DEVELOPMENT OF ROADSIDE SAFETY BARRIERS USING NATURAL BUILDING MATERIALS

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Abstract
Abstract text – The Irish National Roads Authority is seeking low-cost roadside barrier solutions for National Secondary Roads suitable for implementation following road realignment projects. This paper introduces methods for the development of new designs for roadside safety barriers which will utilize freely available low-cost natural building materials (e.g. stone wall, earth etc.) and will meet the cost, aesthetic and engineering requirements.

A fundamental momentum-based impact analysis has indicated that the mass available in natural building materials has the potential to provide sufficient containment of passenger cars on national secondary roads. The analysis indicates that it may be possible to replace the stiffness present in existing steel, concrete and steel-wire barrier designs with mass by using earth and stone mounds of approximately 1 metre depth.

The paper also evaluates the potential of employing well-established computational modelling techniques to test the ability of the proposed new design concepts to meet the required standards of safety as defined by the European Standard EN 1317. The detailed computation modelling has been carried out using the multibody dynamics based software package MADYMO.

The MADYMO models are benchmarked using data from existing tests at the Transport Research Laboratory (TRL) in the UK, and the force deformation response of the proposed components for the designs will be experimentally evaluated.

In addition, a new method for scaling physical impact tests which allows tuning of the required crush characteristics and acceleration time histories will be used. In this way, scaled physical tests will be carried on to get preliminary results and to test the viability of the proposed designs.
Introduction

Safety in motorised road mobility is a critical socio-economic issue in ECMT and EU countries. To maintain and improve safety on roads it is essential to provide appropriate road safety barriers. The performance levels of roadside barriers are stipulated in the European Standard EN 1317 “Road Restraint Systems” [1]. Road safety barriers that meet the Standard provide certain levels of vehicle containment, limit acceleration based injury risk, act to properly redirect errant vehicles back on the road and provide guidance for pedestrians and other road users. In Ireland along with EN1317, the design of safety barriers is guided by the National Standard TD19/09 [2].

In Ireland, the National Road Network comprises of two types of roads: National Primary Roads and National Secondary Roads, of which the latter make up slightly less than 50% of the entire national route (national primary and national secondary) network. National Secondary Roads fall into the speed limit category of ‘National Roads’ and have a speed limit of 100 km/h. However, according to table 5/4 Note 8 in EN1317 [1], minimum containment of N1 may be substituted for N2 for design speeds of 85kph or less. Since new safety system will be provided only in Secondary Roads subjected to Realignment Project and these have a design speed equal to 85km/h, new road safety infrastructure on National Secondary Roads can be designed for N1 containment level.

The proprietary safety barriers and the in-situ concrete safety barriers currently used on Irish National Roads are aesthetically problematic and, above all, have high installation cost (30-50 €/m for steel barrier and 80-110 €/m for concrete barrier) and steel has high maintenance costs. These reasons make their use inappropriate for road realignment projects concerning some low volume National Secondary Roads set in a scenic landscape. The mixed guardrail [3], may be considered a more aesthetically pleasing solution but this is still a proprietary product involving high procurement and installation costs (60-90€/m) as well as expensive maintenance cost for the timber parts. Alternative low cost barriers are therefore needed and the use of natural and local materials can be a crucial key for keeping the installation and maintenance costs of new barriers low. In particular, three types of materials can be envisaged for possible natural barrier designs: earth, stones or hardcore encased in wire mesh and timber.

As for the use of stones, a gabion barrier is already used in Nepal for its affordable cost, [4], [5] but this system was not tested by the Nepal Road Department Safety Unit. On the other hand, a review of the technical literature in Europe and US will show very little previous work on the use of materials other than steel and concrete for roadside barrier designs. In the 1960s, the Bureau of Public roads in the USA evaluated the possibility of using hedgerows [6] and the Transport Research Laboratory (TRL) in the UK evaluated the possibility of using gravel beds [7], but neither of these proposals appears to have been implemented. In the 1990s Strybos [8] evaluated the use of recycled materials such as plastics for roadside barrier designs, but this has also not been implemented, and would probably be of low aesthetic value. It is clear therefore that there is currently limited knowledge about the potential for the use of natural materials for roadside barrier applications.

However, it has been identified that in different European Union countries as well as in US, there are some instances of employing crash barriers made of natural materials: TULIP, a timber only guard rail, [9] (Netherlands); STOPSAFE, a swerving protection consisting in expanded clay ball beds, [10] (Sweden); Earthen berm, an earthen wall system implemented in Belgian highways but not tested under the European Standard EN 1317, [11] (Belgium); A New TL-2 Rough Stone Masonry Guardwall, a stone covered concrete barrier, [12] (USA).

Low-cost Natural Material Barrier Design

This paper will focus on the first design phases of the “Experimental and Numerical Characterisation of Low-Cost Roadside Barrier Solutions” project funded by the NRA, the Irish National Road Authority. This preliminary design is based on the use of stone-wall barrier.

