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Low Velocity Impact of Filament-Wound Glass-Fiber Reinforced Composite Pipes

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Abstract

Low velocity single-bounce impact tests have been conducted on filament-wound glass fiber reinforced/vinylester and glass fiber reinforced/epoxy composite pipes. An instrumented drop weight testing system was used for the impact testing. The tests were performed on 300 mm long sections of 150 mm diameter pipes having 6 mm wall thickness. The impact energy required to just initiate the damage in glass fiber reinforced/epoxy pipes was found to be larger than the energy needed for glass fiber reinforced/vinylester pipe. The load-time curves also reveal that vinyl ester-based pipes exhibit a ductile failure under impact, whereas, in the epoxy-based pipes the failure was rather brittle in nature.

Keywords: Low velocity impact; GFRP; Filament-wound pipes

Introduction

Although Glass Fiber Reinforced Plastic (GFRP) composites are known for high degree of tailor ability and many excellent chemical and mechanical properties, a major concern that limits the usage of GFRP composites is their low resistance to impact loading. Low velocity impacts can induce significant damage in the material in the form of matrix cracking, delamination, and fiber fracture. Very often these types of damages remain invisible to the naked eye, but may causes serious degradation in the otherwise excellent mechanical properties of the FRP composites and cause premature and unexpected failure. The response of composite materials to these impact loadings is complex, as it depends on the structural configuration as well as on the intrinsic material properties. Furthermore, it depends on the type of material, geometry, and velocity of the impactor. Each plays an important role in characterizing the overall effect of transverse impact.

Generally, impact with impactor speeds less than 100 m/s are classified as low velocity impact. But there are several other definitions of low velocity impact, with no universal agreement. Sometimes low velocity impact is used in the context of low energy impact, i.e., less than 136 J (100 ft-lb). Low velocity impact normally involves deformation of the entire structure during the contact duration of the impactor, and this situation is considered quasi-static with no consideration of the stress waves that propagate between the impactor and the boundary of the impacted component.

The effect of low-velocity impact damage on the FRP composites laminates and pipes has been studied by a number of researchers over the past several years [1-5]. It is well established that the impact damage occurs in two phases: fracture initiation phase, and fracture propagation phase where ratio of damage initiation energy to damage propagation energy is shown to be a function of material ductility as higher ductility exhibit higher initiation energy to propagation energy ratio than the more brittle ones [6]. Static and single-bounce low velocity (up to 10 m/s) drop weight impact tests on ± 55° filament-wound E-glass/epoxy resin pipes produces a two-part failure process of an elastic deformation followed by failure due to delamination initiation and local crushing [7]. In curved graphite/epoxy composite plates, low velocity impact can cause a dent formation on the impacted surface of the plate while cracking and ply separation occurs on the opposite surface [8]. In the typical load time plots the first load drop indicates on set of matrix cracking [9] which corresponds to impact damage initiation and becomes the cause of subsequent delamination immediately along the top or bottom interface of the cracked layer [10].

The impact damage development in ± 55° filament wound glass/epoxy tubes of 55-mm ID and 6-mm thick tubes intended for underwater applications the mean damage threshold values were 3 to 4 J and subsequent through thickness delamination damage occurs at energies up to 7 J [11]. In glass, carbon, and aramid fabrics-reinforced composites, dome shaped fracture occurs on the front face as a result of the localized matrix crushing and fiber shearing, while the damage on the rear face shows a characteristic pattern of cracks in the fiber direction [12].

Though a large number low velocity impact studies on FRP composites have been carried out during the past twenty years, the work involving GFRP pipes have remained significantly limited. It is obvious that due to the increasing use of GFRP pipes in many diverse applications and due to the advent of new materials and processing techniques the area of understanding and characterization of impact behavior of GFRP pipes continues to draw considerable attention of the research and design communities. In the present investigation low velocity impact behavior has been investigated in two FRP pipes, the filament-wound glass fiber reinforced/vinylester and the glass fiber reinforced/epoxy composite pipes. Fiber reinforced polymers have captured a significant market as a material of preferred choice in a variety of structural applications around the globe.

