Lateral Compression after Impact of GFRP Composite Pipes

T.A. Sebaey, E. Mahdi

Abstract**—**Composite materials are currently used in several application, including aeronautic marine and piping. Composites are well known for its specific strength and stiffness however, its tolerance under out-of-plane loading is one of the disadvantages. Impact can dramatically reduce the load carrying capacity down to 30%. The topic is well characterized for flat plates but for tubes it is not. In the current paper, glass/epoxy pipes is laterally compressed after being impacted using Charpy impact tester. The value of the impact energy ranges from 41 J to 171 J. The load-carrying capacity under lateral compression is used to assess the damage tolerance of the composite pipes.

Keywords**—**Composite; Pipes; Damage Tolerance; Impact; Compression.

I. Introduction

Due to properties such as good corrosion resistance, durability and high strength-to- weight ratio, glass-fiber reinforced plastic (GRP) are being used in many diverse industries including aeronautical structures, automotive structures, off-shore marine applications, chemical processing and pressure piping. Recently, fuel cell vehicles adopt composite vessels as hydrogen storage [1]. If an external object strikes a composite structure in the direction perpendicular to a surface, it can degrade both its static and fatigue load-bearing capacity [2]. Low-velocity impacts arise from situations such as accidental dropping or, for example, of hand tools, producing local indentation and delamination. These are often difficult to detect, but it is important to assess the extent of such damage and its effects on structure properties, since it can result in premature failure. However it is easier to be detected, higher velocity events can be more severe on the structural performance. Example of high velocity impact is the impact of a stone on the car or aircraft body [3]. Therefore, there is a need to understand the impact behavior of these materials/structures in order for them to be safely and effectively driven into the ground [4].

Studies have generally focused on plate and beam structures. Few studies were carried out on the performance of composite pipes and tubular structures [5]. However the response of tubes under impact is expected to be different than that of the monotonic plates [6].

The residual properties after impact are of interest for the structural applications. After impacting square tubes, Guades and Aravinthan [7] measured the tensile, compression and flexural properties of Coupons taken from the specimen walls. Results showed that the levels of impact energy, number of impacts, and the mass of the impactor significantly influenced the residual strength degradation of the impacted tubes. For the test matrix tested in [8], the residual properties were also addressed in [9]. About 25% reduction in the load carrying capacity was monitored within the examined impact energies. Corbett and Reid [10] compared the static and dynamic tests and studied the effect of the impact energy on the burst strength of glass/epoxy pipes. They concluded that the damage tolerance of GFRP pipes is very low as compared to steel tubes due to the excessive matrix cracking at very low impact energy. Deniz et al. [5] studied the effect of impact energy on the fatigue life of a pre-conditioned (short and medium time aging under seawater) glass/epoxy pipes. The results showed that fatigue life increased in the impacted specimens up to 3 months in seawater immersion then it decreased by increasing the immersion time. The effect of low velocity impact on the maximum internal pressure was investigated in [11]. More than 50% reduction in the leak pressure was reported by increasing the impact energy from 0 to 10 J. The burst strength after impact was also addressed by Kara et al. [12] and Uyaner et al. [13]. According to the results, as the striking velocity increases, the largest contact force, contact time interval, displacement, quantity of energy absorbed by the material and the extent of damages on the specimens increase too. Moreover, it was found that the increase in impact energy causes decreases in the value of burst pressure of the tubes. The residual burst strength was also addressed by Wakayama et al. [14]. It is clarified that the primary cause of the degradation of residual burst strength is fiber breakage caused by microbuckling. Mortas et al. [15] impacted carbon/epoxy and kevlar/epoxy tubes after immersion in hydrochloric acid and sodium hydroxide and assessed the degradation of the residual bending strength. The results showed huge reduction (down to 30%) in the residual bending strength as a function of the concentration of the corrosive media.

Composite pipes are continuously subjected to impacts; either during storage and transportation, installation or in-service. For most of the pipeline setups, pipes are being subjected to lateral compression. In the current state of the art, it is hard to find a study fully characterized the composite pipes under compression after impact. This is the main

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motivation for the current study. The composite pipes were firstly impacted using the Charpy impact testing machine. The history of the impact load and energy was not recorded because it was not of interest for the authors. The most interesting was the residual load carrying capacity after impact with known impact energy. For symmetry, each pipe was impacted 4 times (equal intervals on the Circumference) with the same impact energy.

