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Title: *Equi-energetic Low-velocity Impact Effects on the Compression After Impact Strength of Carbon Fiber Composite Tube Structures*

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ABSTRACT

This study explores the effect of equi-energetic low-velocity impact on the compression after impact (CAI) strength of tubular composite structures. The effects of equi-energetic impact energies are explored, where high-mass-low-velocity (HMLV) and low-mass-high-velocity (LMHV) test configurations are used at three impact energy levels using Instron CEAST 9350 impact test machine. Various tube diameters (76.2 mm and 101.6 mm) are also considered to achieve a better understanding of tube geometries on CAI residual strength.

The impact force-time graphs and force-displacement curves are used to analyze the impact responses and damage mechanisms. The results indicate that impact energy, impactor mass, and tube diameter play a significant role in impact response. The larger diameter tubes can withstand higher compressive loads regardless of impact damage, showing significant drops for smaller UT tubes while the larger diameter tube can maintain more of their compressive strength. This study provides insights into the behavior of composite tubes under LVI and highlights the importance of considering impact effects when evaluating the structural integrity and strength of composite materials.

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INTRODUCTION

Recently, composite tubular structures have been replacing traditional metal structures for load-carrying applications. It is well-known that composite materials are susceptible to impact damage and often cause a reduction in its strength. Impacts such as low-velocity impacts (LVI) often from tool drop and debris hits can cause damage to the structure causing matrix cracks, fiber breaks, and delamination. Often these damages may not be easy to observe, known as barely visible impact damage (BVID), although there can be internal damages which can cause the reduction in residual strength [1].

The residual compressive strength of composite tubes after damage was investigated by Ochoa *et al.* [2] and found that there was a significant drop in compressive strength due to localized damages. Zhang and Tan [3] explored the effects of LVI on the compression after impact (CAI) strength of tubular structures using hemispherical and cylindrical impactors. The hemispherical impactor caused more localized damage to the tubular structure and lead to a lower specific CAI strength in the composite tubes.

Impact responses for composites may be different under the same impact energy but with varying impact mass and velocity conditions, due to different impact duration and deformations [4]. These impacts are referred to as being equi-energetic. Zabala *et al.* [5] studied the influence of equi-energetic impacts on woven carbon fiber reinforced polymer (CFRP) samples and learned that higher velocities caused a greater delamination area in specimens. Equi-energetic impacts of composite laminates was also observed by Banik *et al.* [6] and found that the low mass-high velocity impacts cause more significant damage.

In this study, we experimentally investigate the effect of equi-energetic LVI on the impact response and residual CAI strength of CFRP composite tubular structures. Two different tube diameters are studied (76.2 mm and 101.6 mm). These tubes were impacted using the Instron CEAST 9350 drop tower. History data of force-time, energy-time, and force-displacement curves are used to analyze the effects of equi-energetic impact. Tubes are then subjected to compression tests to explore their residual CAI strength with particular attention on the effects of the equi-energetic impact.

EXPERIMENTAL METHODOLOGY

Material Configurations

The composite tubular structures consist of two different inner diameters, 76.2 mm and 101.6 mm. The different layup structures are shown in Figure 1. The smaller diameter tubes are labeled UT3, while the larger tubes are UT4. UT tubes are fabricated with a unidirectional carbon fiber with a twill outer layer. The unidirectional layers are oriented to provide the structure high bending stiffness and axial strength, while the outer twill layer provides a bias support layer and aesthetics. Tubular structures were cut to 300 mm in length for testing.