The aim of the project is to provide recommendations to the NRA for potential low-cost roadside barrier designs constructed from natural building materials which can be implemented on National Secondary Roads. These designs must meet safety, cost and aesthetic criteria.

According to the Standards it is mandatory that the proposed low-cost barriers, made of
natural materials, comply with the EN1317 and TD19 Standards. The performance of this alternative barrier will be thus tested for Containment level N1; severity index A or B, working width class W6.

Full scale testing of a proposed prototype design is though very expensive and a design process based on 1) fundamental analysis; 2) numerical simulation; and 3) scaled prototype test; has been set to develop and evaluate the feasibility of proposed design as a precursor to full scale testing. The design prototype, rigorously analysed, will then undergo a final full-scale TB31 crash test for validation, as ultimately required by the Standards.

**Step 1, Fundamental Considerations**

A stone-wall based barrier design has been envisaged as the possible alternative to the existing proprietary safety barriers and in-situ concrete works currently used to provide containment on motorways and National Primary Roads. The design consists of linked steel gabions filled of stones, a type of structure generally used as retaining wall (but with different linkages).

In particular a barrier section of 0.75x0.75 m was preliminary decided for manufacturing and aesthetical reasons. The mass was calculated assuming a porosity of 30 – 40% and stone density of 2600 kg/m$^3$.

The standard test for Containment level N1 barriers (test TB31) consists of an impact test with a vehicle of 1500 kg mass at speed of 80 km/h and impact angle of 20 degree. The impact test standard requirements are guided by three criteria: 1) the vehicle (and its occupants) must not be decelerated too heavily, 2) barrier and car cannot move beyond the barrier working width, 3) the barrier must redirect the car in the road direction.

The first target can be obtained by having a deformable barrier, as in the case of steel and wire rope safety systems, or, as in a mass based mechanism, by transferring some of the vehicle kinetic energy to the barrier. Since the gabion barrier will work in the same way as a concrete barrier, that is to say its functioning mechanism is mass based, conservation of momentum law has been used to calculate the barrier effective mass necessary to slow the vehicle. The minimum mass needed is obtained by imposing car and barrier displacement less than the barrier working width.

![Figure 1 - (a) car-barrier primary impact scheme; (b) car motion](image)

The displacement of the barrier after the primary impact (with the front of the car) and the secondary one (with the rear of the car) was calculated as a function of the barrier length. The assumptions of instant transfer of energy, plastic impact and no friction between vehicle and barrier and between vehicle and ground were made; interface conditions of roller contact were used. Moreover it was assumed that the barrier doesn’t move in the longitudinal direction. In Figure 1a the scheme of the primary car-barrier impact is sketched and Figure 1b shows the car position calculated under the previous assumptions in the first 125 milliseconds.

The standard EN1317 allows for a working width of 2.1 m (working width W6) for normal
containment barriers. The length of the barrier required to keep the displacement under the limit imposed by the code was calculated for two values of the coefficient of friction between barrier and soil, $\mu=0.3$ and $\mu=0.7$. This resulted in changing the minimum length of barrier needed from about 2 m to 1 m (Figure 2), showing that the coefficient of friction is not a large contributing factor to the competency of the barrier.

This moment based analysis, although simplified, showed that any barrier design having mass and dimensions and friction characteristics similar to those calculated is theoretically capable of stopping the vehicle with a short length of activated barrier.

![Figure 2 - Length of barrier needed for barrier-ground friction coefficient equal to 0.3 and 0.7](image)

**Step 2, Computational Modelling Method**

Computational models have already been used as a cost efficient way of evaluating the performance of safety barrier under vehicle impact [13]. MADYMO and other simulation packages like MEPHISTO and LS-DYNA, has been successfully used to estimate safety barrier performance [14, 15, 16] and MADYMO has been chosen for designing the new barrier. Madymo is a crash simulation software which combines multibody analysis (MB) and finite element method (FE) for describing multibody systems both as rigid or deformable bodies interconnected by kinematic joints. To date only the MB capabilities have been used. In particular multibody modelling is probably a more appropriate numerical tool for fundamental analysis when the detailed stress strain failure response of individual components are unknown but the overall force deformation properties can be measured or estimated [17].

A comprehensive validation for assessing the overall ability of the Madymo vehicle and contact models to simulate the tests required by the Standard has been set as a first step of the safety barrier designing process. The Madymo simulation of the EN1317 test procedure has been comprehensively validated through the time histories of vehicle trajectory, velocity and the acceleration at the centre of gravity etc. A comparison has been run between the acceleration severity index of the car experimental accelerations and that obtained through the numerical simulation. Moreover the detailed modelling of the barrier joints has allowed the prediction of the barrier displacement and will be used to aid the design of the connection of the new barrier. The benchmarking of the MADYMO models has been performed by simulating the full-scale response of two temporary vertical concrete barriers tested according to the EN1317 test procedures. Reports F203 [18], and M0044 [19], describing the two full scale impact tests on 800 mm high, portable vertical concrete barriers, carried out on the High Energy Facility of the Motor Industry Research Association, for the Transport and Road Research Laboratory (TRRL) of the UK Department of Transport, were made available by the Transport Research Laboratory (TRL).

