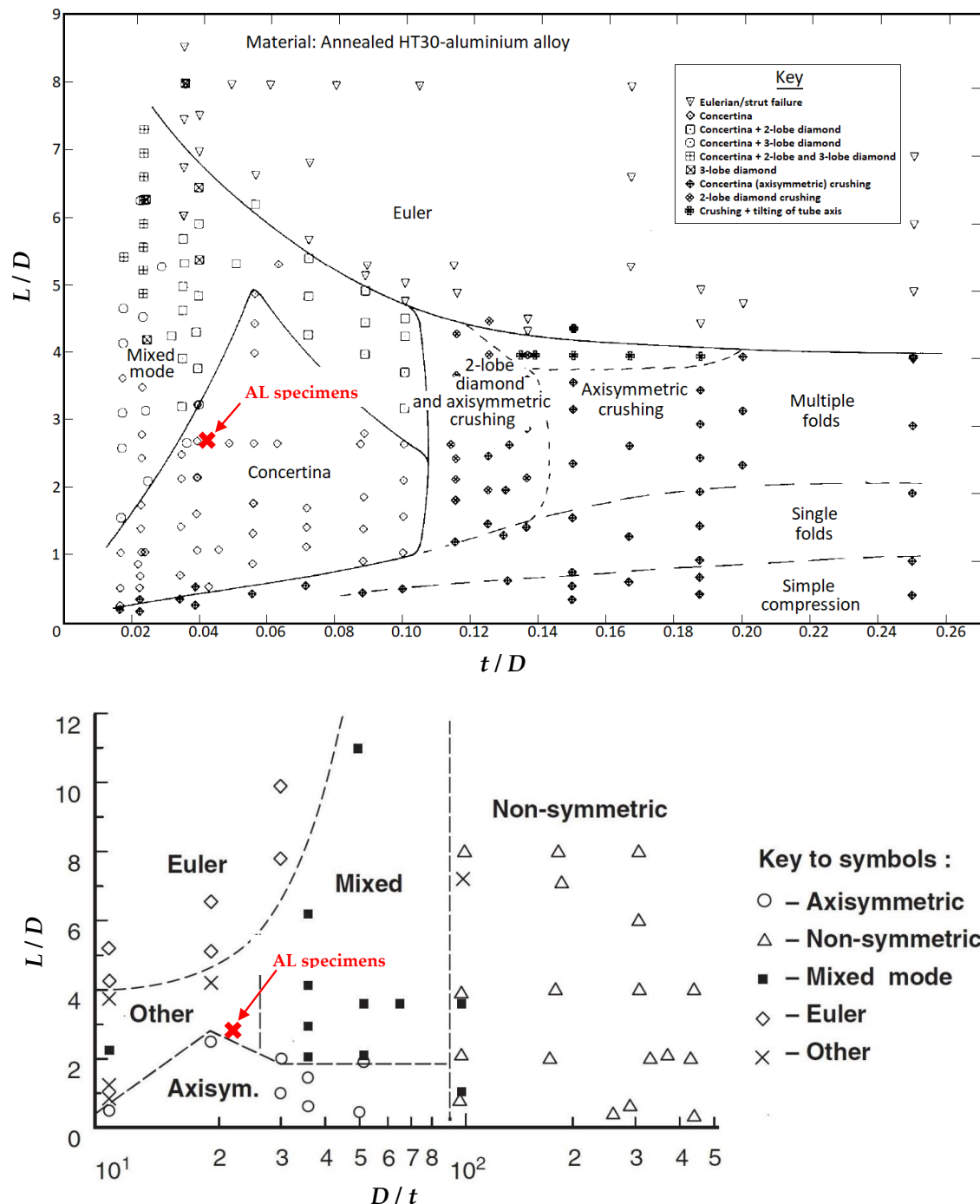


Figure 12. Andrews et al. [21] (top) and Guillow et al. [22] (bottom) deformation mode classification charts for aluminium alloy circular tubes under low-speed axial compression (L , D and t refer to the tube axial length, diameter and wall thickness, respectively). Reprinted with permission from References [21,22]. Copyright (1983, 2001) Elsevier.

