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# Revolute Joint Approach to Model Joint Mechanism in Water-filled Road Safety Barriers

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## Abstract

Portable water-filled road barriers (PWFB) are roadside structures placed on temporary construction zones to separate work site from traffic. Recent changes in governing standards require PWFB to adhere to strict compliance in terms of lateral displacement and vehicle redirectionality. Actual PWFB test can be very costly, thus researchers resort to Finite Element Analysis (FEA) in the initial designs phase. There has been many research conducted on concrete barriers and flexible steel barriers using FEA, however not many was done pertaining to PWFB. This research probes a new technique to model joints in PWFB. Two methods to model the joining mechanism are presented and discussed in relation to its practicality and accuracy. Moreover, the study of the physical gap and mass of the barrier was investigated. Outcome from this research will benefit PWFB research and allow road barrier designers better knowledge in developing the next generation of road safety structures.

## Introduction

Portable water-filled road barriers (PWFB) are roadside structures placed on temporary construction zones to separate work site from moving traffic. Recent changes in governing standards require PWFB to adhere to strict compliance in terms of lateral displacement of the road barriers and the vehicle redirectional response. The structure of PWFB consists of two main parts defined as the main body and the joint mechanism. The main body is the central part of a barrier unit where it is main area of impact by vehicles. Hence, the main body of the barrier is usually designed to house additional energy absorption materials such as water, steel frames and crash energy foams. The main body is hollow on the inside, which allows water to be added for additional mass in the system. It is common practice for the barrier to be empty when transported to the worksite. Then, it is filled with water to ensure the barrier remain static after installation. The weakest sections in most structures are often the joints. This is where the product fails, wears or tears apart [1]. The joining mechanism of a barrier system is an important part as it enables the consolidated action of the barriers in the system and prevents errant vehicles from intruding into unwanted spaces. The connections are designed for a short-term usage and are meant to be easy for the roadside crew to install and disassemble. Joints represent a discontinuity in the road safety structure. In the event of vehicular impact, the joints are expected to structurally withstand the shear load exerted by the impact force. Failure of the joint will render the barrier ineffective as a crash attenuator. There is considerable literature on the currently available mechanical fasteners; most pertain to fasteners made for steel and concrete road barriers yet not much on PWFB joint mechanism.

Real standardize test involving actual vehicle impacting a system of PWFB is costly (up to $25,000 per test). Therefore, researchers and designers opted for more cost effective solution to develop next generation PWFB. The use of explicit model analysis allows thorough research with the aid of super-computing facility. This method is cost-beneficial for the initial developmental stages of product design. Currently there are four methods to model joining mechanism on road safety barriers as outlined by Tabiei et.al [2] which are ***merging nodes, using tied node sets with failure, using non-linear springs*** **and** ***detailed modeling of the bolts***. Each of these methods has implementation advantages and disadvantages during the design phase. However, none of these methods were suitable to achieve rapid modeling of the joints that outputs realistic results to mimic real joint response in water-filled barriers. This paper proposed a new method in modeling the joints between adjacent units of PWFB. A nodal based approach is suggested to represent the connection of the road barrier joints. This research probes valuable information pertaining to the redirecting qualities of PWFB after impact with an errant vehicle. This will in turn allow road safety barrier designers to create adequate joint support that produce predictable outcome from the system. The correct specifications of joint characteristics alongside composite crash attenuators [3] are envisioned to decrease the severity of single vehicle impact involving PWFB.

