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Impact and energy absorption of portable water-filled road safety barrier system fitted with foam

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ABSTRACT

Portable water-filled barriers (PWFBs) are roadside appurtenances that are used to prevent errant vehicles from penetrating into temporary construction zones on roadways. A numerical model of the composite PWFB, consisting of a plastic shell, steel frame, water and foam was developed and validated against results from full scale experimental tests. This model can be extended to larger scale impact cases, specifically ones that include actual vehicle models. The cost-benefit of having a validated numerical model is significant and this allows the road barrier designer to conduct extensive tests via numerical simulations prior to standard impact tests. Effects of foam cladding as additional energy absorption material in the PWFB were investigated. Different types of foam were treated and it was found that XPS foam was the most suitable foam type. Results from this study will aid PWFB designers in developing new generation of roadside structures which will provide enhanced road safety.

1. Introduction

Traffic accidents in Australia cost billions of dollars with an average loss of 1400 lives and over 22,000 serious injuries to road users [1,2]. Study conducted by Zhao [3] indicated that roadside construction zones increased the probability of accidents compared to regular roadways. Serious injuries sustained from accidents have long-term impacts with high medical costs, rehabilitation and permanent disabilities affecting the society. A single vehicle accident is defined as one in which a single vehicle impacts onto roadside objects such as road barriers, trees, traffic poles, etc. In 2007, these types of accidents alone accounted for 44.2% of the overall fatal crashes in Australia [4]; higher than crashes involving multi-vehicles and pedestrians. Portable water-filled barriers (PWFBs) are temporary roadside structures that are used to prevent errant vehicles from penetrating into construction sites on roadways. These barriers are in the semi-rigid group of roadside barriers. Unfilled PWFBs are lightweight and easy to be transported and assembled. Once filled with water, PWFB has the potential to display good crash attenuation characteristics at low to moderate speedways.

There is currently inadequate public knowledge surrounding PWFB systems. Majority of the existing literature pertaining to road safety barrier performance is related to concrete and steel road safety barriers. The recently released Manual of Assessing Safety Hardware (MASH) standard specified the re-directional requirement that road barriers need to exhibit, with which some of the currently approved PWFBs may not comply [5]. Furthermore, the Federal Highway Administration (FHWA) explicitly states that all polymeric road barriers should have steel reinforcement augmented to the structure [6]. The addition of the steel frame reinforcement will increase the crashworthiness of the barrier. Moreover, local road transport agencies require that the manufacturer disclose the expected peak lateral displacement of the barriers and the recommended operational length of barrier systems.

The use of PWFB at road-works has been plagued with very high lateral displacements compared to other road safety barriers in their classification. The flexible material used in the fabrication of its shell (or body) makes the PWFB less stiff and lighter than other portable roadside structures and results in very high lateral displacements upon vehicular impacts. This has led to the current regulations to limit the use of PWFB only up to 50 km/h zones [6,7]. The PWFB is hence susceptible to breakage and the response of the

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vehicle post-impact with the barrier is highly unpredictable. The use of polymeric foam claddings alongside the steel skeleton has been proposed to supplement the crash energy absorption of the PWFB and to enhance its performance with regards to restricting lateral displacement and enabling the re-direction of the impacting vehicle. Crash attenuating foams have been widely applied across many industries for crashworthiness due to their lower manufacturing costs and high energy absorption capabilities [8–10]. There are many kinds of foam in the market, and a plethora of choices are available due to the freedom in the chemical composition of the manufactured foam. Initially, polymeric foam was fitted onto permanent concrete walls for protection in racing circuits [11–13]. The application of foam as crash attenuators fitted onto temporary concrete barriers has also shown the potential to mitigate crash severity in racing car accidents [10]. The use of foam as a primary crash attenuator in passenger vehicles has been extensively studied [14–16]. It is envisioned that the combined composite action of steel and polymeric foam will increase the stiffness of PWFB to restrict displacements and redirect errant vehicles in a during a vehicle impact. The application of foam in crash attenuation of a single PWFB has been studied by Gover [17] who found that the composite action could provide supplemental energy absorption. However, the impact energy absorption and performance of a realistic PWFB system is yet to be investigated.

In order for a PWFB system to be deemed acceptable, it must exhibit two key performance characteristics. The MASH Test Level-3 standard states that a PWFB system must be tested under a crash condition by a 2270 kg pickup truck at 25° with 100 km/h impact speed. The PWFB must redirect the encroached vehicle within the acceptable range, in-line with the exit box concept [18]; and secondly the lateral displacement must be accurately estimated by the PWFB developer and it should ideally be less than 2.0 m. The effect of foam as a suitable crash energy attenuator and its contribution towards the performance of the PWFB has not been investigated. The type of foam used as the cladding may have a positive effect on the composite action and crashworthiness of the PWFB system. But, the high displacement synonymous with the PWFB may yet be an impediment towards the acceptable performance of the composite PWFB system.