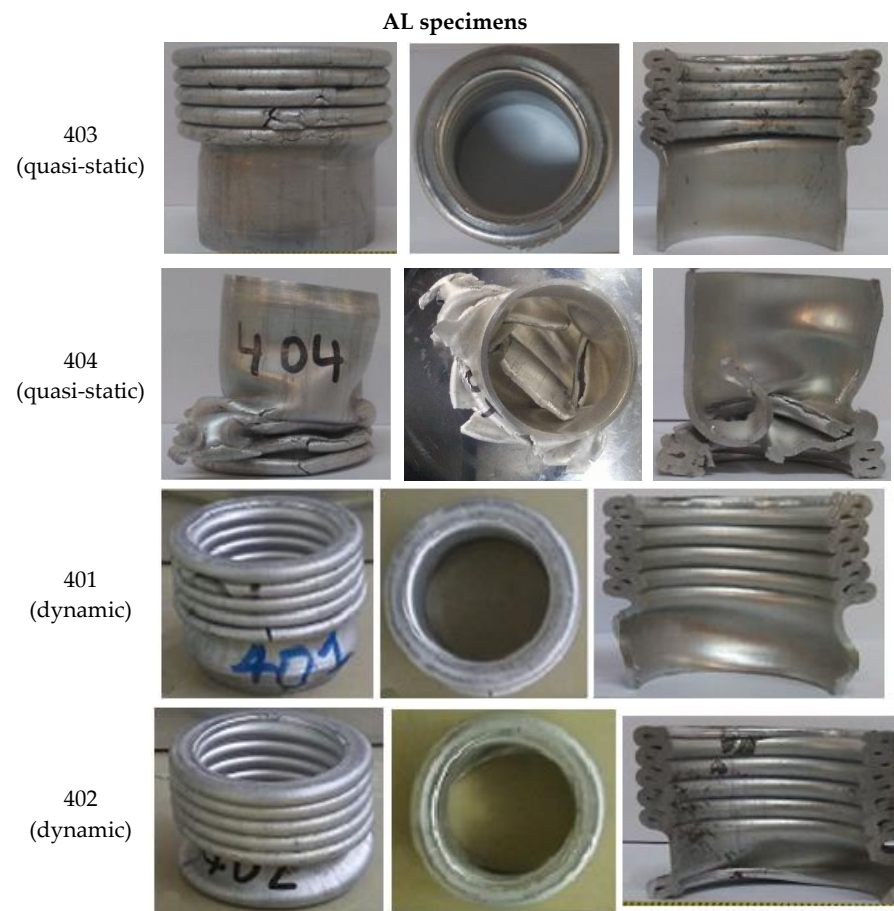


Figure 13. Final views of the aluminium (AL) specimens.

The GFRP specimens (410 and 412) collapsed in mode Ia ‘mushrooming’ (Figure 14), which has been found to be the most efficient collapse mode for composite tubes in terms of energy absorption [5]. This mode is characterised by progressive crushing due to micro fragmentation of the composite wall and the formation of fronts that bend inwards and outwards due to debris wedge penetration (Figure 14). Dynamic tests of the GFRP specimens were not conducted due to the technical difficulties mentioned in Section 3.

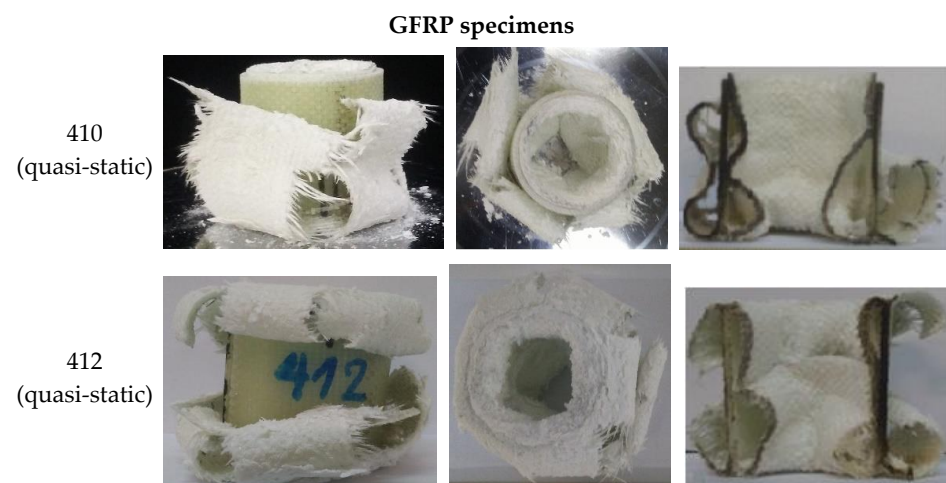


Figure 14. Final views of the GFRP specimens.

The hybrid configurations (GFRP–AL and AL–GFRP) demonstrated distinct collapse patterns that were relatively dissimilar to those of the AL and GFRP specimens and without any obvious sensitivity to the loading speed (Figures 13–16). As expected, the GFRP layers bent either inwards (mode Ib for AL–GFRP specimens) or outwards (mode Ic for GFRP–AL specimens) due to the restrictive action of the aluminium layer, which prevented GFRP layer to collapse in mode Ia as the GFRP specimens did. Contrariwise, the patterns of the aluminium layers were not that easy to categorise. Wall fracture was observed in all hybrid specimens due to the relatively low ductility AA6063-F in conjunction with the restrictive action of the GFRP layer. AL–GFRP 415, however, managed to form two axisymmetric lobes followed by two 2-D lobes (Figure 11 top)—a pattern that, to some extent, resembles the mixed mode of metallic tubes.

