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SAFETY ENHANCEMENT OF WATER-FILLED ROAD SAFETY BARRIER USING INTERACTION OF COMPOSITE MATERIALS

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ABSTRACT

Road safety barriers are used to redirect traffic at roadside work-zones. When filled with water, these barriers are able to withstand low to moderate impact speeds up to 50kmh^{-1}. Despite this feature, there are challenges when using portable water-filled barriers (PWFBs) such as large lateral displacements as well as tearing and breakage during impact, especially at higher speeds. In this study, the authors explore the use of composite action to enhance the crashworthiness of PWFBs and enable their use at higher speeds. Initially, we investigated the energy absorption capability of water in PWFB. Then, we considered the composite action of a PWFB with the introduction of a steel frame to evaluate its impact on performance. Findings of the study show that the initial height of impact must be lower than the free surface level of water in a PWFB for the water to provide significant crash energy absorption. In general, impact of a road barrier that is 80% filled is a good estimation. Furthermore, the addition of a composite structure greatly reduces the probability of tearing by decreasing the strain and impact energy transferred to the shell container. This allows the water to remain longer in the barrier to absorb energy via inertial displacement and sloshing response. Information from this research will aid in the design of next generation roadside safety structures aimed to increase safety on modern roadways.

Keywords: Composite; Coupled analysis; Impact; Portable water-filled barriers; Safety

1. INTRODUCTION

Traffic accidents in Australia cost approximately $17.85 billion per year i.e. 1.7% of the nation's GDP. This figure includes the costs of road maintenance, emergency response units, road reconstruction crew and insurance claims (Sorock et al., 1996). A single vehicle accident is defined as a crash that involves a single vehicle impacting roadside objects, such as road barriers, trees, traffic poles, etc. In 2010, these types of accidents accounted for 44.2% of the fatal crashes in Australia; this percentage was higher than crashes involving multiple vehicles and pedestrians. Road safety barriers are secondary crash attenuation safety mechanisms that restrain and redirect an errant vehicle away from roadside persons or objects. Several types of road safety barriers presently in use and have been studied extensively; they include permanent concrete barriers, wire-rope safety barriers and flexible W-beam barriers. Current safety features focus on crash mitigation through the vehicle's primary crash attenuation mechanism (Ahmad & Thambiratnam, 2009; Bignell et al., 2001).

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To improve overall safety pertaining to vehicular impacts, both the primary and secondary crash attenuation mechanism must be at par with one another.

PWFBs are temporary safety structures in roadside construction zones to protect workers from oncoming traffic. They are made of medium density polyethylene (MDPE) and classified as semi-rigid safety barriers. PWFBs are preferred due to their lightweight characteristics and multi-colored fluorescent exteriors which make them highly-visible to approaching traffic (Grzebieta et al., 2001). They are lightweight and moveable when empty, and they can be filled with up to 600kg of water mass to keep them stationary. The water inside a barrier increases the mass so that it is able to absorb and dissipate impact energy through sloshing (Tabri et al., 2009). However, the large post-impact translational distance of the PWFB compared to its counterparts, has caused some transport authorities to not use it.

To increase the performance of the PWFB, designers incorporated the use of steel frames with the road barriers (Energy Absorption Systems, 2010; Guardian Plastic Safety Products, 2006; Barron & Rawson, 2010). Moreover, the US Federal Highway Administration (AASHTO, 2009) stated that PWFB can be deemed crashworthy only if it incorporates steel reinforcements in its design. This step must be taken to increase the barrier’s stiffness for resisting penetration. Moreover, other safety structures such as the SAFER barrier system have used composite materials to absorb the impact energy at racing circuits around the world (Indycar, 2011; Grand Prix Champ, 2007; Midwest Roadside Safety Facility, 2010). From these observations, it can be implied that water alone is not enough to absorb crash energy and the performance of a PWFB system is somewhat dependent on the structural design of each individual barrier unit (Hammonds et al., 2012).

