

STUDY ON IMPACT RESPONSES OF PULTRUDED GFRP, STEEL AND ALUMINUM BEAMS BY USING DROP-WEIGHT IMPACT TEST

Sittichai Seangatith

Received: Sept 29, 2007; Revised: Jun 5, 2008; Accepted: Aug 29, 2008

Abstract

Pultruded glass fiber-reinforced plastic composite (PFRP) structural sections have been used successfully in a wide range of civil engineering structures such as cooling tower systems and industrial buildings, especially in hostile and corrosive environments. In recent years, the applications of this material have been extended into roadside safety structures such as guard rails, bridge rails and sign posts. These structures are mainly subjected to an impact loading which is a complicated process where both structural and material properties can influence the impact responses of the structures. Also, the impact responses of the material cannot be predicted from the engineering material properties of the material. In this paper, an experimental study on the impact responses of the PFRP composites and conventional metal beams will be presented. The PFRP composite beams were commercially produced by a pultrusion process. The experiments were performed on a drop-weight impact-testing machine. The test specimens will be subjected to low velocity impact with the impact energy of about 40 J for sub-critical energy tests and 160 J for critical energy tests. The impact responses, impact energy absorption and failure modes will be discussed.

Keywords: Impact responses, pultruded GFRP, steel, aluminium, drop-weight impact test

Introduction

In recent years, pultruded fiber-reinforced plastic composites (PFRP) made with glass fiber and vinyl ester resin have been used widely in civil engineering structures (ASCE, 1984) and have been selected to be the potential candidate materials for roadside safety structures, ships, and moving vehicles, where these structures are loaded dynamically in collision (Ye, 1994). Studies of impact loading of advanced polymeric composites and conventional metals have been

performed by a number of investigators by using Charpy and Izod impact tests (Svenson *et al.*, 1994; Ye, 1994). It has been shown that the impact energies of glass fiber reinforced composite are equal or higher than those of steel and aluminium, and the impact responses and damage mechanisms are complex and depend on a number of parameters including impact velocity, impact mass, impact angle, shape of striker, target geometry, and target material.

School of Civil Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000 Thailand. E-mail: sitichai@sut.ac.th

However, it is well known that the Charpy and Izod impact tests have limitations on test variables such as impact velocity and impact energy which are held constant. Therefore, the drop-weight impact test has been increasingly used for the study the impact responses of composite materials. In this paper an experimental study on the impact responses of the pultruded glass fiber-reinforced plastic composites (PFRP) composites and conventional metal beams will be presented and the impact responses, failure mode, and impact energy absorption will be discussed.

Experimental Details

The low-velocity impact test was conducted by using a drop-weight impact testing machine as shown in Figure 1. The principle of the drop-weight impact testing machine is to let a weight or a striker of a given material and size drops to a prescribed distance to impact on a specimen. Two test configuration were used in this study: sub-critical energy test and critical energy test. The first was an impact from a height of 0.457 m which is equivalent to the impact velocity of approximately 0.3 m/sec and the mass of the striker is 9.09 kg, representing the sub-critical energy test of 40 J. This energy level was used to study the impact responses of the beams without causing serious damage to the beams due to the impact. The second was an impact from a height of 0.914 m which is equivalent to the impact velocity of approximately 4.2 m/sec, and the mass of the striker is 17.98 kg. This energy level of 160 J was used to study the impact responses of the beams causing serious damage to the beams due to the impact. In this machine, a cross-head striker is located and guided by two frictionless stainless steel bars and moved up and down into position by a motor-operated hoist system located on the top of the machine. After impact, the cross-head striker is arrested by means of a pneumatically activated system.

The data acquisition system is used in the tests. It consisted of an analog-to-digital board, National Instrument model AT-MIO-16E-2, interface with a desktop computer and connected

to a strain gauge signal conditioning board, National Instrument model SC-2043-SG. A graphical programming software was used to develop a virtual instrument to collect the acceleration due to the impact and time during the test.