II. Experimental Procedure

The commercially available wounded GFRE tubes were subjected to ignition in order to define the constituent materials volume fractions and the fiber orientations of the individual plies. The tests were conducted on 9 test specimens of different places along the tube according to the ASTM D3171 test standard [16]. The average value of the fiber volume fraction was 61.1% with a coefficient of variation of 6.7%. The fiber orientation of the whole cross-section was ±56°. The average tube wall thickness was 11.8 mm with inner and outer diameters of 111.7 mm and 88.0 mm, respectively. The tubes were then cut into specimens of 50 mm width for the impact tests.

The Charpy impact test is a standardized high strain-rate test which determines the amount of energy absorbed by the material during fracture. The apparatus consists of a pendulum of known mass (14.325 kg) and length (812.6 mm) that is dropped with an impact angle to impact specimens. The energy transferred to the material, in the case of fully specimen fracture, can be inferred by comparing the difference in the height of the hammer before and after the fracture (energy absorbed by the fracture event). In our case the mass and impact angle were selected to create damage to the pipe wall (indentation and delamination) without perforation. The impactor mass (*m*) were kept constant during this study. Four values of the impact angle (α) were considered. The impact angles and the corresponding impact properties (height *h*, velocity *v* and energy *E*) are shown in Table I.

TABLE I
IMPACT EVENT CONFIGURATIONS

$\alpha°$	h (m)	v (m/s)	E (J)	i (mm)
120	1.219	4.891	171.342	5.365
90	0.813	3.994	114.284	4.652
70	0.535	3.241	75.241	3.524
50	0.291	2.389	40.892	2.216

The induced indentation (*i*) on the specimen impacted surface is also listed in Table 1. The indentation value, at each impact energy, is the average of measurements taken for three specimens. As it can be noted from the readings, the indentation value is decreasing by reducing the impact energy. This notice is of agreement with the indentation results available in the literature for composite plates (see for example the results presented by Sebaey et al. [17]).

The damage on the tube surface due to the impact is shown in Fig. 1. Visually, the damage is localized at the impact point and includes fiber and matrix damage. At 171.3 J impact energy ply splitting can be noticed at the impact side. No back face splitting occurs within the range of the applied impact energies. This is due to the wall thickness of the tube [18, 19].

Fig. 1 Visual observations of the specimens after impact

Quasi-static compression tests were carried out using an Instron 8500 digital-testing machine with a full-scale load range of 250 kN. Steel platens were set parallel to each other prior to the initiation of the test. Three tests were conducted for each configuration for data reproducibility. The average of the three tests was undertaken. The acquisition system of the universal testing machine recorded the load-displacement data at a constant cross head speed of 15 mm/min. More details of the test set up can be shown in [20, 21]. The effect of the impact energy was also investigated. The four levels of impact energies listed in Table 1 were used with the impact configuration to examine this effect. The failure load was recorded as the compression after impact load. This load corresponds to the first decrease in the load-displacement diagram and is associated to the appearance of the first delamination.

III. Results and Discussion

The load corresponding to first drop in the load-displacement diagram, during compression after impact, is considered as the failure load and can be shown in Fig. 2 as a function of the impact energy. The error bars show the degree of repeatability of the tests. At least three specimens were tested at each impact energy. The maximum value of the coefficient of variation was 13.2% recorded for the specimens pre-impacted with 171.34 J. This value is acceptable as a standard experimental error.

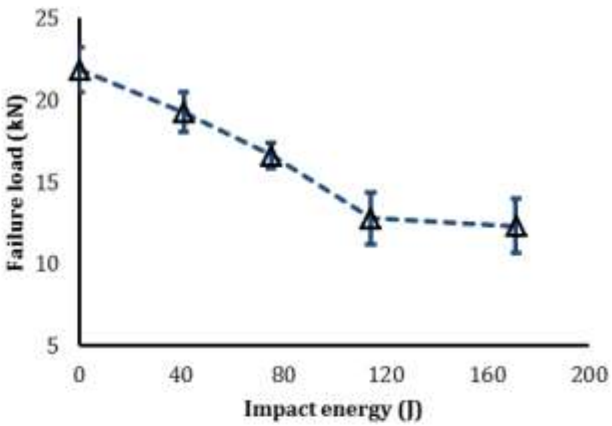


Fig. 2 Failure load as a function of the impact energy.