Fiber reinforced polymer (FRP) composite materials show great potential for integration into the highway infrastructure. Typically, these materials have long and useful lives; are light in weight and easy

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to construct; provide excellent strength-to weight characteristics; and can be fabricated for "made-to-order" strength, stiffness, geometry, and other properties. FRP composite materials may be the most cost-effective solution for repair, rehabilitation, and construction of portions of the highway infrastructure. FRP composite materials have a high strength-to-weight ratio and are generally not affected by the harsh highway environment (they do not corrode, and they have excellent fatigue resistance). These composite materials while offer a range of advantages in terms of excellent formability, high specific mechanical strength, better thermal resistance, excellent chemical and corrosion resistance, are at the same time quite susceptible to damage under impact loading. This impact damage can severely impair the otherwise excellent mechanical properties and often results in causing premature failure of the composite. The conventional materials, which are being replaced by the composite materials, have well-defined impact characteristics and the standards are well defined but the laminated composites are more susceptible to impact damages which are often internal and cannot be observed visually [13].

Material and Methods

The specimens used for impact testing were 300-mm long pipe section cut from commercially available filament-wound E-glass fiber reinforced vinyl ester and epoxy based pipes. Both types of pipes had internal diameters of 150 mm and wall thickness of 6 mm. The winding angle of all the pipes was ± 54.5° to the pipe axis. Glass fiber reinforced/vinyl ester pipes are referred as GFRV pipes, whereas, the glass fiber reinforced/epoxy pipes are referred as GFRE pipes.

Single bounced low velocity impact tests were carried out using an instrumented free falling drop weight impact test system (Dynatup 9250G, Instron Corp., USA). A 1.27 cm diameter spherical head steel tup was used as the impactor. Tests at different impact energies were performed by choosing suitable combinations of crosshead mass and drop height. The contact force was measured with a load transducer located between the cross head and hemispherical tup nose. Impact tests were carried out by varying mass and energy until the energy required to just initiate the impact damage and the energy required for total penetration were determined. The tests were then carried out at intermediate energies to examine the impact behavior of the pipe samples. A total of four impact energy levels, 6, 30, 70, and 100 J were investigated for the GFRV pipes, while the impact energy levels for the GFRE pipes were 12, 35, 80, and 110 J. Three impact tests were performed at each energy level. For low impact energy (up to 50 J) tests, the impactor mass of 10 kg was used, while a 25 kg mass was used for higher energy tests. The data used for microscopic evaluation in the study is 60X magnification power is used. The resolution of optical images used in the images is 600 dpi for various images.

Visual and optical inspections of the impact damaged pipes were performed after each test. With the drop height and weight known the data acquisition system provided the calculated values of maximum (peak) load, energy at maximum load, impact energy, deflection at maximum load, and impact velocities.

Results and Discussion

The results of the impact tests carried out at various impact energies for the GFRV and GFRE composite pipes are presented in the tabular form in Tables 1 and 2. The load-time, energy-time, and load-deflection histories for the two materials are shown in the Figures 1-6.

It is well known now that the load-time history can be divided into two distinct regions, a region of damage initiation and a region of damage propagation. As the load increases during damage initiation phase, elastic strain energy is accumulated in the specimen and no gross failure takes place. However, failure on a micro-scale, for example, transverse matrix cracking, fiber micro-buckling, or debonding at the fiber-matrix interface is possible. These micro damage events are indicated by the pronounced fluctuations in the load-time curves. When a critical load is reached at the end of the initiation phase, the load monotonically decrease with time indicating damage propagation and the composite specimen may fail either by a tensile or a shear failure depending on the relative values of the tensile and inter-laminar shear strengths. At this point the fracture propagates either in a catastrophic manner, indicated by continual load drop or in a progressive manner by continuing to absorb energy at smaller loads, indicated by the load fluctuations in the load-time history. Energy to peak force is the energy that the specimen has absorbed up to the point of maximum load. The total penetration energy is thus the sum of the initiation energy i.e., energy to reach the peak point on the load-time trace and the energy consumed in the damage propagation. Deflection at peak load is the maximum deflection that the specimen experience during the impact loading. It is the deflection value at the point where the load-time curve reaches its peak.