## Experimental Test

The standard approach to the study of an event consists of developing a numerical model based on experimental data. Very little data is available with regards to flexible water-filled barriers. Initially, laboratory tensile testing was conducted to obtained properties of the MDPE [4] and afterwards experiment testing of PWFB was executed. The aim of the test was to corroborate results between numerical model and experimental results. A chain of road safety barriers consisted of 3 PWFB units were assembled and impacted using a pneumatic horizontal impact rig. The barrier was impacted at 6ms$^{-1}$ with angle of 55° by the fabricated impact head which represents a vehicle front bumper. The mass of 300kg were assigned to the impact head. The lateral displacement of impacted barrier and adjacent ones (aptly assigned *Barrier A* and *Barrier B*) was recorded by high-speed camera video and subsequently plotted to get the displacement-time history. Friction in the test was accounted via a simple friction test. These tests were conducted to determine the coefficient of friction between the barriers and the covered PE floor. It was found that the static and dynamic coefficient of friction to be 0.39 and 0.34 respectively.

Firstly, a full scale model was constructed. The joint mechanism follows recommendation by Tabiei [2] to construct detailed model of the actual joint itself. Subsequently, the joint mechanism was replaced with the revolute joints as proposed in this paper. Results of the numerical models and experimental test were combined in a single plot. Both numerical simulations were executed with similar impact parameters to the performed experiment. The displacement over time of *Barrier A* and *Barrier B* were plotted. Comparative evaluations were done by analysing the lateral displacement response of the model with the lateral displacement from experiment.

## FE Numerical Model

### FE Model of Portable Water-Filled Barrier System

In general, a PWFB consists of a hollow rectangular polymeric structure that can be filled with water. The external dimensions of a single water-filled barrier are approximately 2000mm (L) x 500mm (W) x 900mm (H). Each PWFB consists of two separate parts (main body & joint mechanism). The main body is the central section of the barrier which is subjected to impact. The joint mechanism connects the barrier to adjacent ones. The main body of the road barriers was constructed from 2D shell elements with 8.0 mm specified thickness. The Belytschko-Tsay [5] single integration-point shell formulation was used with volume and stiffness based hourglass control element formulation. Based on the friction test conducted in the experiments, the friction coefficient in the model was set at 0.35 as an average between static and dynamic coefficient of friction.

Previous methods of modeling joints as outlined were either time-consuming or inapplicable in PWFB. Thus this research investigates the use of revolute joint to model connections in the FE model of PWFB. The revolute joint described by Hallquist [6] is defined as a rigid constraint in the model to represent the pin-joint setup. This method consists of nodal points within two nodal pairs e.g. (1, 2) and (3, 4) shown in Figure 1 (i) and (ii). These nodal pairs must coincide in the initial configurations and be far apart as possible to obtain best behavior of a pin-joint. The nodal pairs are connected to the main body of the barrier via beam elements. The use of revolute joint simplifies the joints as an ideal rigid connection between barriers i.e. friction, slips, and disjoints were disregarded for quicker solution time. The objective in this research is the rotational attributes of PWFB in redirecting vehicles; therefore the deformation at the main shell was assigned rigid properties. Furthermore, water is surrogated with mass of 300kg/m over the longitudinal length of the PWFB. Overall, the system consisted of 15 separated rectangular barriers connected by 14 joining mechanism. The vehicle impacts the middle section of the system close to Joint No.7. All joints were allowed free rotation; limited to only the physical gap separating one barrier from the other. A FE vehicle model was used against the expanded PWFB barrier system and with impact velocity 100kmh$^{-1}$ at 25°. The lateral displacement at the main impacted joint (Joint No.7) was extracted for analysis. The mass effect and physical gap between PWFB was then investigated in relation to the lateral displacement response of the PWFB after collision with a vehicle model under standardized test. Furthermore, the friction contact between the PWFB and ground was set nominally at 0.30 as per the friction test conducted in the experimental phase.