As it can be shown in Fig. 2, the maximum (failure) load under compression is highly dependent on the impact energy. The failure load dropped from 23 kN to 13 kN due to the impact event. Similar results were reported for monotonic plates (see for example the results presented by Sebaey et al. [17]). After 120 J impact energy, it seems that the failure load was kept constant at almost 13 kN. The reason for that is the saturation of the damage inside the tube during the impact event. This means that these 120 J were mostly consumed in delamination. Any extra Joules were consumed in local indentation damage mechanisms (matrix plasticity and cracking and fiber breakage).

The energy absorbed under compression loading can be shown in Fig. 3 as a function of the impact energy. The trend is very similar to the ones we experienced for monotonic plates however, quantitatively, less impact energies can produce more effects in the case of monotonic plates due to the geometrical effect. Very limited effect is shown when moving from 0 J to 40.9 J. This means that the impact induced delaminations, at this impact level, are small and not connected through the thickness. After 40.9 J, higher effect can be shown on the energy absorbed by the specimens in different damage mechanisms. This reduction is a result of the reduction in the failure load (see Fig. 2).

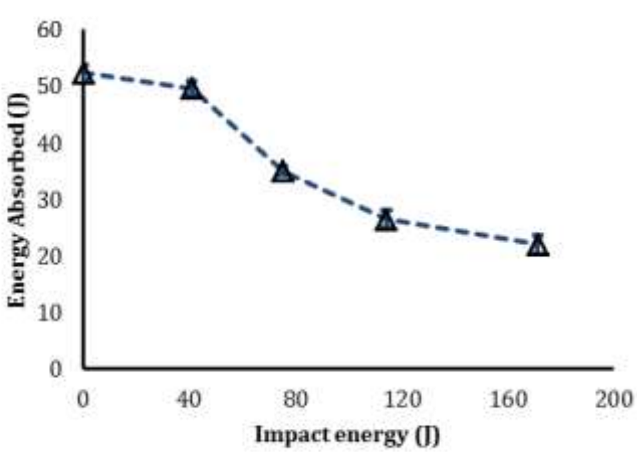
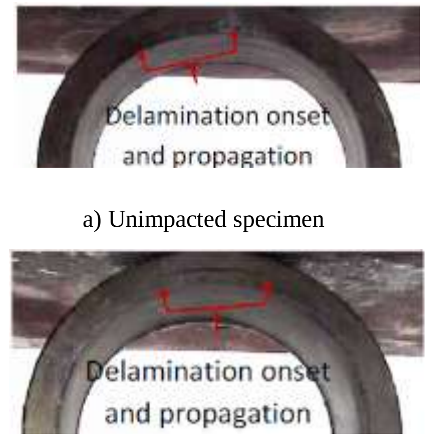


Fig. 3 Energy absorbed as a function of the impact energy.

For all the specimens, the damage onset under compression was the same. The effect of the impact energy on the damage initiation is insignificant. Fig. 4 shows the delamination initiation under compression for two different specimens. The images show that the main damage mechanism under the compression platen is the delamination with some matrix cracking that joins the different delamination interfaces. It is expected that these cracking were formed after several delamination.



a) Unimpacted specimen

a) Impacted specimen with 171.34 J

Fig. 4 Damage initiation

IV. Conclusions

This paper studied the effect of the impact energy on the damage initiation of GFRP tubes/pipes. The damage can be a result of installation or in-service impact event. The tubes were cut and impacted using Charpy impact tester with different impact angle to define different impact energies (0 J to 171.34 J). After being impacted, the specimens were laterally quasi-statically compressed up to the first drop in the load-displacement diagram which is being considered as the failure load.

The results showed that the effect of the impact energy is of great importance for the residual strength of the tube. More than 30% reduction on the failure load and the energy absorbed. With respect to the damage initiation, the results showed that there is no significant effect on the damage initiation and even propagation due to impact loading.

Currently, the GFRP are being used in piping however, unlike monotonic plates, the tolerance of the tubes of that material to impact loading is not well characterized. With the current result we aim to open the discussion about the tolerance of composite pipes to impact loading.

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