GFRP–AL specimens

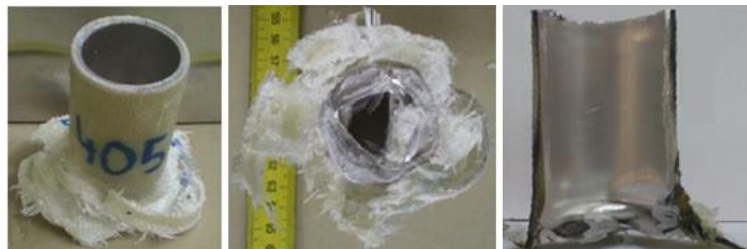
407
(quasi-static)



408
(quasi-static)



405
(dynamic)



406
(dynamic)



Figure 15. Final views of the hybrid GFRP–AL specimens.

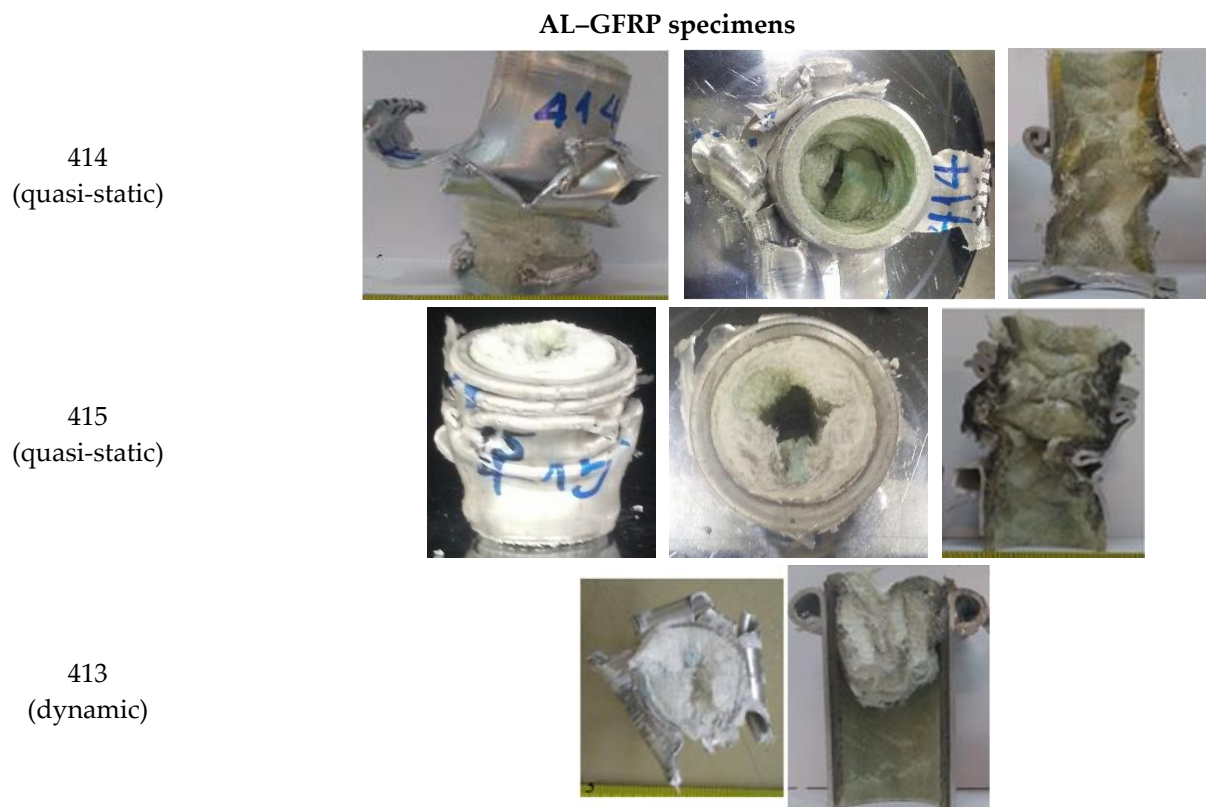


Figure 16. Final views of the hybrid AL–GFRP specimens.

5.2. Force–Displacement Curves

5.2.1. Quasi-Static Tests

The ‘teeth shaped’ force peaks in the force–displacement curve of AL 403 (Figure 8 green circles) corresponded to microcrack formation of the aluminium wall during lobe formation. Apart from that, the curve had the typical characteristics of metallic tubes progressive collapse, such as consecutive post-buckling force fluctuations that mark the formation of axial lobes. The curve of AL 404 was almost identical to that of AL 403 until $\delta \approx 20$ mm, where the first lobe fractured (Figure 8 bottom). For greater δ s, AL 404 experienced wall tearing to some extent along with lobe formation, as opposed to AL 403 where no wall tearing was observed, and therefore, its curve followed a separate path of less ‘canonical’ force fluctuations.