This paper developed a numerical model of a composite PWFB system and validated it against results from a series of full scale experimental tests. A newly developed pneumatic impact testing machine was fabricated exclusively for impact testing of the PWFB system. Due to the complexities in obtaining data from the flexible PWFBs, a new procedure to extract data was used to obtain information on their impact response. Dynamic computer simulations were carried out to probe the composite interaction in the PWFB system when impacted with a rigid bumper head (as in the experiments). The impact energy absorption capabilities of different types of foam claddings attached to the composite PWFB system were then treated to evaluate its performance with regards to its re-directional capability and lateral displacement. The commercially available and widely used explicit Finite Element Analysis (FEA) solver code LSTC LS-Dyna v971 was extensively used in the numerical analysis.

2. Experimental testing

2.1. PWFB used in experiments

There are many types of PWFBs produced commercially and available in the market. This research worked closely with an industry partner who provided several regular and retrofitted Centurion 2M road safety barriers as depicted in the drawings in Fig. 1. Fig. 2(a) illustrates the regular Centurion 2M road barrier and Fig. 2(b) the retrofitted one. Regular PWFB is merely a hollow polymeric shell, while the retrofitted PWFB is a modification of the regular barrier with the addition of an inner steel endoskeleton and outer Polyurethane (PU) foam cladding.

The main components of the PWFB comprises of two parts. The main body is the central hollow section of the barrier. Besides this, the joint mechanism is enabled by pins in the pin-hole sections provided on the sides of each individual PWFB as seen in Fig. 2. The road barriers are made of Medium-Density Polyethylene (MDPE) shell and fabricated via a rotational-moulding process. When empty, each regular barrier weighs 30 kg and 56 kg when retrofitted. All the barriers tested were filled with water. The fill level was set to the recommended value of 200 kg per barrier which is 25% fill-capacity. Due to manufacturing uncertainties, the thickness of the shell varied between 3.0 mm and 7.0 mm across the body of the barrier. Hence, an average thickness of 5.0 mm was assumed in the analysis.

2.2. Testing facility

2.2.1. Horizontal impact test rig

Full scale testing was conducted using a newly developed horizontal impact test rig, as shown in Fig. 3. The testing facility consists of a moving carriage which accelerates 550 mm horizontally along specified guide rails; and a fixed section which is bolted to the ground. The impact carriage is accelerated by stored air-pressure inside the pressure vessel. The pressure vessel is connected to several bellows which expand when pressurized air is released into them. This in turns propels the carriage horizontally along its guide rails. The machine is capable of filling up to 8 MPa of pressurized air. The section that travels is mounted with an impact head and additional deadweight mass, as necessary. The custom built impact head, initially weighing 80 kg, was added with 300 kg additional mass using modular deadweight mass. With the mounted mass, the machine is capable of propelling the carriage up to 8 m/s. This impact head which models the front-end bumper of a vehicle was fabricated using two steel elbows connected to a steel pipe and its height matched that of typical vehicle bumper bars.

The horizontal impact test rig is equipped with appropriate instrumentation to obtain kinematic data from the moving carriage. The gauge in the pressure vessel provides real time information of air-pressure in the vessel. A string potentiometer and a 100 G accelerometer mounted on the rig provide analogue data of displacement, velocity and acceleration of the moving carriage throughout the acceleration, impact and end phases. In addition, a proximity probe and a steel encoder rail were used alongside the above mentioned sensors to provide digital outputs of the carriage's kinematics.

2.2.2. High speed camera for data acquisition

High speed cameras are visual acquisition devices which take photos at high sequential rates and compile still images to a video. The IDT X-Stream XS-4 high speed camera was available for this research and effectively used in the experiments. This camera is able to capture up to 5000 frames-per-second with 512 × 512 image resolution. Subsequently, outputs acquired from the tests were analysed using video analysis tracking software. The open-source Tracker video analysis software [19,20] was used in the research to plot the displacement vs. time response of the PWFB. Fig. 4 displays the setup of the high speed camera overlooking the region of interest which is shown as the inset in the figure.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.ijimpeng.2014.04.008.

The dynamic response of the barriers and the joints were captured using the high speed camera. The camera was pre-set to