The accelerometer was the Sensotec's high impact test accelerometer, model CTA-2. It was affixed to the top of the cross-head striker and provided an acceleration-time history during the impact event. The steel striker shape was a cylinder with dimensions of 101.6 mm in length and 25.4 mm in diameter. Data were collected at the sample rate of 15,000 samples per second. After the test, the collected data were filtered (low pass) at 1,600 Hz and imported to computer software to calculate for the displacement and the impact load of the cross-head striker.

The test specimens were in a form of beam having a rectangular cross-section and made of the pultruded glass fiber-reinforced plastic composites (PFRP) with a polyester resin, the A36 structural steel, and the 2014-T6 aluminium. The PFRP specimens were cut from box-section (PFRP-B) and plates (PFRP-P),

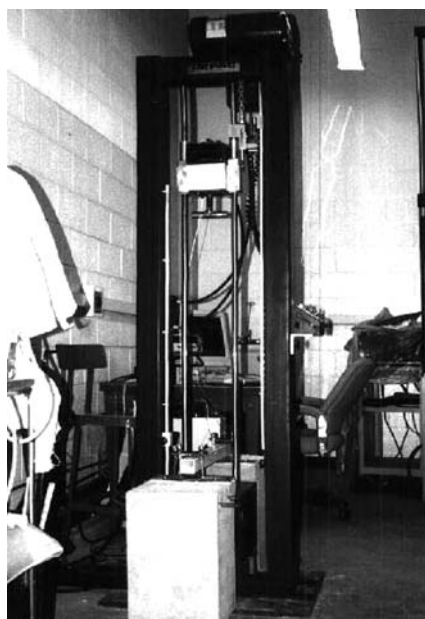


Figure 1. Drop-weight impact testing machine

commercially manufactured by Creative Pultrusions in Alum Bank, Pennsylvania, USA. All test specimens were 25 mm in width and 228.6 mm in length and were simply supported on stiff concrete supports with the span of 177.8 mm. Table 1 provides information of the test specimens used in this study. Table 2 shows the statics engineering material properties of the PFRP specimens which were tested according to the ASTM standards. The A36 structural steel and the 2014-T6 aluminium have the averaged yielding stresses of 250 and 414 MPa, respectively, the averaged ultimate stresses of 400 and 469 MPa, respectively, and averaged modulus elasticity of 200 and 73 GPa, respectively.

Computation of Impact Force and Energy Absorption

The drop-weight impact-testing machine is instrumented with a linear accelerometer. Following the release of the striker, until impact with the specimen, the acceleration of the striker is equal the gravitational acceleration, g . This is based on an assumption that the friction and air resistance are negligible. Thus, the velocity of the striker at the impact, v_o , can be expressed as

$$v_o = g t_o = \sqrt{2gh_o}$$

where h_o is the initial drop height, t_o is the time between release and impact, and $g = 9.81$

Table 1. Test specimen information

Specimen	Number	Cut from	Thickness (mm)	Fiber volume fraction ¹
PFRP-B	5	PFRP Box-Section	6.4	0.55
PFRP-P	5	PFRP Plate	9.5	0.60
ST	5	A36 Steel Plate	6.4	-
AL	5	2014-T6 Aluminium Plate	6.4	-

¹ from Creative Pultrusion Inc (2000).

Table 2. Summary of engineering material properties of PFRP specimens

Engineering material properties	Test method	Unit	PFRP-P	PFRP-B
Tensile stress, LW ¹	ASTM D 3039	MPa	445.42	401.29
Tensile modulus, LW	ASTM D 3039	GPa	26.26	21.88
Compressive stress, LW	ASTM D 695	MPa	308.46	204.52
Compressive stress, CW ²	ASTM D 695	MPa	143.33	99.47
Compressive modulus, LW	ASTM D 695	GPa	32.60	20.77
Compressive modulus, CW	ASTM D 695	GPa	7.69	6.80
Flexural stress, LW	ASTM D 790	MPa	422.57	301.75
Flexural modulus, LW	ASTM D 790	GPa	13.15	6.99
Density	-	kg/m ³	1,849.00	1,688.00

¹ LW = Lengthwise or longitudinal direction.