Although GFRP 410 formed a single collapse front (at the bottom end) while GFRP 412 formed two (at both ends), the curves of both GFRP specimens were very consistent (Figure 9). Their morphology depicted the typical characteristics associated with the progressive collapse of woven GFRP tubes, such as the sharp initial peak followed by an almost constant resisting force along the entire crushing displacement [33].

For the greatest part of the crushing displacement, the curves of the two GFRP–AL specimens were also schematically close to each other (Figure 10). Their form was dissimilar to that of the AL and GFRP specimens (Figures 8 and 9); however, there were some similarities that may indicate the influence of their constituent materials. For example, the first peaks were as rounded as that of the AL specimens, which perhaps denotes a greater effect of the aluminium layer during the first collapse stages, while the post-elastic force was almost constant like in the case of the GFRP specimens. However, the post-elastic curve of GFRP–AL specimens was less abrupt than that of the GFRP specimens. It seems that the layer of aluminium—as a ductile material—smoothens the force microfluctuations due to the fragmentation collapse mechanism of the brittle GFRP layer [5].

An almost stable post-elastic force was also observed in AL–GFRP 414, but the initial peak was much sharper in this case (Figure 11). Likewise, the curve of the other specimen of the same configuration, AL–GFRP 415, followed virtually the same path until $\delta \approx 8$ mm, but it continued forming force fluctuations similar to those observed in the AL specimens. However, in this case each force peak corresponded to an external lobe and there were no force peaks for the internal lobes, as opposed to the AL specimens where every other peak (the higher ones) corresponded to external lobe formation. Contrariwise, the weakened (by tearing) aluminium layer of AL–GFRP 414 allowed the GFRP layer to dictate the form of the curve and demonstrate a roughly stable post-elastic force. In the case of AL–GFRP 415, the aluminium layer kept its integrity, collapsed progressively (in mixed mode), dictating the morphology of the curve by forming post-elastic force fluctuations.

As discussed above, the forms of the initial peaks of AL–GFRP (sharp) and GFRP–AL (rounded) specimens were similar to that of the GFRP and AL specimens, respectively (Figures 8–11). It seems that the external layer of such hybrid configurations weakens first (as it has room to expand in the radial direction as opposed to the internal layer) allowing the internal layer to dictate the curve morphology at the first collapse stages.

5.2.2. Dynamic Tests

The dynamic force–displacement curves of the hybrid specimens were similar to that of the AL specimens until $\delta = 30$ –40 mm, Figure 17. This could be attributed mostly to the aluminium layer of the hybrid configurations rather than the GFRP layer, because in similar loading conditions composite tubes usually depict force–displacement curves of much ‘denser’ fluctuations (Figure 18).