Impact Energy (J)	Specimen Number	Peak Force (kN)	Deformation at Peak Force (mm)	Energy to Peak Force (J)	Total Penetration Energy (J)
6J	6.1	3.22	2.08	3.82	4.92
	6.2	3.29	1.47	2.39	4.97
	6.3	3.29	1.49	2.6	4.37
	Average	3.27	1.68	2.94	4.75
30J	30.1	5.47	7.08	27.39	28.1
	30.2	5.38	7.11	26.8	27.76
	30.3	5.01	7.42	26.15	28.36
	Average	5.28	7.2	26.78	28.07
70J	70.1	6.58	11.29	51.5	66.83
	70.2	6.57	11.54	51.23	66.9
	70.3	6.53	13.51	62.33	68.69
	Average	6.56	12.11	55.02	67.47
100J	100.1	6.57	16.59	79.1	96.22
	100.2	6.58	12.48	58.05	96.35
	100.3	6.57	14.4	44.69	95.13
	Average	6.57	14.49	60.61	95.9

Table 1: Results of the impact tests of GFRV composite pipes.

Impact Energy (J)	Specimen Number	Peak load (kN)	Deformation at Peak Load (mm)	Energy to Peak Load (J)	Total Penetration Energy (J)
12J	12.1	6.55	3.19	10.36	19.54
	12.2	6.55	3.7	12.91	19.63
	12.3	5.81	3.88	12.39	18.78
	Average	6.3	3.59	11.89	19.32
35J	35.1	6.72	3.02	10.1	31.18
	35.2	6.66	3.06	9.83	32.45
	35.3	6.54	3.01	9.66	31.52
	Average	6.64	3.03	9.87	31.72
80J	80.1	6.62	2.97	10.36	80.6
	80.2	6.66	3.19	10.73	80.25
	80.3	6.59	3.12	11.48	81.12
	Average	6.62	3.09	10.86	80.66
110J	110.1	6.62	6.11	28.66	114.47
	110.2	6.56	5.58	25.42	115.14
	110.3	6.58	5.1	23.02	115.3
	Average	6.59	5.59	25.7	114.97

Table 2: Results of the impact tests of GFRE composite pipes.

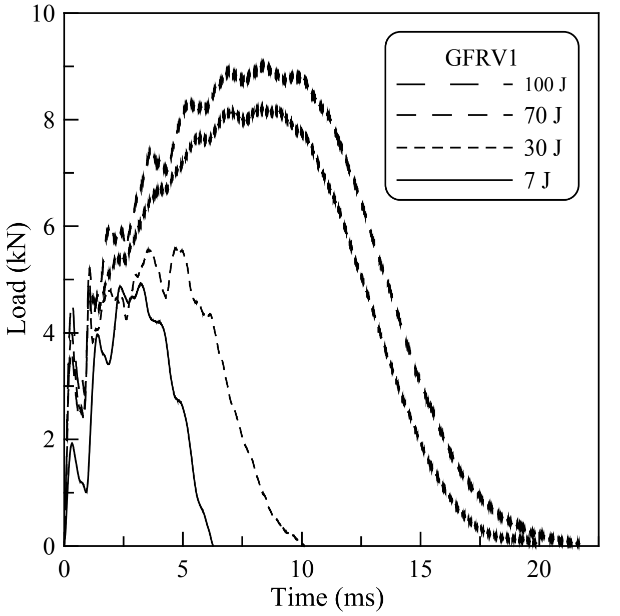

Figure 1: Load-Time traces for GFRV at incident impact energies of 6, 30, 70 and 100 J.