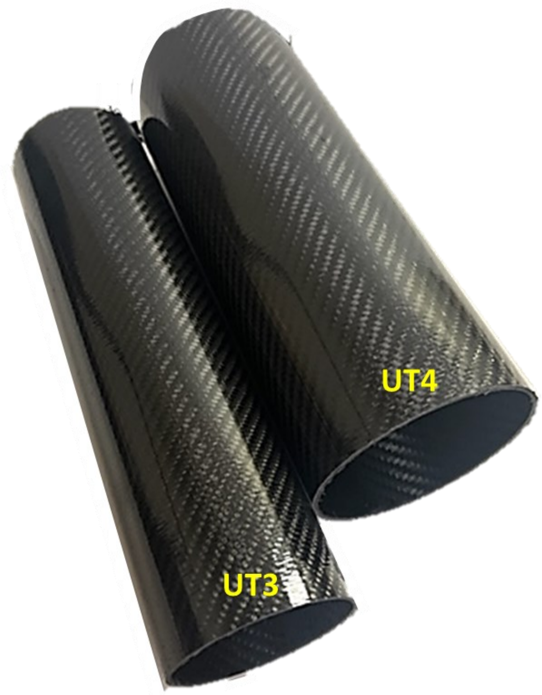

Figure 1. Tubular composite specimens used in this study.

Impact and Compression After Impact Test

Impact tests are carried out with Instron CEAST 9350 drop tower using a 16 mm diameter hemispherical striker, as shown in Figure 2. The samples are placed on a V-shaped support frame. Two impactor configurations are used to achieve the equi-energetic impacts: A low-mass-high-velocity (LMHV) impactor of 2.482 kg and a high-mass-low-velocity (HMLV) impactor of 12.482 kg. UT tubes are impacted with 10 J, 15 J, and 20 J impact energies. Test repeatability is confirmed with two specimens tested for each impact configuration.

After the impact tests, the CAI tests are conducted with the Instron 5582 universal testing machine with 100 kN load cell and MTS 793 with 667 kN capacity, shown in Figure 3. Tubes are compressed between two parallel steel plates with a 4 mm/min displacement rate.

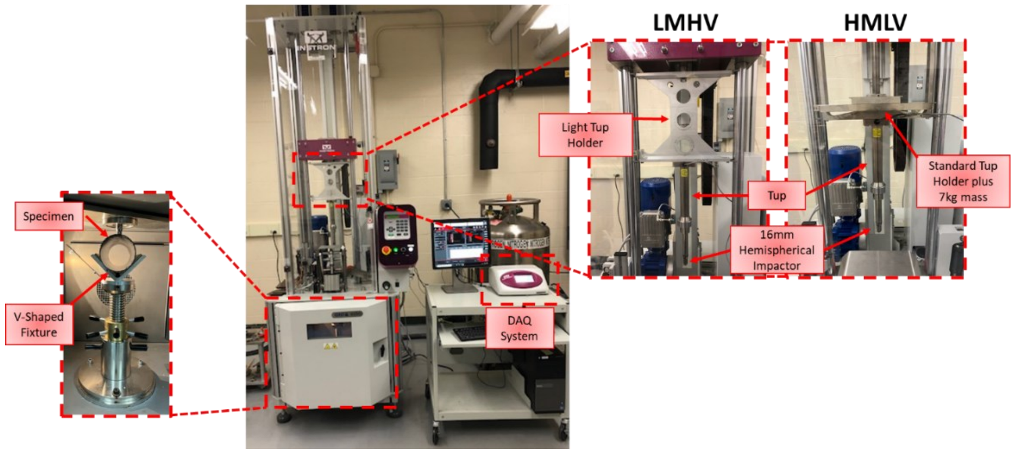

Figure 2. Impact test setup.