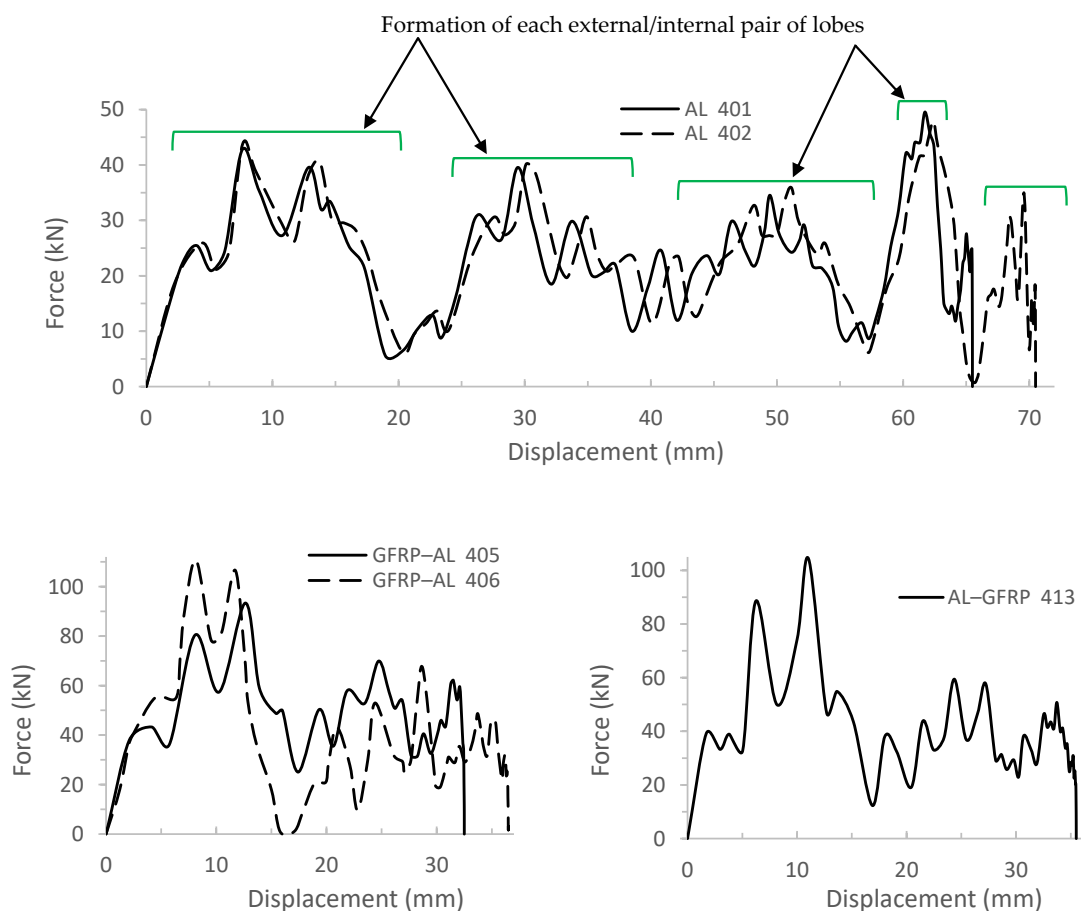


Figure 17. Force–displacement curves of the dynamic tests.

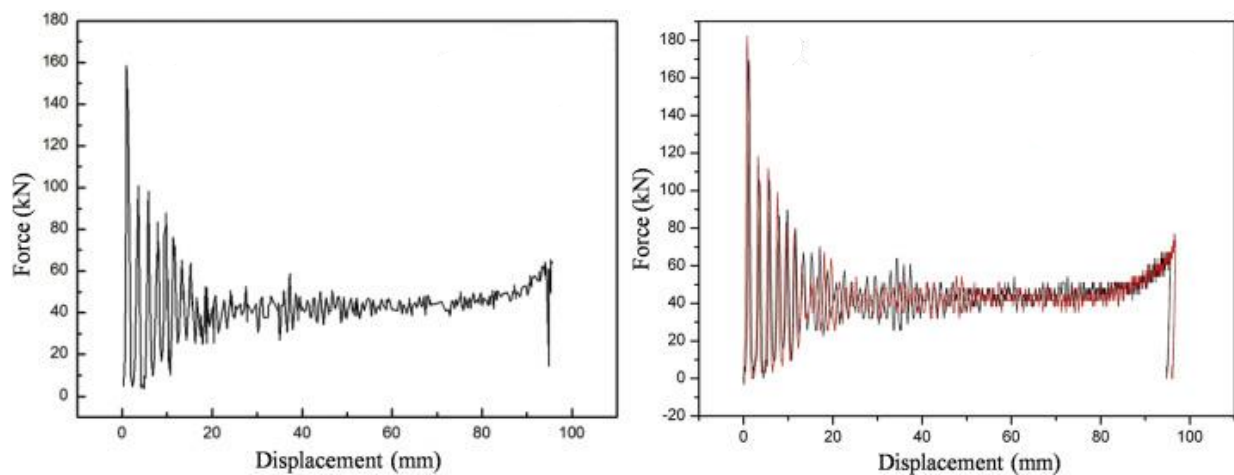


Figure 18. Force–displacement curves of woven CFRP tubes under dynamic axial loading of 10.2 m/s (Reprinted with permission from Reference [39]. Copyright 2016 Elsevier).

As opposed to the static tests, the initial peak force (*IPF*) was not the maximum force ($F_{\max}$) (Figures 8–11 and Figure 17). $F_{\max}$ was the 2nd–4th force peak in the case of hybrid specimens, while in the case of AL specimens the $F_{\max}$ was measured much later, at circa 2/3 of the total crushing displacement. Perhaps, if the drop mass was adjusted to produce similar total crushing displacements, $F_{\max}$ would have corresponded to similar crushing displacements.

The curves of the AL specimens exhibited some periodicity of force peaks grouped together (Figure 17). Five groups were identified that happened to coincide with the number of the internal/external lobes (Figures 13 and 17 top). The hybrid specimens also showed some signs of such periodicity but it was less pronounced, perhaps, due to the much smaller crushing displacement achieved during the dynamic tests, and the hybridisation of materials with dissimilar crushing curves.

5.3. Crashworthiness Parameters

Apart from exceptions, the crashworthiness parameters between the two specimens of the same configuration (AL, GFRP, AL–GFRP or GFRP–AL) and loading conditions (quasi-static or dynamic) were relatively close to each other (Table 2). Therefore, to facilitate comparisons, charts of their mean values were created (Figure 19). For the same reason an additional column (AL + GFRP) was created that represents the combined crashworthiness parameter of the AL and GFRP specimens (i.e., as if they were a single energy absorber of two separate non-interacting tubes).