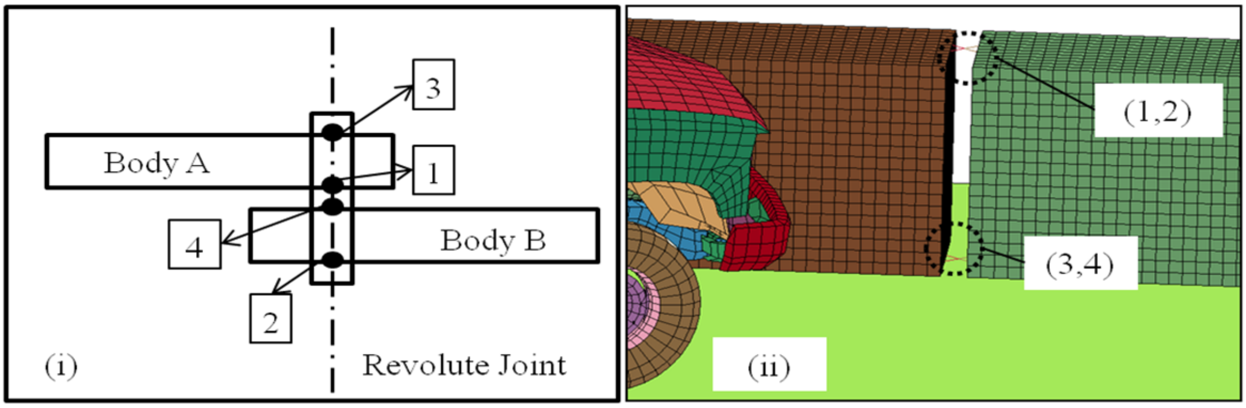

Figure 1: (i) Revolute joint as described in [6]; and (ii) Revolute joint in the numerical model

### FE Model of Vehicle

To understand the performance characteristics of a PWFB, it must be impacted by a vehicle. This research opted to use the opportunity to include a real vehicle in the study in order to increase the applicability of this research in real-world crash. The vehicle chosen was the 2000 Chevrolet C2500 pickup truck [7]. The FE model was developed by the NCAC through reverse-engineering an actual truck model. The FE model was then tested and validated through numerous analyses [8, 9]. This vehicle model was chosen because it fits the criterion of vehicles to be tested in MASH 08 standard.

## Results and Discussion

### Validation of Joint Mechanism Method

Three unit of PWFB was assembled and impacted in the experiment. Figure 2 illustrates the performance of each joint modelling methods compared to experimental result. It can be seen that detailed modelling of the joint yield close correlation with the experimental test. In detailed FEA, the delay in *Barrier B's* reaction is attributed to the joining mechanism. The joint creates a discontinuity between the barriers, which reflect on the lag of reaction in *Barrier B* when *Barrier A* was impacted. On the other hand, simulation with simplified revolute joints shows the movement of *Barrier B* instantaneously when *Barrier A* was impacted.

The revolute joint resulted in an almost direct response of *Barrier B* after impact. This was expected because the revolute joint creates an 'ideal' joint between adjacent barriers. However, in an extended array of PWFB, the delayed response of barriers further downstream or upstream from the impact location will be more apparent when detailed FEA of the joints are used. Nonetheless, the revolute joint option provides a middle-of-the-road alternative between oversimplified nodal options and full detailed FEA option as outlined by Tabiei [2]. The simplified nodal and spring options inaccurately model the joint mechanism. The simplification requires nodes proximity to be near enough to one another. This inhibits the total response of the PWFB system consisting of many units of PWFB aligned in series from being observed. On the other hand, full detailed FEA requires significant modelling time to produce design-specific joints. The trial-by-error repetition for detailed FEA method requires significant amount of design and computational time. The utilization of revolute joint concept creates a generic joint of the mechanism definition for simplification of the problem at hand. From the validated numerical model, the results indicate that the revolute joint is a viable method to model the joint mechanism in PWFB.