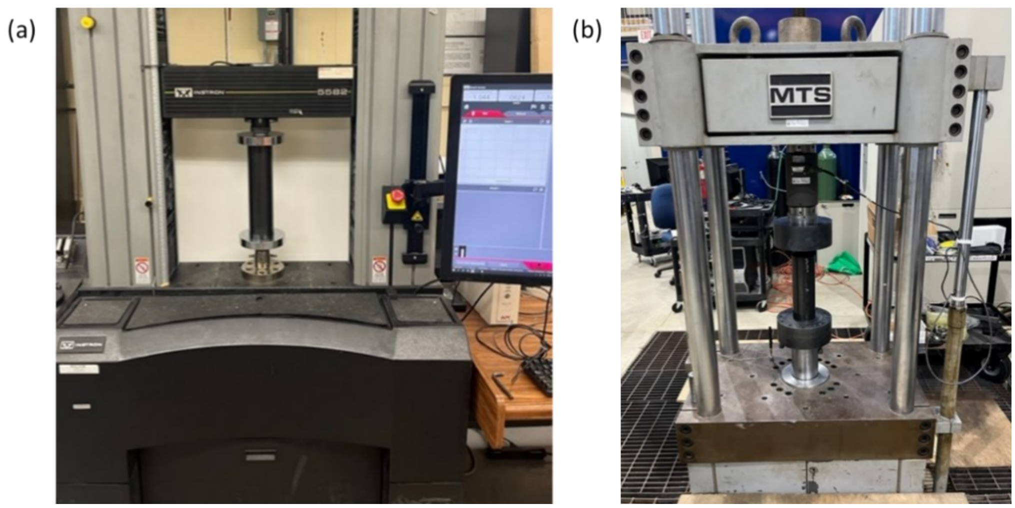

Figure 3. CAI test setup (a) Instron 5582 (b) MTS 793.

RESULTS AND DISCUSSION

Impact Damage Response

The impact force-time graphs for the UT tubes are presented in Figures 4-6. The diameter of the tubes appears to not affect the peak force of the impact. For 15 J and 20 J impacts in Figures 5-6, the UT4 tubes have less significant load drops indicating less overall damage to the structure. At 20 J, both diameter tubes were punctured by the impactor during the test, shown by the increasing force later in the impact of Figure 6 due to the shape of the impactor which is tapered towards the top. At low impact energy, visible impact damage to the UT tubes was in the form of matrix cracks in a cross pattern, but as the energy increased, fiber breaks until the puncturing occurred.

The difference in the mass-velocity configuration of the impactor plays a significant role in the impact response of the specimens. HMLV impacts have a much longer impact duration. At low impact energy, the duration almost triples in length from about

10 ms to 30 ms. There are also less severe oscillations in the force-time graphs suggesting less overall damage to the CFRP tubes under HMLV impact. In Figures 4-5, there is a difference in the response of HMLV events. The UT3 tubes have a load drop once the peak force is reached, while the UT4 tubes do not and have a much more symmetrical force-time graph shape showing again less damage. This sudden load drop is indicative of fiber failures in the composite structure.

Once the impact energy reaches a level that will induce puncturing of the tubular structure, there appears to be less of an effect on the impact response due to impactor configuration. Namely, the time in which the peak force is achieved is sooner for LMHV due to the fact the impactor has a higher velocity.

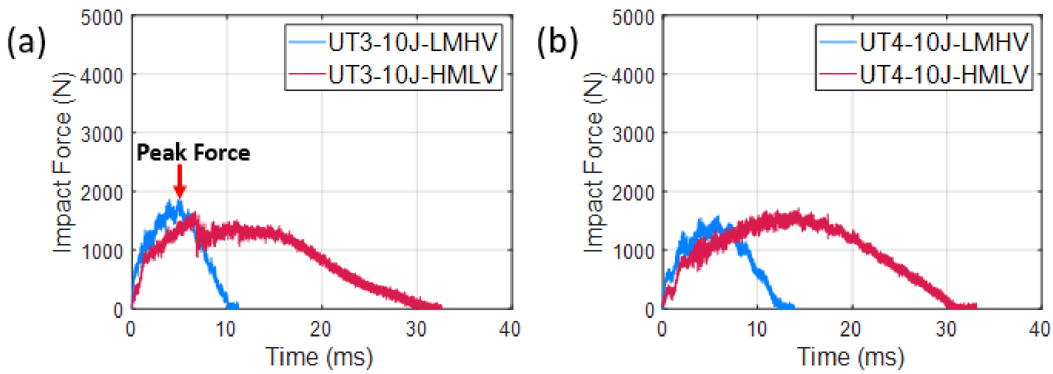

Figure 4. Force-time graphs of 10 J equi-energetic impacts of (a) UT3 and (b) UT4 tubes.