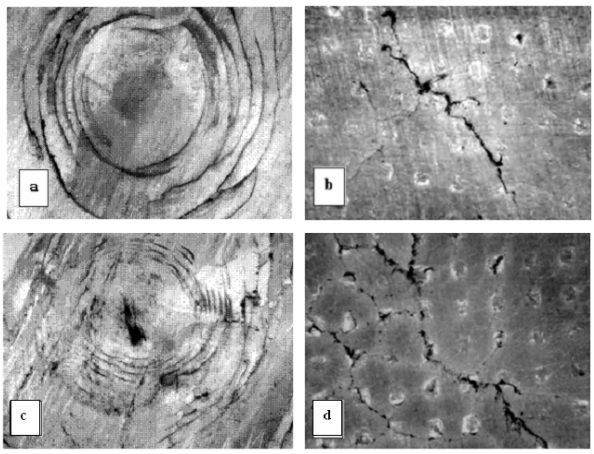

Figure 2: View of the impact damage in a GFRV pipe sample at incident impact energy of, (a) 35 J front (impacted) surface (b) 35 J, back (inner surface), (c) 70 J outer (impacted) surface, (d) 70 J, back (inner surface).

An examination of the load-time traces presented in Figure 1 shows that for low to intermediate incident energies of 6 J and 30 J the damage initiation phase predominates as indicated by the pronounced fluctuations in the load-time history.

The damage at 6 J remains mostly invisible on the impacted surface with no sign of cracking on the back (inner) surface. The impact damage however becomes extensive at higher incident energy levels. Figure 2 provides view of the front (impacted) and back (inner) surface of the specimen impacted with the incident energy of 35 J and 70 J.

It is evident from Figure 2a that at this energy level the specimen shows clear indentation (gross plastic deformation) on the front (impacted) surface and cracking on the back (inner) surface (Figure 2b). At 70 J the damage on the front (impacted) surface shows signs of cracking along around the indentation, while extensive cracking occurs on the back (inner) surface of the pipe sample.

For the GFRV pipes the total absorbed energy (which is the sum of energy absorbed to peak load and the energy absorbed after the peak load) also increases with an increase in incident impact energy as evidenced by Figure 3.

The energy up to the peak load is absorbed through elastic deformation and increases linearly with time, followed by the energy absorbed by the damage initiation and propagation events. This energy absorption increases non-linearly with time, which is suggestive of the fact that the damage events beyond the peak load occurs in an inelastic manner. The examination of the load-deflection traces for GFRV pipes tested at different incident energy levels (Figure 4) also reveal the existence of different stages of deformation and damage creation events.

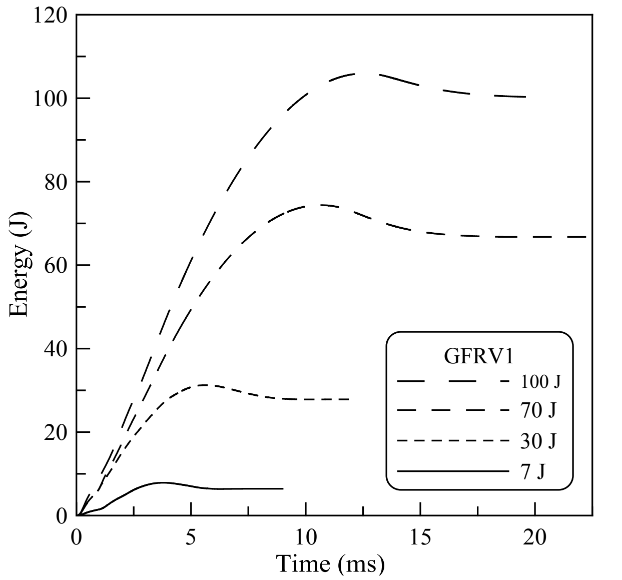

Figure 3: Energy -Time traces for GFRV at incident impact energies of 6, 30, 70, 100 J.