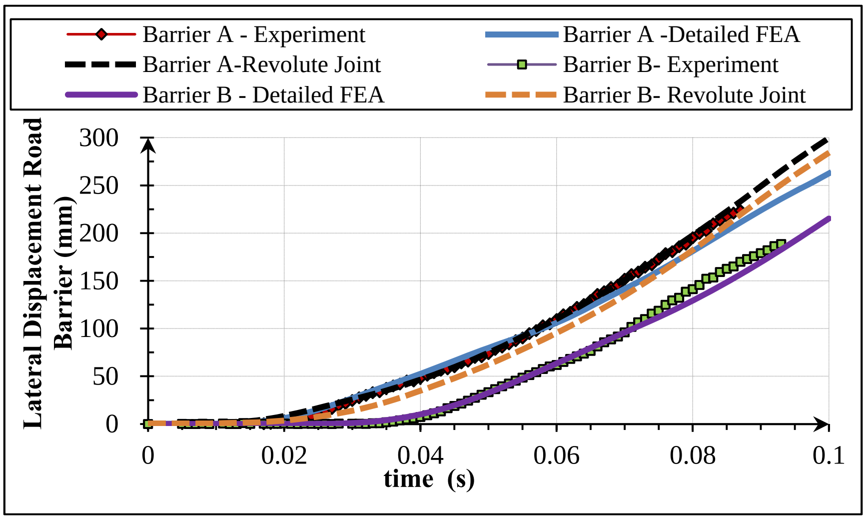

Figure 2: Validation of joint modelling simulation methods with experimental results

## Numerical Study of Joint Mechanism and Road Safety Barrier Chain

PWFB with revolute joint system was extended to include a vehicle model and a longer PWFB section. The impact of the vehicle was executed in accordance with MASH08 standards i.e. 100kmh$^{-1}$ impact at 25°. An example of the event is illustrated in Figure 3. The vehicle was observed to contact the chain of barriers approximately at 0.01 seconds. A secondary impact was recorded at 0.25 seconds when the rear of the vehicle hit the PWFB. Next, the response of the vehicle after impact varied depending on the parameters such as the physical gaps, mass and angle of impact in the simulation.

The physical gap between road barriers is defined as the distance between two adjacent individual units aligned in a system of PWFB. Joints were allowed to freely rotate before touching adjacent barriers. The deformation of the road barriers due to impact with the vehicle and interaction of the barriers on the edges when touching were considered rigid. Observation of simulation reiterations suggests that the revolute-joint method was able to represent a discontinuity similar to a pin joint in real application. The joint allows rotational movement limited to the space available to the barrier. The movement of the barrier is stopped only when one edge touches with the adjacent barrier. The vehicle was redirected after impact with varying exit angle which correspond to the initial gaps in the barriers.

The results shown in Table 1 reflect the effect of the physical rotational freedom caused by the discontinuity in the PWFB system. Large rotations exhibited at the barrier joints allow bigger lateral displacement in the system in order to redirect the vehicle at 60kmh$^{-1}$. Based on these results, the maximum lateral displacement will be larger than 2.0 meter if the data was extrapolated to higher velocity of 100kmh$^{-1}$ regardless of the physical gaps assigned between the barriers. This is not preferred considering the width of road that needs to be closed so that the system is able to be installed. On the other hand, it can be observed that in order to limit the maximum lateral displacement, the distance between each individual barrier must be as near to one another.