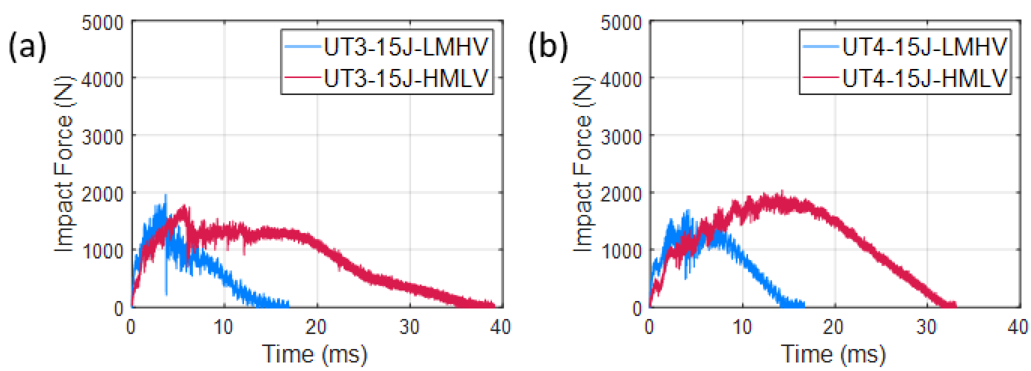

Figure 5. Force-time graphs of 15 J equi-energetic impacts of (a) UT3 and (b) UT4 tubes.

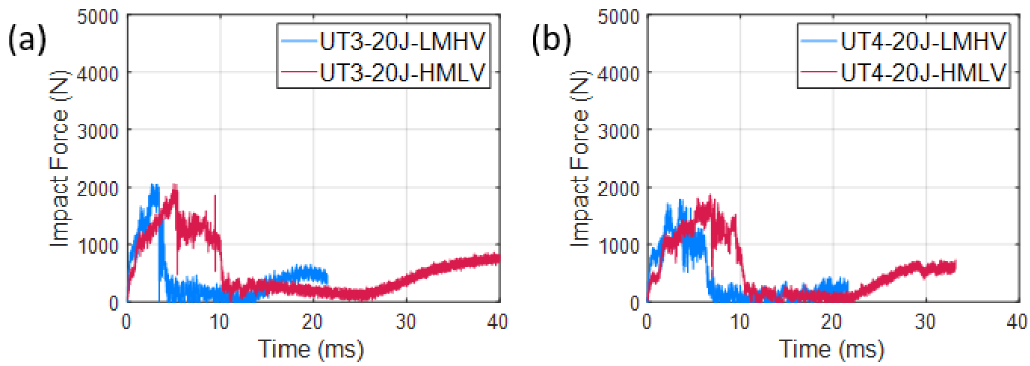

Figure 6. Force-time graphs of 20 J equi-energetic impacts of (a) UT3 and (b) UT4 tubes.

Compression After Impact Response

The CAI force-displacement plots for the UT3 and UT4 tubes are shown in Figures 7-9. The larger diameter tubes can withstand higher compressive loads regardless of impact damage. This difference is due to the larger undamaged span remaining for the larger diameter tube.

Figure 7(a) shows the force-displacement for UT3 and 10 J impact energy. There is a slight decrease in peak compression force for the LMHV case, while there is a greater drop of about 20 kN for the HMLV case. This reduction in strength indicates there was more damage induced on the HMLV tube at 10 J, which can be seen by the sudden load drop in the HMLV impact case in Figure 4(a) and not in the LMHV. The 15 J impact, shown in Figure 8(a), shows a decrease in residual compressive strength of both impacted tubes, with little difference between LMHV and HMLV. At high energy, Figure 9(a), there is a large decrease in residual strength of damaged tubes, as well as a significant difference between LMHV and HMLV. The tube impacted with the LMHV configuration fails at a lower peak force, indicating that more damage was induced during impact. At this energy level, the tubes were penetrated, leaving a hole in the specimens for CAI testing.

UT4 tubes impacted at 10 J appear to have no difference in the peak compressive strength, most likely due to the larger span of undamaged area. Although, the tube impacted with HMLV at peak force has a sudden load drop and fails completely. A similar trend is observable in Figure 8(b), where there is no significant difference in peak force of the damaged tubes compared to the pristine specimen. Both the LMHV and HMLV tubes have sudden failure at peak force in this case. Figure 9(b) shows the force-displacement of CAI test for UT4 at 20 J. Both HMLV and LMHV tubes have reduction in CAI strength and fail at the same displacement. There appears to be no significant difference in the equi-energetic impact of UT4 tubes.