5.3.1. Initial Peak Force and Maximum Force

As discussed in Section 5.2, the initial peak force (*IPF*) and the maximum force ($F_{\max}$) coincided in the quasi-static tests, but in the dynamic tests the picture was different (Figure 19 top). Not only was *IPF* unequal to $F_{\max}$ in the dynamic tests, but the ‘dynamic’ *IPF* was also noticeably smaller than the ‘quasi-static’ *IPF*. However, the dynamic $F_{\max}$ was greater than the quasi-static $F_{\max}$, although this increase was much less obvious in the AL specimens. This yields that low dynamic loading conditions may increase the maximum force during the test, but they reduce the elastic limit of such tubes.

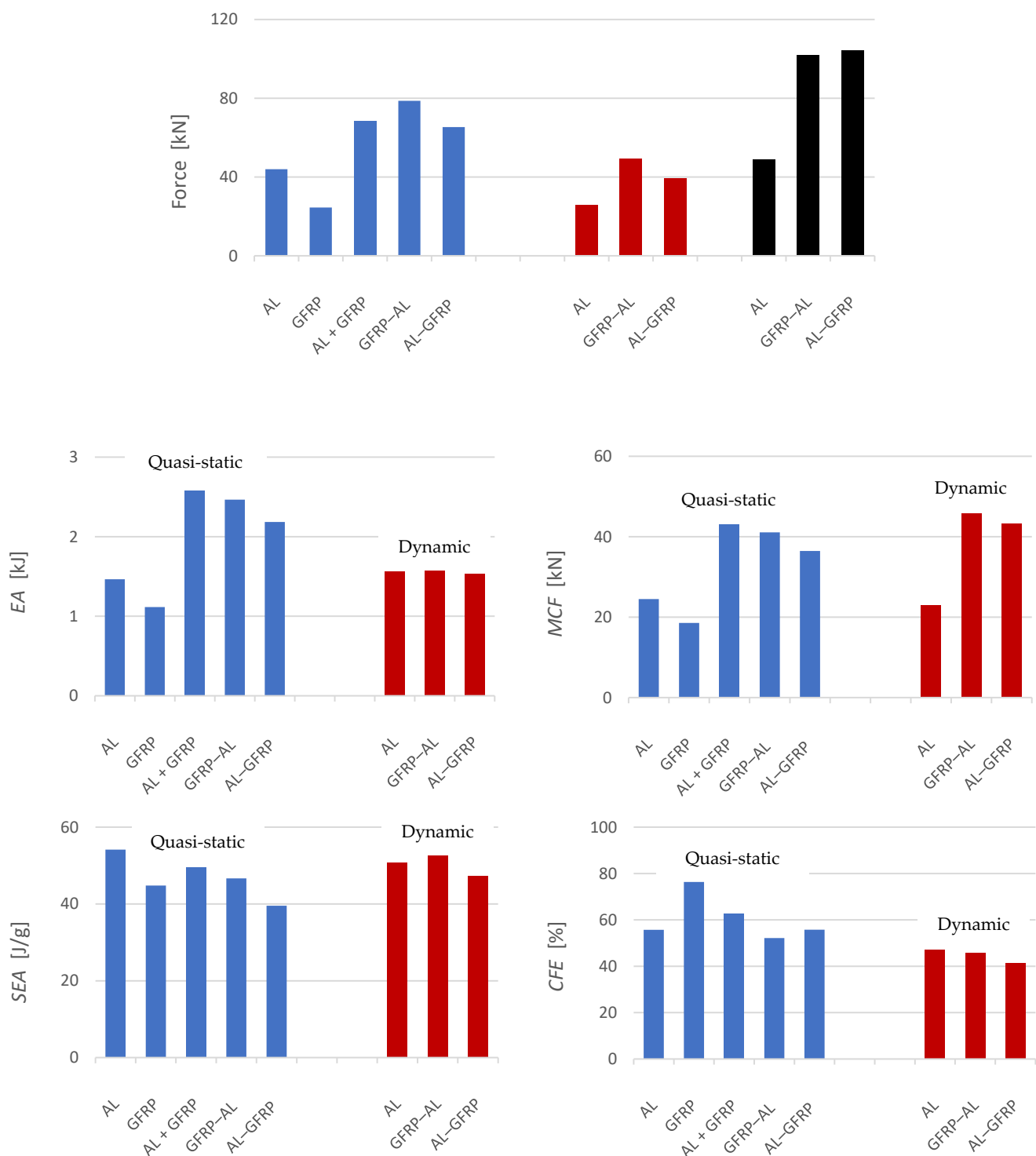


Figure 19. Crashworthiness parameters of the specimens tested. The left (blue) and right (red) stack of columns in each chart refer to the quasi-static and dynamic tests, respectively. The ‘AL + GFRP’ column represents the combined crashworthiness parameter of the AL and GFRP specimens as if they were a single energy absorber of two separate tubes that do not interact with each other. The columns represent the mean values between the two specimens of the same configuration (AL, GFRP, AL-GFRP and GFRP-AL).