² CW = Crosswise or transverse direction.

m/sec². The kinetic energy of the striker, E_o , just before the impact is given by

$$E_o = \frac{1}{2}mv^2$$

where m is the mass of the striker. During and after initial impact, the velocity of the striker becomes nonlinear and is reduced due to the flexural resistance and failure mechanism of the specimen. The velocity can be computed from the output of the accelerometer by the following relationship

$$v = g \int a \, dt \approx g \sum a \, \Delta t$$

where a is the instantaneous acceleration of the striker expressed in terms of g , and dt or Δt is the time step increment expressed in seconds. The Δt is set to be 0.000067 sec in the tests which is equivalent to the sample rate of the data acquisition system at 15,000 samples per second.

The displacement of the specimen at any time during the impact can be calculated by

$$d = \int v \, dt \approx \sum v \, \Delta t$$

The linear accelerometer data is also used to determine the instantaneous impact resistance load at any time during the impact. Since a translating acceleration of rigid body is proportional to the resultant force acting on the rigid body,

$$F = ma$$

where F is the instantaneous impact resistance load. This equation is applicable in the case that the weight or mass of the striker is significantly greater than that of the specimen so that the inertia effect of the specimen can be neglected.

The instantaneous energy absorbed by the specimen at any time during the impact is expressed as

$$E = \int P \, v \, dt \approx \sum P \, v \, \Delta t$$

The geometrical parameters in the test are one of the most important factors that influence

the impact test results. To allow the comparison of the impact load and energy absorption with different geometric parameters, two well-known normalization procedures are used to normalize the data. They are the specimen cross-sectional area and the quantity $(8I/Lh)$, where h is the thickness of the beam, I is the moment area of the cross-sectional area, and L is the span length of the beam. The normalization by the quantity of $(8I/Lh)$ was presented by Svenson *et al.*, 1994.

Experimental Results and Discussions

Load-time History

Figures 2 to 5 show the impact force versus time curves obtained from the tests. In Figure 2 we can see that, for the critical energy test on the PFRP-B specimens, the impact force which occurred in the PFRP-B specimen reaches a maximum value of about 2,500 N and drops abruptly to about 70 percent of that value, representing the fractures of the outermost layers of the glass fiber in the specimens. It then starts with a tendency to increase in the impact force and then gradually decrease, representing the second outermost layer of the glass fiber cracks. Finally, an abrupt drop of the impact force occurred, representing the total failure of the specimens. In the sub-critical energy test on the PFRP-B specimens, the beams resist the impact by firstly an increase in impact force and then abruptly drop. Small cracks were detected on the bottom surface of the specimens. Then, the specimens started to absorb the impact energy without further noticeable fractures. It should be noted that the impact force-time responses of the specimens in this case is approximately in a form of sine function which is similar to a single degree-of-freedom (SDOF) massless spring responses under an impact load. It is also interesting to note that the impact duration of both cases is similar. This may be explained by the fact that after the first crack, both specimens have the same amount of reduced rigidity in most of the impact process since it is well known that the impact duration is a function of the rigidity of the beams. The impact force versus time curves of PFRP-P in Figure 3 are in general quite similar to those in Figure 2,

excepting for higher maximum force and shorter impact duration, and the larger drop in impact forces after the maximum force has been reached. These mean that the PFRP-P specimens, having higher fiber volume fraction, are more stiff and brittle than the PFRP-B specimens. This type of critical energy impact response may not be appropriate to be used in the structures loaded dynamically in collision since the mode of failure under impact is quite abrupt.

Figures 4 and 5 show the impact force-time history for A36 steel and 2014-T6 aluminium specimens, respectively. In general, they are quite similar to one another. In the sub-critical energy, both types of specimens have reached their plastic behavior and they absorb the impact energy through developing a plastic hinge at the impact point area. For the critical energy impact, the steel specimens still absorb the energy by the plastic hinge without fracture, however, the aluminium specimens reached their fracture point and separated into two pieces as shown in Figure 8. This shows that the steel is more ductile than the aluminium under the same impact energy level. If we compare the impact force-time history of the PFRP specimens in Figures 2 and 3 with those in Figures 4 and 5, we can see clearly that in the sub-critical energy tests, all of the specimens responses approximately in a form of sine function. Thus, it may be assumed that the responses of the specimens are similar to a single degree-of-freedom massless spring under an

impact. But, for the critical energy impact, the responses are very complex due to the series of fractures which occurred in the PFRP specimens and the plastic hinges which occurred in the steel and aluminium during the impact. Therefore, the simulation of the impact responses of the specimens under the critical energy impact will be very difficult and time consuming, but, it should still be performed since understanding the impact responses is very important in the design of structures subjected to collision. More research must be executed to simulate the critical energy impact response of the PFRP.