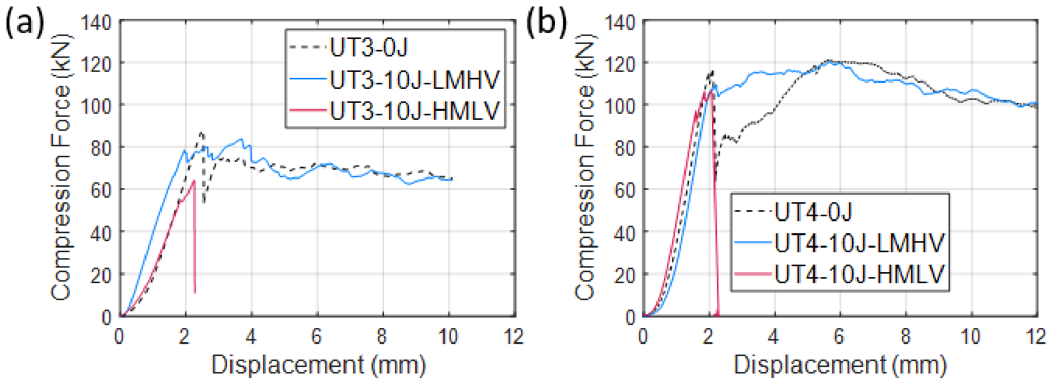

Figure 7. Force-displacement graphs of CAI test for (a) UT3 and (b) UT4 impacted at 10 J equi-energetic impact energy.

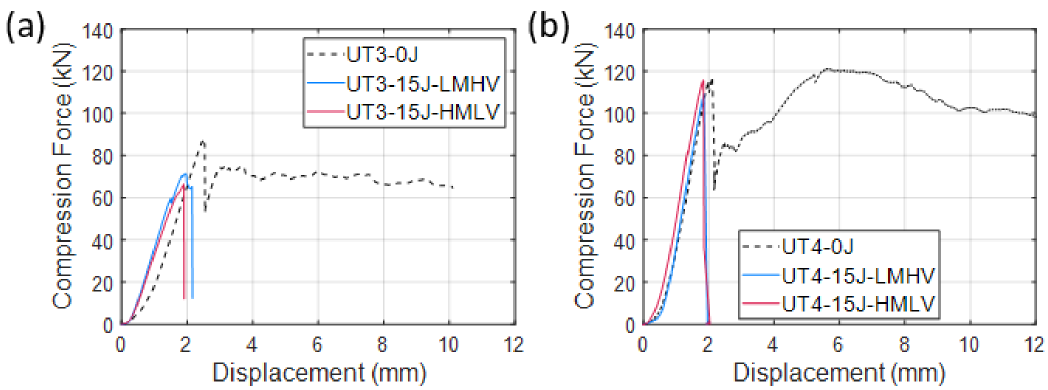

Figure 8. Force-displacement graphs of CAI test for (a) UT3 and (b) UT4 impacted at 15 J equi-energetic impact energy.

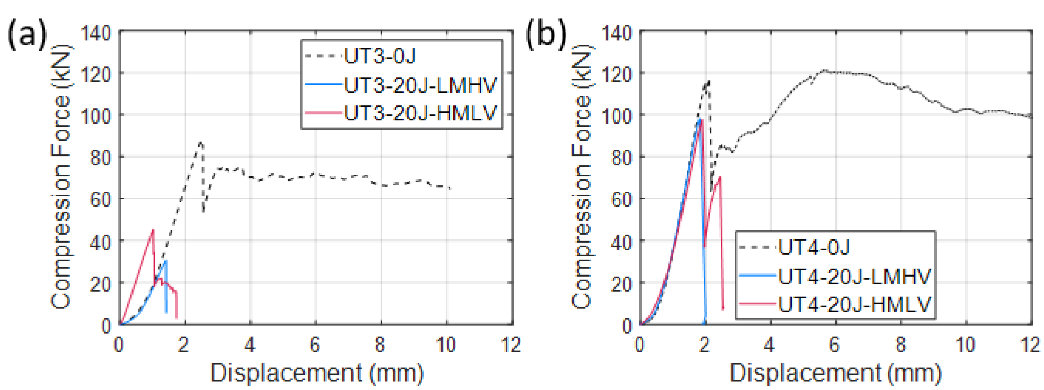

Figure 9. Force-displacement graphs of CAI test for (a) UT3 and (b) UT4 impacted at 20 J equi-energetic impact energy.