Many parameters must be considered when studying the response of PWFB subjected to vehicular impact. Some external parameters include the vehicle type, impact velocity, impact angle, impact point from head and end of the barrier system, and length of the road barrier system. Furthermore, internal parameters that need to be taken into account comprise of the type of joining mechanism, impact area on the road barrier, water fill level, composition of composite materials, and the barrier design. Different types of impact will yield different responses from PWFB even with similar road barrier units are used in the study.

Under new standards, current PWFBs are deemed inadequate for redirecting vehicles and are limited to roadways under 50kmh^{-1}. Thus, the addition of composite materials is expected to improve the performance of PWFBs by decreasing lateral displacement distance of the barriers through increased overall energy absorption by its components. Full-scale vehicle-barrier tests are costly (i.e. up to $25,000 per test), and only the impact reactions of the barriers and vehicles are obtained as outputs of normal testing. Hence, researchers and road barrier designers have opted to utilize numerical simulations during the design stages prior to testing with actual vehicles.

In this paper, we examine the performance characteristics of regular PWFBs under impact conditions and investigate the effects of composite action and safety enhancement with the addition of steel frames. The research information generated can be used in the design of next generation roadside structures.

2. METHODOLOGY

The research used extensive numerical simulations complemented by experimental impact tests. A type of road safety barrier commonly used in Australia was utilized throughout the study. This barrier has geometrical dimensions of 2000 mm (length) × 900 mm (height) × 600mm (width). It was designed and fabricated to meet the criteria of NCHRP 350 TL-1, with a recommended fill level of 225kg or 25% of its fill capacity.

2.1. Experimental Test Validation

Initially, material samples from the road barrier were obtained for testing of the polyethylene shell membrane, and steel frames in accordance with outlined standards (ASTM, A. S. o. T. M. I., 2010; ASTM, A. S. o. T. M. I., 2009). Then, experimental tests were conducted on the road safety barrier. Tests were carried out using a horizontal pneumatic impact testing machine and speed of impact was set between 6ms-1 to 8ms-1 with impact mass of 300kg (Gover, 2013). Results were compared with those from simulations to validate the modeling techniques used in this research.

2.2. Numerical Model

The finite element (FE) model of the road barrier was developed using the commercially available software LS-Prepost and LS-Dyna3D was used for problem solving. The numerical model of PWFBs consisted of both solid and fluid domains. Figure 1(a) and (b) illustrates the generated numerical model used in the numerical analysis. The application of coupled SPH/FEA, which combines traditional meshed elements with meshless SPH particles, is depicted in the fluid-structure interaction in Figure 1(a). In addition, the steel endoskeleton shown in Figure 1(b) was added to see the effect of composite behavior in the response of the barrier unit.

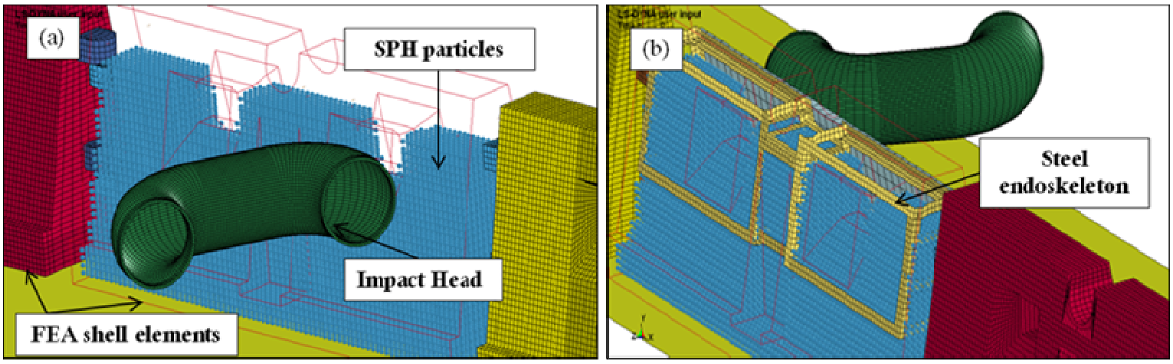

Figure 1 Model of road safety barrier: (a) fluid-structure interaction; (b) steel endoskeleton