The GFRP-AL configuration exhibited a noticeable greater *IPF* than that of the AL-GFRP configuration in both dynamic and quasi-static tests. This seems unexpected since the GFRP and aluminium masses and the aluminium layer slenderness (i.e., mean diameter to wall thickness ratio) in both hybrid configurations were roughly the same, while the

GFRP layer in the GFRP–AL configuration was more slender than that in the AL–GFRP configuration—the *IPF* of the AL–GFRP configuration should have been greater. However, this normally applies to specimens free from inconsistencies. In this case, the GFRP layers of both hybrid configurations may have built from the same fabric (same material and dimensions), but the AL–GFRP specimens ended up with a smaller fibre volume fraction (Table 2). The inflatable mandrel (AL–GFRP specimens, Figure 5), was unable to match the pressure induced by ‘hand-rolling’ (GFRP–AL specimens) on the GFRP layer and discard the excessive resin to achieve similar fibre volume fractions in both configurations. As a result, the AL–GFRP fibre volume fraction was smaller, fibre micro buckling became easier and thus, the *IPF* values between the two hybrid configurations were inconsistent.

However, GFRP–AL configuration exhibited even greater *IPF* values than the sum of the *IPFs* of the AL and GFRP specimens (AL + GFRP column in Figure 19 top), although, the latter had virtually the same dimensions and fibre volume fraction as those of the corresponding layers of the GFRP–AL specimens (Table 2). This was attributed to the interlayer bonding achieved during the fabrication process of the GFRP–AL specimens (Section 2), which tended to increase the wall bending stiffness over the sum of the bending stiffnesses of their constituent layers. As a result of the increased bending stiffness, the GFRP–AL specimens demonstrated a greater elastic buckling resistance and thus greater *IPF* values.

5.3.2. Energy Absorption

In terms of *EA*, the hybrid configurations underperformed compared to their constituents when crushed independently at quasi-static conditions (see, the AL + GFRP versus AL–GFRP and GFRP–AL columns in Figure 19 middle). The layer interaction effect seems to have reduced the *EA* capacity of the hybrid specimens rather than enhancing it, which contradicts the findings of previous similar studies [40,41]. The interlayer friction that usually develops during crushing in multi-layered configurations indeed dissipates some of the kinetic energy, however, the layer interaction prevented the aluminium and GFRP layers from collapsing in the most *EA*-efficient modes (i.e., concertina and mushrooming) as the AL and GFRP specimens did when crushed independently (Figures 13–16). It seems that the interlayer friction was unable to equal the *EA* loss due to the non-ideal collapsing mechanisms of the layers, and thus, the hybrid configurations ended up absorbing less energy.

Although at first look the GFRP–AL configuration seems to perform better than the AL–GFRP configuration (Figure 19 middle), the *EA* values of the specimens overlap with each other, and thus no clear observation on which configuration performs better can be made (Table 2). However, it seems safe to say that the hybrid specimens of each configuration that demonstrated excessive tearing of the aluminium layer (GFRP–AL 407 and AL–GFRP 414) absorbed less energy than their counterparts of the same configuration (GFRP–AL 407 and AL–GFRP 415), see Figures 15 and 16 along with Table 2 (quasi-static loading condition). These findings agree with observations of previous studies that have linked wall tearing of metallic tubes as a less *EA*-effective collapse mechanism [42].

In dynamic conditions, on the other hand, the drop mass and height, as well as the apparatus were the same among the tests, therefore, all specimens absorbed virtually the same energy.

5.3.3. Mean Crushing Force

The morphology of the *MCF* and *EA* charts (Figure 19) was the same under quasi-static conditions because the crushing length was chosen to be the same among all specimens. Therefore, the discussion around the specimens’ quasi-static behaviour is the same as that in the previous section.

Comparing the results of the quasi-static and dynamic tests, the *MCF* of the hybrid configurations increased under dynamic conditions. The dynamic response of the aluminium layer could not be held responsible for this increase, because not only the *MCF* of

the AL specimens slightly decreased under dynamic conditions, but also previous studies on circular tubes have found that AA6063 is essentially strain rate insensitive up to 118 s^{-1} [43]. On the other hand, the energy dissipation ability of GFRP tubes has been found to increase under dynamic loading conditions [44]. Therefore, the authors attributed this increase to the dynamic response of the GFRP layer, which, apart from the beneficial influence of the mass inertia, could perhaps have been enhanced further by the increase of layer interaction effect with respect to the strain rate.

As in the case of *EA* no clear observation can be drawn on which hybrid configuration (GFRP–AL and AL–GFRP) performs better because the values of the specimens overlap (Table 2).