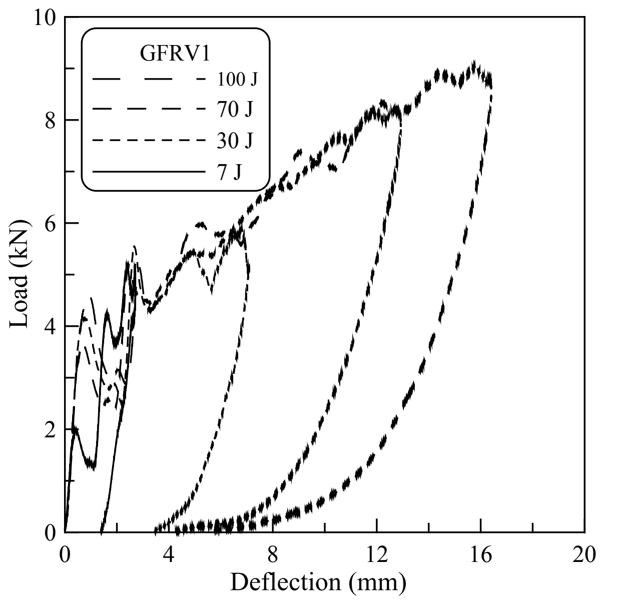

Figure 4: Load -deflection traces for GFRV at impact energies of 6, 30, 70, and 100 J.

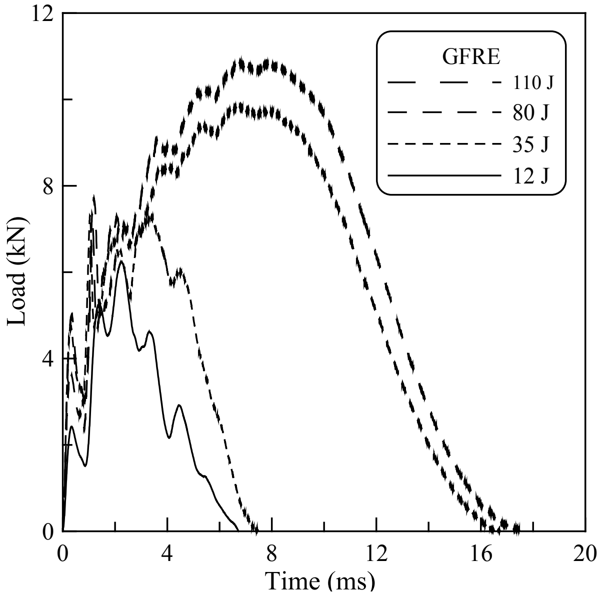

Figure 5: Load-Time traces for GFRE at impact energies of 12, 35, 80 and 110 J.

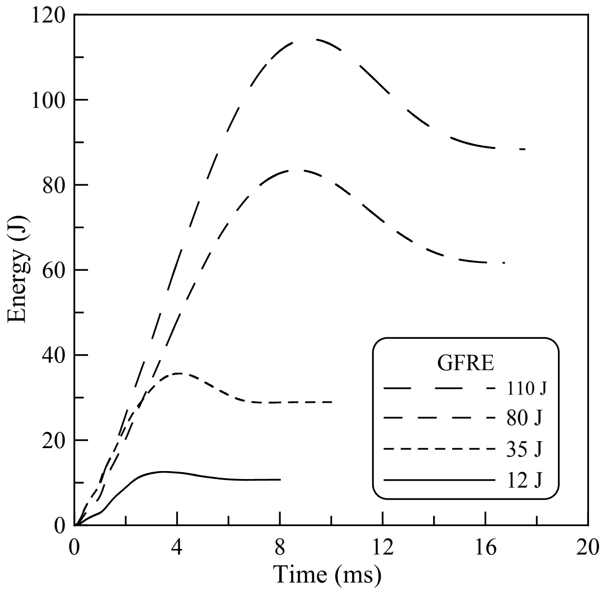

Figure 6: Energy -Time traces for GFRE at impact energies of 12, 35, 80 and 110 J.