The model of the barrier system consisted of three road barriers assembled in a row; they were generated using 47,581 shell elements with an edge length of 20mm. Each PWFB was constructed from two separate parts (main body and joint mechanism). The main body is the central section of the barrier that is subjected to impact and the joint mechanism connects the road barrier to adjacent ones. The road barriers were constructed using a polymeric material typical in plastic road barriers with an elasto-plastic material formulation to model the membrane of the road safety barrier. Contacts at the surface joints between road barriers follow the standard penalty methods in explicit program codes, which are the most generally used interface algorithms. The algorithm applies an interface force between slave nodes and their contact point whenever penetration is detected. The impact head is shaped similarly to the impact head used in testing, it was inspired from a front bumper of a vehicle and placed 600mm from the ground. The impact head was given rigid material properties and the contact definition followed the similar penalty method discussed earlier.

The simulations expanded the experimental studies with impacts at higher velocities of 40 kmh^{-1}, 50kmh^{-1}, and 80kmh^{-1}; with the same impacting mass of 300kg. These velocities were chosen because the PWFBs were used in construction work zones adjacent to roads with speeds within this range (Road & Maritimes Services New South Wales, 2012). A FE model of the barrier system depicted in Figure 1(a) was first developed to test the effect of water in the system of barriers. The fill level of water was varied between 182mm to 882mm (25%-100% filled). Then, to investigate the enhanced performance of the road barrier with composite structures, an additional steel endoskeleton was added to the barrier. The steel endoskeleton is shown when the Polyethylene (PE) shell is made transparent in Figure 1(b). No contacts were defined between water and the endoskeleton. Furthermore, adjacent road barriers were assigned a non-structural mass which correspond to the water mass of the impacted barrier in order to efficiently manage computational resources.

The materials in the composite PWFBs in this research were MDPE, steel, and water. Material properties are listed in Table 1. Results from the laboratory tensile testing of the MDPE agreed with the material specification sheets from the manufacturer. Furthermore, the properties of the steel endoskeleton correlated with low-carbon steel which is widely available.

Table 1 Material properties of road safety barrier components

Material	Density (kg/m^3)	Elastic Modulus (GPa)	Poisson’s Ratio	Yield Stress (MPa)
MDPE	958	0.312	0.40	20
Steel	7580	210	0.3	550
Water	1000	-	-	-

Additional steps were taken to model the fluid properties of water. Fluid in the barrier was modeled via SPH particles representing volumetric sections of water in the barrier. The implementation of coupled SPH/FEA was utilized for fluid-structure interaction of the shell membrane with water. SPH particle generation creates free surface regions for two-phase interacting fluids because the particles represent water and empty space represent air inside the hollow container. Generated particles were used efficiently in the system and rapid water sloshing was visualized in the model. The study of water in road safety barrier was studied extensively by the authors in previous research (Gover et al., 2012; Thiyahuddin et al., 2012a; Thiyahuddin et al., 2012b; Jiang et al., 2002).

3. RESULTS

Numerical simulations were executed using multi-processors at the high-performance computing facility that was available to the researchers. The models were solved for 0.2s. Furthermore, bulk kinetic energy, internal energy, plastic strains and dynamic water sloshing were extracted as output analysis parameters.

3.1. Impact Response of Regular PWFB System

In the simulations, the dynamic interaction at the road barrier wall replicates the response of water impacted by a projectile. As illustrated in Figure 2, the numerical simulations provided a realistic description of the behavior of water depicting energy absorption through sloshing and inertial displacement. The variation of peak kinetic energy in relation to the height of water is shown in Figure 3.