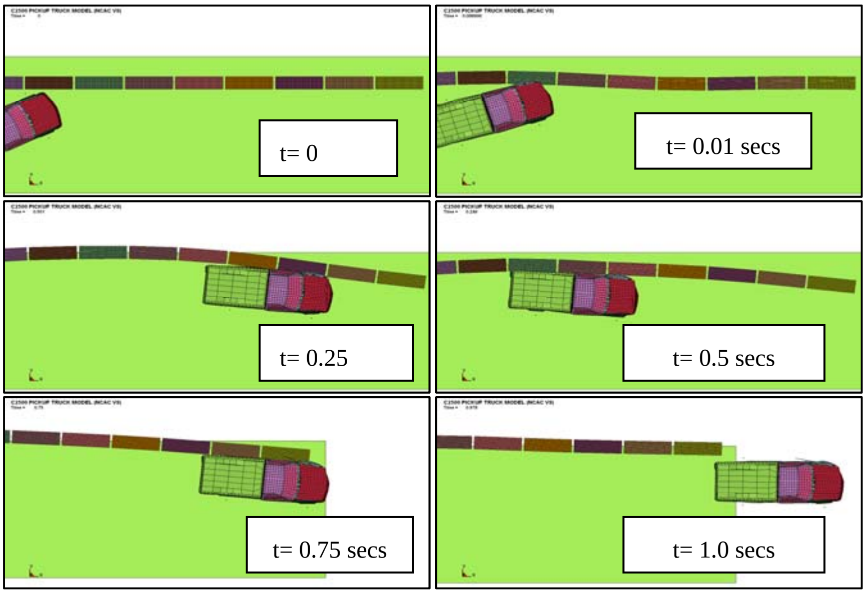

Figure 3: Time lapse of vehicle-barrier 100kmh$^{-1}$ impact at 25°

Table 1: Analysis result of physical gap between road barriers at 60kmh$^{-1}$ (at Joint No.7)

| **Physical Gap, mm** | **Maximum rotation Θ, (degrees)** | **Maximum Lateral displacement, (m)** |
|---|---|---|
| 20 | 3.40 | 0.973 |
| 60 | 13.3 | 1.525 |
| 100 | 18.6 | 1.701 |

Water provides additional deadweight in the PWFB system. Additional mass ensures the barriers remained stationary once it is installed. Furthermore, increased resistance of the PWFB to movement allows energy to be absorbed by the crash energy absorbers integrated onto the PWFB. Water fills the cavity of the hollow plastic road barriers. The barrier's capacity to contain water depends on the individual design of the barriers. In general, for a barrier with 2000mm (length) x 900mm (height) x 500mm (width) dimension, the fill capacity of the water inside the barrier is 900 litres. Water mass is defined in the form of kg/m longitudinally with respect of the PWFB system. Therefore, mass was varied from 300, 360 to 400 kg/m to represent the mass of water within the system. The initial gap of the barrier was set at 20mm based on the best result from analysis. The PWFB system with different water levels was impacted with a vehicle at 100kmh$^{-1}$ and 25°. Results of the maximum lateral displacement inputted from the maximum lateral translation of the PWFB system was recorded and tabulated in Table 2.

Table 2 : Mass effect of water in PWFB system for impact at 100kmh$^{-1}$ at 25°

| **Fill Level (%)** | **Fill Rate (kg/m)** | **Maximum Lateral Displacement (m)** |
|---|---|---|
| 66 | 300 | 1.70 |
| 80 | 360 | 1.52 |
| 88 | 400 | 1.40 |

Based on the result presented in Table 2, it is evident that more water in a unit of PWFB will yield less lateral displacement in the unit of barrier. However, additional water in a barrier means water requirement in the barriers will exponentially increase the longer the length of the barrier system is in a work zone. Thus, high fill levels are not a prudent water management option.

## Conclusion

This study examined the feasibility of a new method to model pin-joints in PWFB impact with vehicle applications. Experimental test were conducted and validated with numerical model. Other parameters were varied to see the performance of the joints in which encourages vehicle redirection in a MASH08 impact. Furthermore, revolute joints could be integrated with other aspects of the PWFB such as fluid-structure interaction to obtained accurate response of vehicle-PWFB impact [10-12]. Hence, future analysis of PWFB system can be cost-effectively probed with great accuracy. From this research, it can be concluded that

- Revolute joint is a practical method to model pin joint connection in PWFB application.
- For best result in redirection, the physical gap between adjacent barriers must be minimal as possible.
- Lower rotational angle from a pin joint will encourage redirection in the vehicle.
- Mass effect of water in PWFB is evident with more water purely for inertial displacement.

## Acknowledgement

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