The initial linear portion of the load-deflection traces points at the elastic response. This is followed by a portion of inelastic response with characteristic pronounced fluctuations in the load-deflection traces. Maximum specimen deflection is attained at the peak load and as the load begins to drop from its peak value the deflection also begins to reverse through elastic recovery and attains its minimum value at failure. The plateaus in the load-deflection traces for tests at incident energies of 70 and 100 J once again indicate that for full penetration impact events very large deflections are attained due to the physical passing of the impactor through the sample thickness.

The load-time traces from the impact tests at various incident energy levels for GFRE material are provided in Figure 5. It is evident that for the GFRE pipes, the impact damage was also produced in a similar two stage damage initiation and damage propagation process.

The energy-time and the load-deflection for the GFRE pipe samples tested at different incident energy levels are displayed in Figures 6 and 7, respectively. These traces are approximately analogues to the traces observed for GFRV pipe samples and follow the same trends of increase in absorbed energy and deflection with increase in the incident impact energy as seen in GFRV material.

The impact damage areas for the GFRE pipes impacted at two incident energy levels of 35 and 80 J are shown in Figure 8. At 35 J the impacted surface shows clear indentation at the impacted surface (Figure 8a) and a network of very fine cracks on the back (inner) surface (Figure 8b) of the pipe sample. At 80 J large indentation has formed but the area surrounding the indentation remains much more intact (Figure 8c) than what was observed in the GFRV pipe samples where the indentation was associated with a much larger damage area with wide spread plastic deformation. The back (inner) surface of the GFRE pipe sample at this 80 J incident impact energy also show much less pronounced cracking (Figure 8d) than that observed in GFRV pipe samples impacted with incident energy of 80 J.

The back (inner) surface of the GFRE pipe sample at this 80 J incident impact energy also show much less pronounced cracking (Figure 8d) than that observed in GFRV pipe samples impacted with incident energy of 80 J. The data presented in Tables 1 and 2 summarizes the impact test results for the GFRV and GFRE pipes. Table 1 shows that for GFRV pipe the average peak loads at which the samples failed were 3.27 kN, 5.28 kN, 6.56 kN, and 6.57 kN for the impact energies of 6, 30, 70, and 100 J, respectively. This means that in GFRV pipes the failure occurs at increasingly higher impact loads as the incident impact energy levels are increased. Table 1 also show that for GFRV pipes, the average absorbed energy values (absorbed energy = the total penetration energy minus energy at peak load) for impact energies of 6, 30, 70, and 100 J were, 1.81, 1.29, 12.45, and 35.2 J, respectively. The average deflection at peak load also increase with increase in the incident impact energy level. For GFRV pipes these deflection values

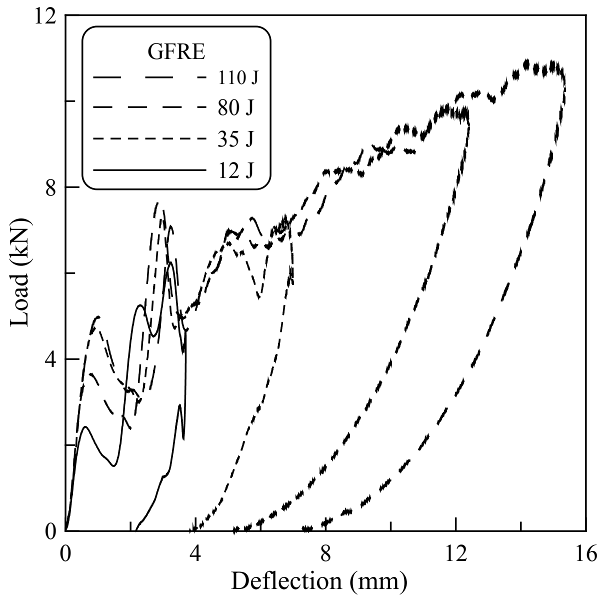

Figure 7: Load -deflection traces for GFRE at impact energies of 12, 35, 80 and 110 J.