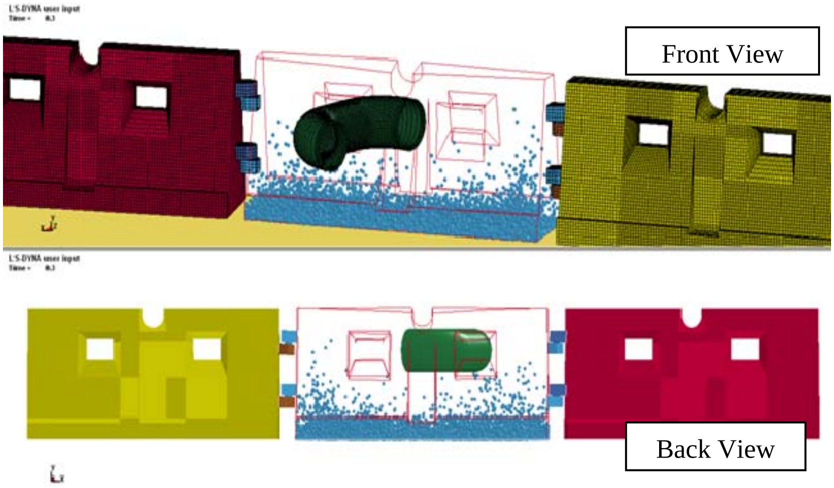

Figure 2 Impact of 25% filled barriers at 80kmh^{-1}

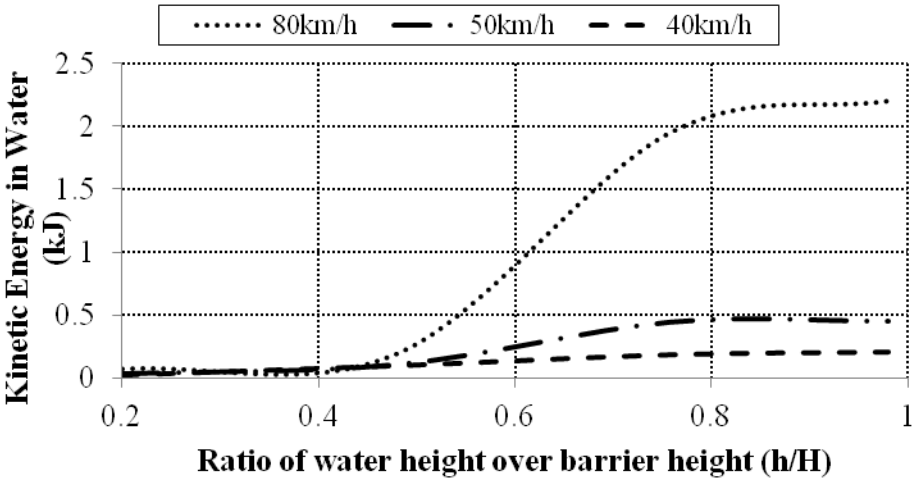

Figure 3 Kinetic energy of water over fill level

Based on the results of the range of the tested impact velocities and water height ratios, energy absorption by water in PWFBs can be optimized if the initial impact is below the free surface level of the water. It is evident that the height of the water must be at least 700mm or 80% filled. The increase of water fill from 80% to 100% will only increase the crash energy absorption by up to 1kJ. Thus, it is recommended that the height of water must be at least at the bumper bar level of a vehicle or slightly higher. Based on these findings, it can be inferred that water alone is inadequate for absorbing the kinetic energy of the impact. Thus, additional materials must be added to increase the energy absorption capability of PWFB systems.