Impact Energy Absorption

Impact energy absorption is an important factor in studying the impact properties of materials. The impact performance of materials can be determined and compared from an impact test by keeping the specimen shape and boundary condition unchanged. The impact load and energy absorption for the case of the critical impact energy were calculated and normalized by using the method presented by Svenson *et al*, (1994) as mentioned previously. Figures 6 and 7 show the averaged normalized load and energy of the test specimens. In Figure 6 we can see that both PFRP composites have the initiation normalized impact load P_i smaller than the maximum normalized impact load P_m , which means that they have ductile-like behavior under impact loads, and the specimen PFRP-B

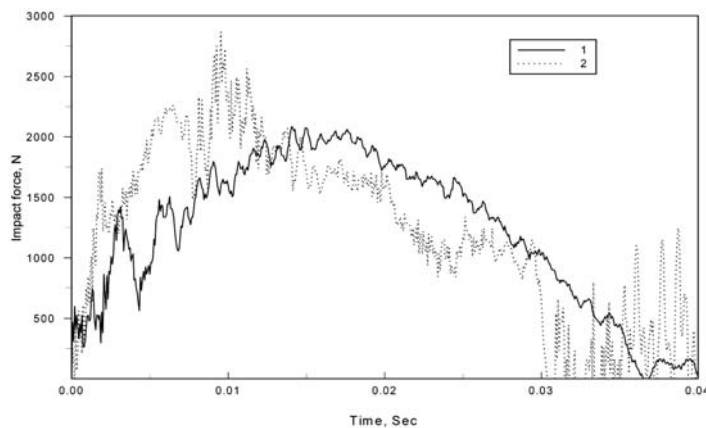


Figure 2. Load-time history of PFRP-B specimens: sub-critical (1) and critical (2) energy

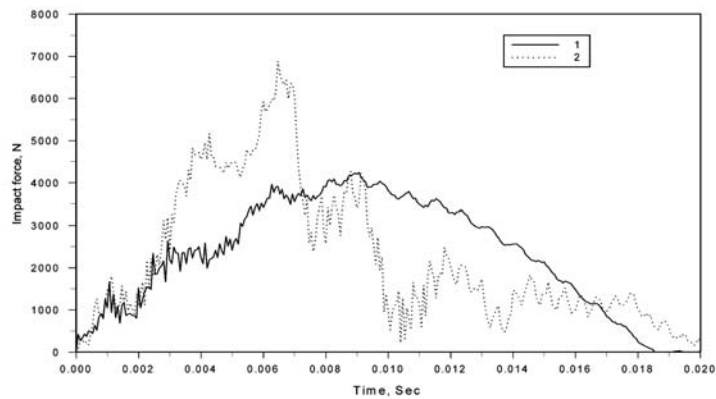


Figure 3. Load-time history of PFRP-P specimens: sub-critical (1) and critical (2) energy

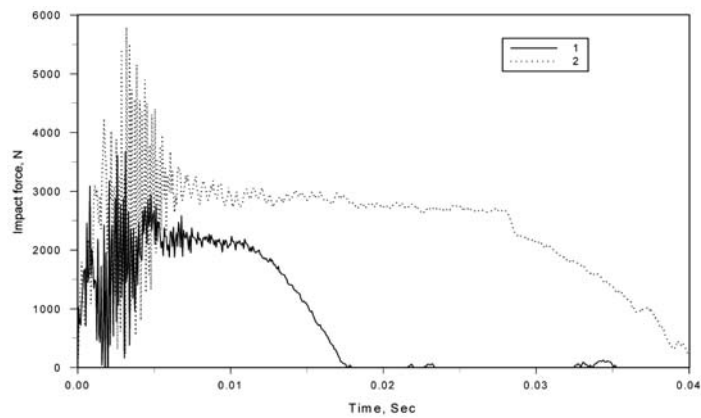


Figure 4. Load-time history of ST specimens: sub-critical (1) and critical (2) energy