The analysed impact tests correspond to N1 and N2 containment level, meaning that the tests were carried out to establish the performance of the portable vertical concrete barriers when impacted by a vehicle of 1500 kg mass at an angle of 20 degrees to the line of the fence, at speed of 80 (test TB31) and 110 km/h (test TB32) respectively (see Figure 3). The Temporary Vertical Concrete Barriers tested are normal containment RC barrier having 3.0 x 0.8 x 0.4 m dimension. The total length of the barriers was approximately 60 m long.
consisting of 20 concrete units. Each unit was secured to the next by means of M20 and M24 bolts. There is no fixed contact with the ground.

The external shape of the multibody vehicle model (see Figure 4) used to run the simulation has been built in Madymo by adapting a finite element model of a ford Taurus available in the Finite Element Model Archive page, [20] to the actual test car shape, a Rover SD1. The vehicle stiffness in contacting the barrier, has been evaluated in two steps. In the first phase frontal stiffness data, obtained by accident record reported in Jiang et al. (2004) [14], were scaled according to the contact surface area in the 20° angle impact. In the second phase the contact stiffness of each surface was tuned by a trial and error process aimed to obtain acceleration, velocity and displacement time histories of the vehicle in good agreement with the test results. The same car model was used for simulate both the N1 and N2 containment level tests. Since the concrete barrier is much stiffer than the car, the goal of this calibration process is to model the car stiffness. The final stiffness obtained are reported in Appendix A. The multibody vehicle built will than be used for running the simulated crash test on the new low-cost, natural material barrier.

The Acceleration Severity Index is the key factor for evaluating the crash test performance. It is defined as the maximum value of the normalized accelerations undergone by the centre of gravity of the car during the impact. In Figure 5 a comparison between the experimental normalized accelerations and those obtained by the numerical crash analysis are plotted for the N1 and N2 containment level tests. In the case of TB31 test the multibody analysis gives a difference of +6% of the ASI value (0.70 vs. 0.66) while in the case of TB32 test the errors are negligible since almost the same ASI (0.99 vs. 0.98) is obtained. It can be seen that these results were obtained with the same car and barrier models. Therefore the impact simulation can be considered reliable for predicting the acceleration severity index.

As for the barrier displacement, the barrier-ground friction coefficient was put to 0.45 according to Marzougui et al. (1998) [21] and the barrier joints were set according to bolt size. The same stiffness characteristics of the barrier surface were used for the two tests. The numerical displacement of the barrier obtained in this way are close to the value experimentally recorded as shown in Figure 6. The good agreement between simulated and experimental results is demonstrated also by the car trajectory and exit box in Figure 7. In Figure 8 the overall motion of car and barrier of the N2 test simulation is shown.
Figure 5 - F203, M0044 - Acceleration Severity Index

Figure 6 - F203, M0044 - Barrier final displacement

Figure 7 - Test M0044 - Car exit box and trajectory

Figure 8 - Test M0044 - Car and barrier motion (Madymo)
Step 3, Scaling

Once the computational modelling of the new barrier design is concluded it will be checked by running a TB31 test on a scaled prototype. A simplified scaled rigid test vehicle will be constructed using a geometric scaling of about 1:24. Running a scaled version of the impact test on a simplified prototype specimen will involve modelling stiffness and strength of car, barrier units and joints. Mechanical material properties are though the real challenge since stress-strain relationship, plasticity, viscosity and generally non-linear properties are difficult to be consistently scaled and can be an actual obstacle for the test [22, 23]. In particular it will be necessary to set a consistent initial velocity for the scaled impact test and to correlate the accelerations and displacement measured for predicting the full scale values. In this framework a study has been started and will be carried on in the nex phase of the project.

Conclusions

The “Experimental and Numerical Characterisation of Low-Cost Roadside Barrier Solutions” project funded by the National Road Administration (NRA) was begun in February 2011 with the aim of designing a new roadside low-cost barrier using natural materials for the Irish National Secondary Roads. In the first phase of the project a steel gabion filled with stones is under analysis. This preliminary design is a mass-based barrier and fundamental calculations showed that barrier units of 0.75x0.75x2 m are theoretically capable of stopping the vehicle with a short length of activated barrier. Computer modeling will be used for designing in detail the gabion safety barrier and benchmarking the crash analysis software Madymo has been carried out by reproducing the experimental results of an N1 and one N2 EN1317 tests on concrete barriers. The validation process has shown that the numerical modelling can reliably predict the Acceleration Severity Index (ASI), the barrier displacement and the car Exit Box.

In the next phase of the project a scaled test will be run to check the computational analysis of the prototype design.

Appendix A

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Table 1 - Contact loading and unloading functions for the car multibody model

Reference

[23] B. S. Holmes and J. D. Colton, Scale model experiments for safety car development. SAE Paper no. 730073.