3.2. Impact Response of Composite PWFB System

In this study, the introduction of composite material lightened the strain that was exerted on the main MDPE membrane shell of the barrier. This was evidenced by lower internal energy and reduced strain of the plastic shell compared to those in barriers without integrated steel frames. Such a response lowers the likelihood of breakage occurring in the shell section of the body; thus keeping the water inside the container longer for energy absorption. Figures 4 and 5 indicate the respective energies for impact at 80kmh^{-1} and 25°. We noted that the composite action that occurred in the retrofitted road barriers reduced the demand of energy to be absorbed by water. Maximum kinetic energy absorbed by water was observed in the impact of 100%

filled regular road barriers. With (instead of without) composite materials, water absorbed less energy by up to 62%. The difference in kinetic energy between fill levels was attributed to the amount of water in the road barrier as evidence by an average difference of 17% when using regular barriers instead of composite barriers.

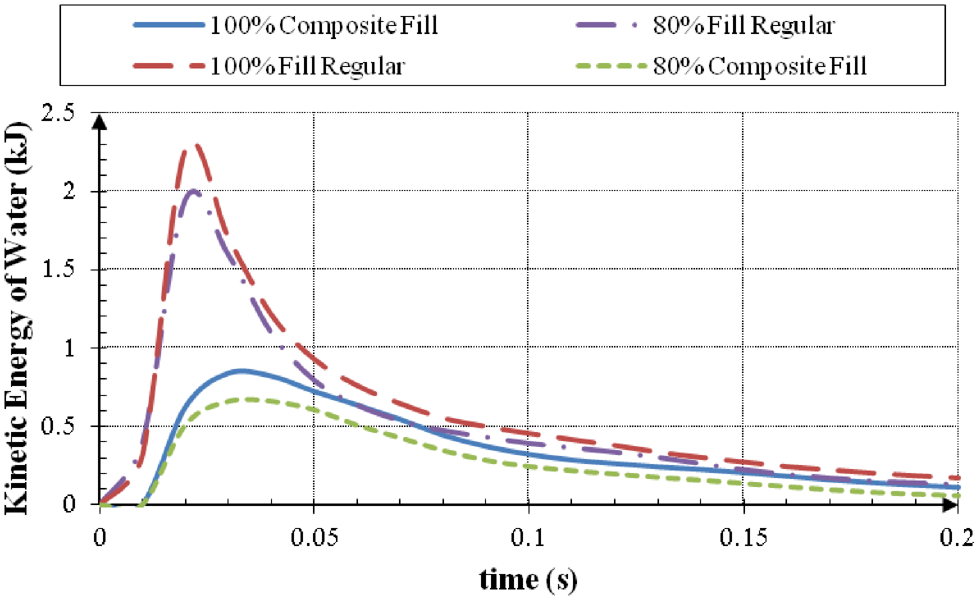

Figure 4 Kinetic energy of water in composite and regular road barriers

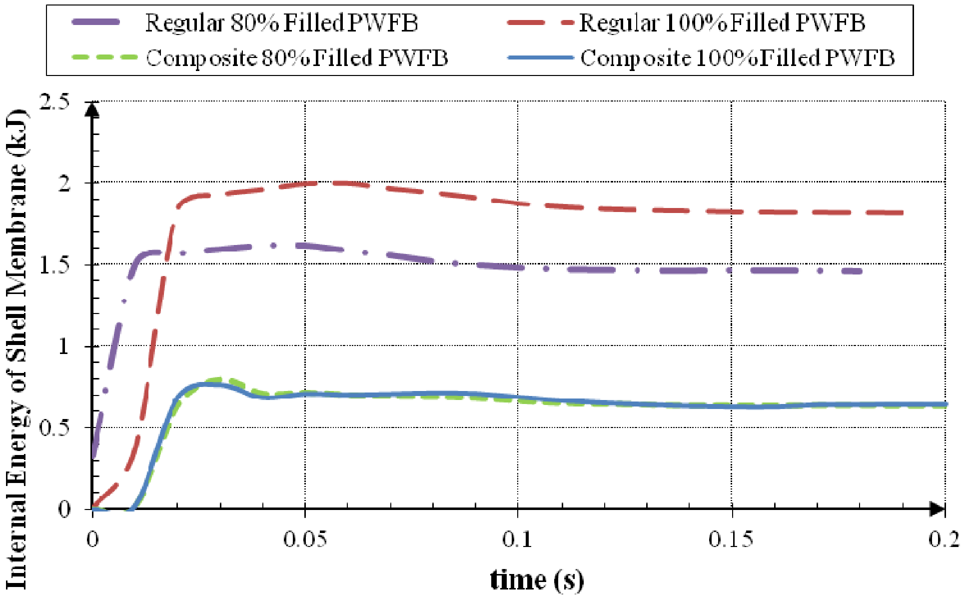

Figure 5 Internal energy timeline-history of composite and regular road barriers