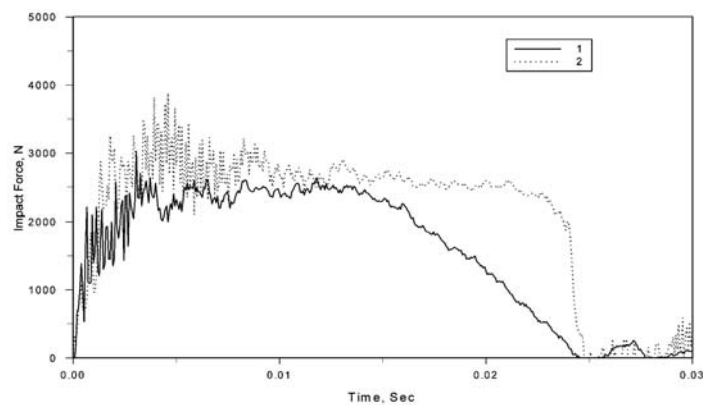


Figure 5. Load-time history of AL specimens: sub-critical (1) and critical (2) energy

is more ductile-like than the specimen PFRP-P. Although P_i values of the PFRP specimens are less than those of the steel and aluminium, their P_m values are comparable. In Figure 7 we can see that the specimen PFRP-B has the total normalized energy absorption E_t which is less than that of the steel by about 24 percent and slightly larger than that of the aluminium. However, the normalized energy absorption at the maximum impact load E_m of the PFRP-B specimen is about 45 percent larger than that of the steel and aluminium. Although the E_t of the PFRP-P specimen is less than that of the steel and aluminium, its E_m is slightly higher.

Modes of Failure

The side view of the specimens tested under the critical energy is shown in Figure 8. The fracture patterns of the specimens follow the classical form of a flexural failure. For the PFRP-B specimens, the fracture started at the outermost layer on the tension side following the delamination between layers and fiber breakage. However, the top surface did not fail in compression, and the striker head did not penetrate through the specimens which are opposite to the fracture which occurred in the PFRP-P specimens. The PFRP-P specimens