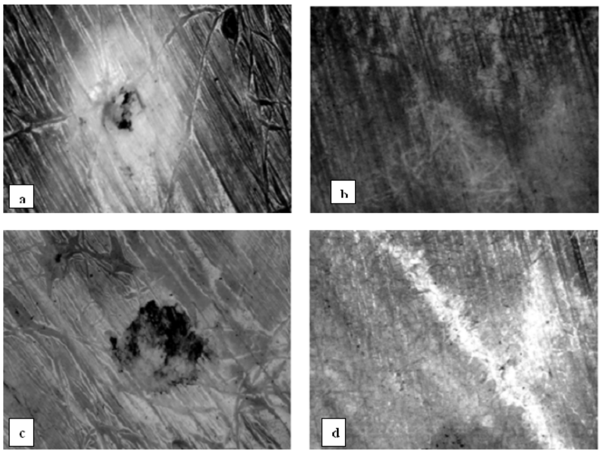

Figure 8: View of the impact damage in a GFRV pipe sample at incident impact energy of 35 J, (a) outer (impacted) surface (b) inner surface.

were 1.68, 7.2, 12.11, and 14.49 mm for incident energy levels of 6, 30, 70, and 100 J, respectively.

The GFRE pipes require higher incident impact energies for damage initiation and propagation. The damage initiation threshes hold for GFRE was 12 J and the full penetration was achieved at 110 J as against the corresponding 6 and 100 J for GFRV pipes. Table 2 shows that for GFRE pipes the peak load was independent of the incident impact energy and for all the four energy levels the peak load remained essentially constant at approximately 6.5 kN.

The average absorbed energy for GFRE pipes increased with increase in the incident impact energy and was noted as 7.4, 21.9, 69.8, and 89.3 J for the incident impact energies of 12, 35, 80, and 110 J, respectively. The energy at all peak load values for the GFRE pipes at various impact energy levels were studied and the deflections at peak load values for GFRE pipe were substantially lower than those for the GFRV pipes. GFRV pipes were noted as 3.59, 3.03, 3.09, and 3.59 mm for the incident impact energy levels of 12, 35, 80, and 110 J. The lower the energy of peak load and deflection at peak load values for GFRE pipes in comparison to GFRV pipes indicates brittle nature of the epoxy matrix as compared to the relatively less brittle vinyl ester matrix.

Conclusion

Low velocity impact response of filament-wound Glass Fiber Reinforced/vinylester (GFRV) and Glass Fiber Reinforced/epoxy (GFRE) pipes have been examined using instrumented drop weight testing machine. From the impact response data and damage evaluation the following conclusions can be made like Load-time, energy-time, and load-deflection histories are indicative of the damage initiation and damage propagation. Two distinct responses to impact can be identified. The first response is elastic deformation during which no gross damage takes place. The second response is the initiation and propagation of major damage under elastic and plastic deformation. Energy up to the peak load is dissipated in elastic deformation followed by energy dissipation in major damage initiation and propagation. For GFRV pipes, the peak load increases with increase in the incident impact energy, while for the GFRE pipes the peak load remains essentially constant and could be considered independent of the magnitude of the incident impact energy. The energy to peak load and the deflection at peak load values for GFRE pipes were found to be substantially lower than the values observed for the GFRV pipes. The lower energy to peak load and deflection at peak load values were indicative of the rather brittle nature of the epoxy matrix as compared to the relatively less brittle vinyl ester matrix.

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