Although deformation is expected in the MDPE shell membrane, local deformation of the outer casing of the composite barrier can be reduced by composite action, and it will prevent the main shell body from being breached due to impact. By comparing the plastic strains between the models, it is evident that the composite barrier is superior to the regular water-filled road barrier. In this research, less strain was exhibited by the shell membrane of the composite barrier over the regular ones. Therefore, preventing breakage of the shell membranes on PWFBs will enable water to remain longer inside the enclosed shell, which in turns prolongs energy absorption through fluid sloshing.

Water inside water-filled barriers absorbs energy by sloshing and inertial displacement. Water also plays another important role inside composite PWFBs. It increases the overall mass of the road barrier, which in turns allows the constituent of the composite in the barrier to absorb energy through water sloshing, deformation and displacement movement. We observed that the addition of water increased the resistance of the road barrier to translational movement, thus allowing composite action to take place when the barrier was subjected to impact.

In the composite barrier, both the kinetic energy of water (Figure 4) and the internal energy of the shell (Figure 5) were nearly identical for both fill levels. This finding reinforces the proposed suggestion that, with the use of composite materials, the amount of water could be limited to 80% of fill capacity for prudent use of water. Figure 6 depicts the sharing of impact energy by the constituents of the composite barrier with 80% fill level and under similar impact conditions. It can be observed that the internal steel frame absorbed the most energy in the composite system for a unit of barrier.