Compression After Impact Failure Mechanisms

Typical CAI failures occurred in either one of two modes: (1) end crushing at the grips or (2) collapse at the damage formation from impact. For UT tubes, the damage was typically more localized to the impact site, so the collapse would form at the midspan where the impact occurred. Although, for some UT4 tubes the crack would begin to propagate at the end of a longitudinal crack in the upper portion of tube. The crack would begin to propagate starting at the damage site where the tube is weakest and grow radially around the tube. End crushing at the grips occurs when the impact damage was not enough to induce the collapse failure. Figure 10 shows the CAI damage modes for the UT3 composite tubes. All tubes shown have a failure in the midspan except the LMHV at 10 J, shown in Figure 10(a), this is evident from the force-displacement curve in Figure 7(a) as there were no sudden load drops. Sudden load drops occurred for all UT tubes that failed by collapse.

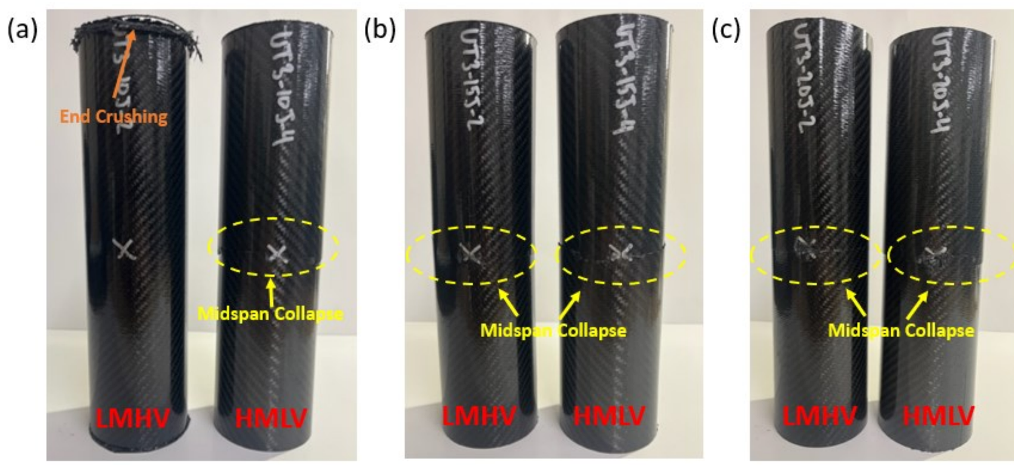

Figure 10. Post-CAI damage of UT3 tubes for LMHV and HMLV at (a) 10 J, (b) 15 J and (c) 20 J.

CONCLUSIONS

The study includes impact tests using a drop tower with two different impactor configurations: a low-mass-high-velocity (LMHV) impactor and a high-mass-low-velocity (HMLV) impactor. The impact force-time graphs and force-displacement curves are analyzed to evaluate the impact response and damage mechanisms. After impact tests, the tubes are subjected to compression tests to assess their residual CAI strength.

The results indicate that the impact response and residual CAI strength of the composite tubes are influenced by factors such as impact energy, impactor mass-velocity configuration, and tube diameter. Such configurations cause different amounts of damage to the tubular specimens, which also varies by the impact energy and tube geometry. The force-time graphs show the load drops and oscillations associated with impact-induced damage, such as matrix cracks and fiber breaks. The force-displacement curves in CAI tests reveal the reduction in compressive strength due to impact damage, showing significant drops for smaller UT tubes while the larger diameter tubes can maintain more of their compressive strength.

Overall, the study provides insights into the behavior of composite tubular structures under equi-energetic LVI and highlights the importance of considering impact effects when evaluating the structural integrity and strength of composite materials.

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