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Effect of joint mechanism on vehicle redirectional capability of water-filled road safety barrier systems

M.I. Thiyahuddin[a], D.P. Thambiratnam[b], Y.T. Gu[a,*]

[a] School of Chemistry, Physics and Mechanical Engineering, Science and Engineering Faculty, Queensland University of Technology, Brisbane, Queensland, Australia
[b] School of Civil Engineering and Built Environment, Science and Engineering Faculty, Queensland University of Technology, Brisbane, Queensland, Australia

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ABSTRACT

Portable water-filled barriers (PWFBs) are roadside appurtenances that prevent vehicles from penetrating into temporary construction zones on roadways. PWFBs are required to satisfy the strict regulations for vehicle re-direction in tests. However, many of the current PWFBs fail to re-direct the vehicle at high speeds due to the inability of the joints to provide appropriate stiffness. The joint mechanism hence plays a crucial role in the performance of a PWFB system at high speed impacts. This paper investigates the desired features of the joint mechanism in a PWFB system that can re-direct vehicles at high speeds, while limiting the lateral displacement to acceptable limits. A rectangular "wall" representative of a 30 m long barrier system was modeled and a novel method of joining adjacent road barriers was introduced through appropriate pin-joint connections. The impact response of the barrier "wall" and the vehicle was obtained and the results show that a rotational stiffness of 3000 kNm/rad at the joints seems to provide the desired features of the PWFB system to re-direct impacting vehicles and restrict the lateral deflection. These research findings will be useful to safety engineers and road barrier designers in developing a new generation of PWFBs for increased road safety.

1. Introduction

Road crashes in Australia cost billions of dollars with a yearly average loss of 1400 lives and another 32,500 persons with serious injuries requiring hospitalization (Langford and Newstead, 2008; Australian Transport Council, 2011). A single vehicle crash is defined as one in which a single vehicle impacts onto roadside objects such as road barriers, trees or traffic poles. Run-off-the-road crashes accounted for 30% of serious casualties in single vehicle crashes (Australian Transport Council, 2011). These types of crashes alone accounted for 44.2% of the overall fatal crashes in Australia (Bureau of Infrastructure Transport and Regional Economics (BITRE), 2007); this is higher than crashes involving multi-vehicles and pedestrians. Research conducted by Zhao and Garber (2001) concluded that roadside construction zones increased the probability of crashes compared to regular roadways. Serious injuries sustained from a crash have long-term impacts involving high medical costs, rehabilitation and sometimes permanent disabilities of the injured persons. Research conducted on the causes that induce crashes at roadside construction zones by Harb et al. (2008) found that heavy vehicles and changes in roadway geometry increase the likelihood of single-vehicle crashes due to narrower lanes and driver inattentiveness. Crash mitigation studies are therefore essential to reduce these hazards at work-zones.

Portable water filled barriers (PWFBs) are temporary roadside appurtenances that are used to prevent errant vehicles from penetrating into roadway construction sites. Unfilled PWFBs are lightweight and can easily be transported and moved. Unlike concrete barriers, the kinetic energy imparted to a plastic barrier results in lateral and longitudinal displacements of the barrier. A large lateral displacement increases the probability of vehicle pocketing, snagging and over/under-riding the barrier. Road barriers have undergone significant developments since the inception of the New-Jersey Barrier in 1955. The response of a water-filled barrier is highly dependent on the impact speed, the location of the impact and the angle at which the impact occurs. Large angle impacts (more than 10°) exponentially increase the probability of injuries related to whiplash to the occupants (Salgo, 2004). Testing regulations for the angle of impact are set by the road authorities, with the angles ranging from 20° to 25° (European Committee for Standardization, 1998, 2010; Fishburn, 1999; Rechnitzer, 1999;

* Corresponding author. Tel.: +61 731381009.
E-mail addresses: d.thambiratnam@qut.edu.au (D.P. Thambiratnam), yuantong.gu@qut.edu.au (Y.T. Gu).

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American Association of State Highway and Transportation Officials (AASHTO), 2009). A lower impact angle results in less lateral kinetic energy that the barrier needs to sustain in order to re-direct the vehicle. If the PWFB system is able to re-direct the vehicle at 25°, it is implied that it will be able to do so at lower angles. If improperly designed, these barriers may in fact cause more harm than good (Grzebieta et al., 2005). With this in mind, road barrier designs have undergone numerous revisions to ensure that the barrier itself does not become a hazard to passengers in vehicles and the surroundings (Troutbeck, 1999). In the Australian National Safety Barrier Assessment Panel report, the performance of water-filled barriers to re-direct vehicles was deemed acceptable only for lateral kinetic energy of 40 kJ or less (Hammonds et al., 2012). Based on this, the PWFBs are restricted to roadways where the speed limit is 50 km/h. Hence, it can be deduced from this observation that, at high-speed impacts, current PWFBs are either unable to re-direct vehicles or they exhibit significantly large lateral post-impact displacements.