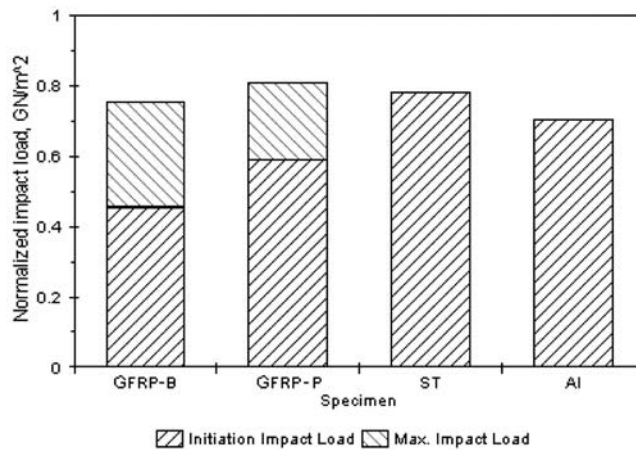


Figure 6. Normalized impact load by the quantity of $(8I/Lh)$

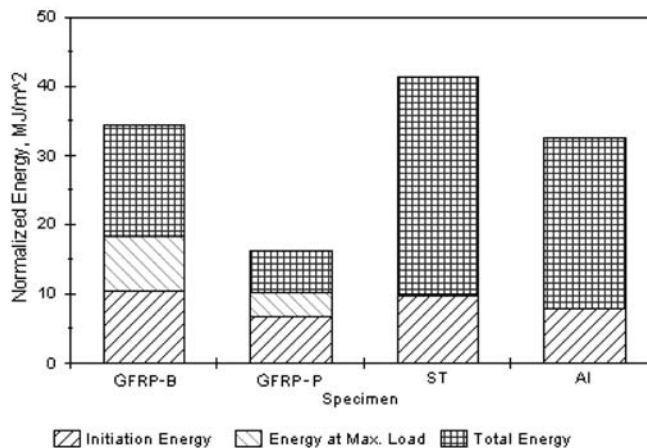


Figure 7. Normalized energy absorption by the quantity of $(8I/Lh)$

failed completely with tearing in tension on the bottom surface and crushing in compression on the top surface with extensive delamination and fiber breakage in the area between the top and bottom surfaces. Thus, for the critical energy level, it is indicated that the PFRP-B specimens have a ductile-like behaviour and a better mode of failure than that of the PFRP-P specimens. However, for the PFRP specimens subjected to sub-critical energy level, there is only a slight crack found on the outermost of the tension surface with no delamination between the layers of the specimens. By further repeating the same impact energy level, there is no sign indicating a failure of the specimens. This indicates that, for sub-critical energy level, the PFRP specimens have the ability to resist the impact load for a number of times.

Conclusions

From the drop-weight impact tests on the pultruded PFRP composite, steel, and aluminium beams with cylindrical loading head and two energy levels of 40 J for the sub-critical impact energy and 160 J for the critical impact energy, the following conclusions can be drawn:

1.) The pultruded PFRP composites have the energy absorption and impact force resistance comparable to the steel and aluminium, and the PFRP-B has higher energy absorption and

impact force resistance than the PFRP-P.

2.) The failure mode of the beam PFRP-B is preferable to the beam PFRP-P since after the impact the beam PFRP-B still has strength to resist a higher impact load and to prevent the penetration of the striker head. In addition, the impact responses of the beam PFRP-B is more ductile-like than the beam PFRP-P.

3.) The impact responses of all the specimens under the sub-critical energy impact loads are approximately in a form of sine function. However, for the critical impact energy, complex impact responses of all the specimens were observed due to the series of fractures occurred in the PFRP specimens and the plastic hinges occurred in the steel and aluminum specimens during the impact. Thus, a material and geometric nonlinear finite element analysis including the fracture and yielding must be used to predict the impact response, the failure mode and the energy absorption of the materials and the beam specimens.

Acknowledgements

The experimental investigations were performed at the University of Texas at Arlington, Texas, USA. The support of Prof. Dr. Robert L. Yuan and Creative Pultrusions, Inc., PA, USA are greatly appreciated.

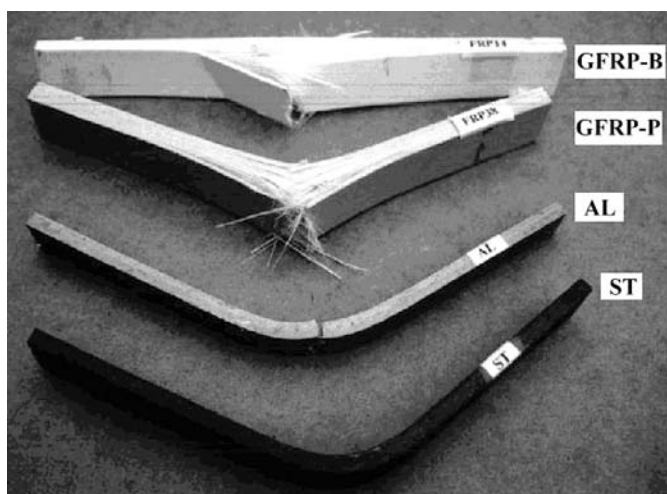


Figure 8. Damages on the specimens subjected to critical impact energy

References

- American Society of Civil Engineers (ADCE). (1984). Structural Plastics Design Manual. ASCE Manuals and Reports on Engineering Practice. NY, USA, No. 63, 1,192p.
- Creative Pultrusion Inc. (2000). The New and Improved Pultex Pultrusion Global Design Manual of Standard and Custom Fiber Reinforced Polymer Structural Profiles Volume 3 – Revision 3 Metric Version. Creative Pultrusion Inc. Alum Bank, PA. USA.
- Svenson, A.L., Hargrave, M.W., Bank, L.C., and Ye, B.S. (1994). Data analysis techniques for impact tests of composite materials. JOTE, ITEVA, 22(5):431-441.
- Ye, B. (1994). Characteristics of glass fiber-reinforced composite materials for use in roadside safety. FHWA, Rep. No. FHWA-RD-94-048. Washington, D.C.