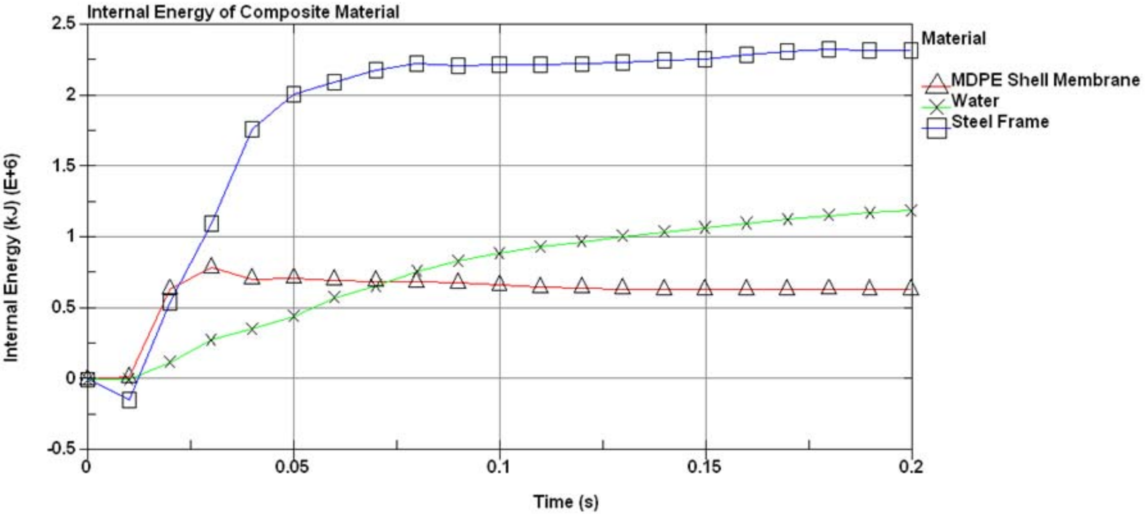

Figure 6 Internal energy of composite materials for impact at 80 kmh^{-1}

The internal energy plot in Figure 6 shows that the stiffness of PWFBs increased because of the addition of internal steel frames to the barriers. The overall shared energy absorption was three times greater than the energy absorbed by a regular water-filled barrier. Ideally, for maximum energy absorption through material deformation by the composite in the road barrier, the unit must not move. Due to the fact that PWFB is temporary road safety structure, it is not possible for road safety barriers to be affixed permanently to the ground. Therefore, although minimal energy absorption and no stiffness increase in the road barrier is be attributed to water inside PWFB, the increase in mass due to the fluid provides the resistance to motion the barrier system required to enable the composite materials to absorb energy from impact.

4. DISCUSSION

4.1. Lateral Displacement of PWFB

Based on the conservation of energy in a PWFB and theoretical method utilized by Hammonds et al. (2012) and Jiang et al. (2002), with E_V as the lateral kinetic energy exerted on a barrier system, m_v as the mass of vehicle, V_v the velocity and θ as the impact angle, Equation 1 gives the lateral kinetic energy produced by a 300kg mass travelling at 80kmh^{-1} at 25° to be 13.2kJ.

$$E_V = \frac{1}{2} m_v (V_v \sin\theta)^2 \tag{1}$$

Equation 1 serves as a rule-of-thumb to observe the redirection capability of vehicles. Based on this equation, any impact that is lower than 40kJ has the tendency to redirect (Hammonds et al., 2012). From the results presented in this paper, composite materials enhance the capability of a PWFB to absorb impact energy which translates to reduction in lateral displacement of the road barrier and increases the threshold value of lateral kinetic energy to allow vehicle redirection.

Although findings from this study remained inconclusive with regards to the post-impact lateral displacement of the road barrier, it is theoretically possible that road barriers with composite action have the ability to reduce lateral displacement. To attain significant lateral displacements however, the length of the barrier model will need to be extended by eight times longer and impacted with a vehicle model with a mass between 1800kg to 2200kg.

4.2. Crashworthiness of PWFB – Regular and Composite Barriers

The kinetic energy of water represents the amount of impact energy absorbed by water, while internal energy of the barrier shell represents the amount of impact energy absorbed by the membrane shell through deformation. In the composite barrier, the impact energy is absorbed by the water, steel frame and the shell membrane. In the regular barrier however, only the water and shell absorb impact energy. The demand to absorb greater energy placed on the shell of the regular barrier can cause an increase in plastic strains, leading to vulnerability of the shell to failure. However, in the composite barrier, there is a reduced demand for the water and the shell to absorb energy. This feature is evident in Figures 4 and 5, which show that the kinetic energy of water and the internal energy of the shell in the composite barrier are less than those in the regular barrier. With composite materials integrated in a PWFB, the road barrier could withstand higher impact velocities. Moreover, the catastrophic deformation of the road barrier can be prevented by integrating steel frame onto the plastic barriers for enhanced crashworthiness.

5. CONCLUSION

From the studies conducted, it can be concluded that:

- It is desirable for the free surface level of water in a PWFB to be higher than the anticipated impact height. A value of 0.8 is recommended for the ratio of the fill level to the barrier height.
- Addition of composite materials to a PWFB enables the sharing in the absorption of the impact energy, and it places a reduced demand on the components.
- The addition of composite material is able to reduce the potential for shell damage under impact, and it enables longer sloshing time of water to dissipate energy.
- The energy absorption capability of a composite barrier is significantly higher than that of a regular barrier and will enable reduced deflection distance in the next generation PWFB.
- Composite barriers with enhanced energy absorption capability and reduced deflection potential will increase the level of safety for motorists and hopefully save lives.

6. ACKNOWLEDGEMENT

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