Since a PWFB is known to perform well at low speeds, its performance at higher speeds of 80 km/h and 100 km/h needs to be improved. Joints represent a discontinuity in a road barrier system. In the event of a vehicular impact, the joints are expected to structurally withstand the loads exerted by the impact force. At present, it is not clear how the characteristics of the joint mechanism affect the performance of road safety barriers in high-speed vehicular impacts. However, failure of the joints due to complete tearing or fracturing of the barrier region surrounding the joint will render the barrier ineffective for vehicle re-direction. There is considerable literature on the available mechanical fasteners, but most of it pertains to fasteners made for portable concrete barriers and W-beam steel sections (Coon and Reid, 2006; Bayton et al., 2008a,b, 2009; Ulker et al., 2008; Bayton, 2009). The joining mechanism of a barrier system is an important feature as it enables the consolidated action of the barriers as a system and prevents errant vehicles from encroaching into work zones. Current PWFB joints consist of pin-joint mechanisms designed for quick setup and disassembly on-site. The pin-joint concept is widely used in the road barrier industry either by the direct male–female connection or by using a steel-pin intermediary. In numerical simulations, there are four methods to model the joining mechanism in road safety barriers: merging nodes, using tied node sets with failure, using non-linear springs, and detailed modeling of the joint (Tabiei and Wu, 2000). The first three methods are easier to implement, but do not provide accurate results, while the detailed modeling method is time-consuming. In this context, the use of rigid revolute joints has provided a simple method to study the effect of stiffness at the joint for vehicle re directional capability of the barrier system in high speed impacts (Thiyahuddin et al., 2013b,c).

This research investigates the response of a Portable water-filled barrier (PWFB) system under vehicular impacts and evaluates the effect of the joint mechanism to enable vehicle re-direction by the PWFB system. Initially a Finite Element (FE) numerical model of an array of PWFBs was developed and validated using results from an impact test. The modeling techniques were then used to develop a 30 m long "wall" consisting of a number of PWFBs connected to each other through appropriate joint mechanisms. This wall was subjected to high-speed impacts by real vehicle models. Numerical modeling of the joint mechanism was achieved via a new technique which provides an attractive option to connect two adjacent bodies via rigid revolute joints. The stiffness of the barrier was varied by varying the shell thickness from 10 mm to 50 mm to evaluate the ability of the barrier system to re-direct vehicles at high speeds. The rotational stiffness required at the joint to re-direct a vehicle using the PWFB system was assessed. The lateral displacement of the PWFB and the rotational angle of the joints were extracted from the numerical results to determine the optimal parameters required for vehicle re-direction.

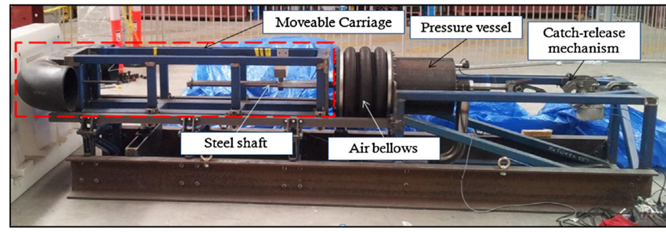

Fig. 1. Horizontal pneumatic impact rig.

2. Experimental

The standard approach to the study of a phenomenon consists of developing a numerical model based on experimental data and then using that model for further analysis and parametric studies. Data related to road safety barriers are based on real vehicle impact tests of the road barriers. Full scale vehicle-barrier tests are very costly (Gupta and Kelkar, 2006) and only the impact reactions of the barriers and vehicles are obtained as the outputs of normal tests. In early 2013, an intensive program was launched at the Pilot Plant Precinct of the Queensland University of Technology to test plastic road safety barriers, as part of a research program to develop a PWFB system that has vehicle re-direction capability at high speed impacts.

2.1. Testing facilities

A novel pneumatic horizontal impact machine (Fig. 1) was built and used as a surrogate to exert an impulsive force on the road safety barrier. This impact rig consists of fixed and unfixed sections. The only moveable section in the rig is the impact carriage (highlighted inside the dashed red rectangle in Fig. 1), which houses the impact head and additional deadweight mass. The rig is capable of propelling the carriage 550 mm horizontally. Multiple sensors are fixed on the impact carriage to record triangulated kinematic data of the impact carriage. A single-axis accelerometer is attached to the carriage to measure accelerations up to 100 G. In addition, a string potentiometer is installed, which measures the transverse displacement when the carriage is propelled. Thirdly, a proximity probe is installed to digitally measure the velocity of the carriage. In the experiment, the height of the impact head was set at 600 mm relative to the ground. Additional modular deadweights could be added on the impact carriage by bolting them directly behind the impact head. The road barriers were impacted at a variety of impact speeds from 4 m/s to 8 m/s with a 300 kg impacting mass. In this paper, results from the first two tests are presented.

The impact head, shaped in the form of a vehicle frontal protection system (bull bar), was fabricated using steel pipes and elbows. Although the shape was rudimentary and not truly representative of the frontal section of a vehicle, it is a surrogate to impart an impulsive force on the PWFB system. At maximum filled capacity of the pressure vessel, the pneumatic impact rig is capable of launching the carriage with 10 kJ of kinetic energy. Although full-scale Manual of Assessing Safety Hardware (MASH) Test Level 3 testing is required to capture the actual PWFB response, the pneumatic horizontal impact rig allows preliminary research to progress with a means to validate the joint stiffness, the re-direction capacity and the lateral displacement of the PWFB, without having to resort to full-scale testing in the early stage of product development. It is acknowledged that such polymeric road barriers often fail as a result of plastic material cutting and fracture (Grzebieta et al., 2005) at high-speed impacts. However, the present research relates to the first stage of design which involves assigning appropriate values of joint stiffness for vehicle re-direction by the PWFB system with