5.3.4. Specific Energy Absorption

AL specimens outperformed both the GFRP and hybrid specimens in the quasi-static tests (Figure 19). The findings seem to contradict the already established merits of composite tubes, namely that they dissipate larger amounts of energy per unit mass than their metallic counterparts [4]. This inconsistency was attributed to the hand lay-up technique used, which resulted in relatively small fibre volume fractions (Table 2) and perhaps air bubbles trapped inside the composite. However, GFRP specimens managed to perform equally well as those of the hybrid configurations.

As a result of considering the mass, the *SEA* values of the hybrid specimens do not overlap as in the cases of *EA* and *MCF* (comparing quasi-static and dynamic loading conditions separately, Table 2). The aluminium and glass fabric masses were the same between the two hybrid configurations; however, the AL–GFRP configuration was heavier because it absorbed more resin as a result of the fabrication method (see, explanation in Section 5.3.1). This time it is safer to assume that the AL–GFRP specimens underperformed compared to their GFRP–AL counterparts in both quasi-static and dynamic loading conditions (Figure 19). However, the converse should have been true since the tube mass is concentrated closer to the axis of the AL–GFRP specimens, and all specimens collapsed progressively. This inconsistency was again attributed to the smaller fibre volume fraction of the AL–GFRP specimens which resulted in less robust walls with respect to their mass, and thus in smaller *SEA* values.

Compared to the quasi-static tests, the *SEA* performance of both hybrid configurations increased in dynamic loading conditions for the same reasons outlined in the previous section. However, this time the best performing configuration was the GFRP–AL, as a result of the AL specimens' trend to slightly decrease their energy dissipation ability at moderately elevated strain rates (Section 5.3.3).

5.3.5. Crush Force Efficiency

Although both GFRP specimens were free from triggers, they managed to achieve *CFE* values over 65% in quasi-static conditions, outperforming by far the other configurations (Figure 19 and Table 2). Once again, the hybrid configurations were unable to match the combined performance of the AL and GFRP specimens (AL + GFRP column), mostly due to the very good performance of the latter.

Compared to the quasi-static tests, the dynamic *CFE* values dropped for all configurations. This indicates, based on the definition of the *CFE* (Equation (4)), that the $F_{\max}$ (denominator) increase for each configuration was greater than the *MCF* (nominator) increase under dynamic conditions.

It is common to introduce geometrical imperfections, such as chamfered ends, as an attempt to increase the *CFE* values of the examined tubular structure. Such imperfections aim to reduce the *IPF*, and thus can only be efficient in the cases where the *IPF* coincides with $F_{\max}$. However, in this study *IPF* coincided with $F_{\max}$ only in the quasi-static tests, while in dynamic conditions the $F_{\max}$ occurred after the first force peak (Figure 17). This indicates that the relatively poor performance of the hybrid configurations under real collision events is hard to be improved by such modifications.

6. Conclusions

Aluminium (AA6063-F), GFRP (woven E-glass/epoxy) and hybrid aluminium/GFRP tubular structural components were tested under both quasi-static and dynamic axial compression to investigate their crashworthiness performance. The external and internal layers of the two hybrid configurations were respectively made of aluminium and GFRP (AL–GFRP specimens), and vice versa (GFRP–AL specimens). The dimensions (and thus the masses) of the aluminium (AL) and GFRP specimens were roughly the same as those of the corresponding layers of the hybrid configurations. The quasi-static and dynamic tests were respectively conducted on a universal testing machine at a prescribed crosshead speed of 10 mm/min, and a conventional 78 kg drop hammer released from 2.5 m. The main conclusions can be summarised as follows:

- The AL and GFRP specimens (i.e., the non-hybrid configurations) respectively collapsed in concertina and mushrooming modes—the most efficient collapse modes for metallic and composite tubular energy absorbers.
- The hybrid specimens were unable to match the combined crashworthiness performance of AL and GFRP specimens (i.e., as if they were a single energy absorber of two separate non-interacting tubes). This was attributed to the disadvantageous layer interaction that prevented each layer to collapse in its efficient mode.
- The tests on the hybrid configurations revealed that even small deviations in the fibre volume fraction can affect the specific energy absorption values and, to a much greater extent, the *IPF* values of the GFRP tubes.
- The energy absorption ability of the hybrid configurations improved in dynamic conditions. It was attributed to the beneficial strain rate sensitivity of the GFRP layer rather than of the aluminium layer (AA6063-F) which exhibited a small decrease in crashworthiness parameters.
- The GFRP specimens outperformed the other configurations in terms of crush force efficiency (*CFE*) reaching values over 65%.
- The *CFE* of the AL and hybrid specimens decreased in dynamic conditions. Considering the definition of *CFE*, this decrease indicates that the $F_{\max}$ strain rate sensitivity was greater than that of *MCF* for the layouts tested.

This comparative study showed that there is no practical interest to macroscopically hybridise AA6063-F and woven E-glass/epoxy into two-layered tubular structures. However, a different outcome could be obtained if more advanced fabrications methods were used, such that to achieve greater fibre volume fractions of the GFRP layers.

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