Gabions: evaluation of potential as low-cost roadside barriers

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Gabions: evaluation of potential as low cost roadside barriers

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This paper evaluates the potential of gabions as roadside safety barriers. Gabions have the capacity to blend into natural landscape, suggesting that they could be used as a safety barrier for low-volume road in scenic environments. In fact, gabions have already been used for this purpose in Nepal, but the impact response was not evaluated. This paper reports on numerical and experimental investigations performed on a new gabion barrier prototype. To assess the potential use as a roadside barrier, the optimal gabion unit size and mass were investigated using multibody analysis and four sets of 1:4 scaled crash tests were carried out to study the local vehicle-barrier interaction. The barrier prototype was then finalized and subjected to a TB31 crash test according to the European EN1317 standard for N1 safety barriers. The test resulted in a failure due to the rollover of the vehicle and tearing of the gabion mesh yielding a large working width. It was found that although the system potentially has the necessary mass to contain a vehicle, the barrier front face does not have the necessary stiffness and strength to contain the gabion stone filling and hence redirect the vehicle. In the EN 1317 test, the gabion barrier acted as a ramp for the impacting vehicle, causing rollover.

Keywords: crash test; safety barriers; gabions.

Introduction

Existing roadside safety barrier systems are often not aesthetically pleasing and expensive to install and maintain, providing scope for developing alternatives with

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improved life-cycle costs and low environmental impact.

The only barrier design with good aesthetics which is used in Europe is the mixed timber and steel guardrail but this is far more expensive than regular steel or concrete barriers. An alternative full timber guardrail for highways has been designed at TU Delft in the Netherlands and tested according to EN1317 for H2 Containment level [25] but it is not currently used. This guardrail meets environmental and engineering criteria but has a high installation and maintenance cost. In the US various Federal Agencies have funded the “New TL-2 Rough Stone Masonry Guardwall” project, a stone covered concrete barrier which has been successfully tested to meet the TL-2 safety performance criteria of Report 350 [21]. This barrier is a variation of the widely used concrete barriers [20] especially designed to meet aesthetic criteria.

This paper reports 1) the modelling and 2) crash testing according to the European Standard EN1317 [8, 9] of a novel Normal Containment (N1) low-cost barrier made using natural materials, a project funded in 2011in Ireland by the National Roads Authority (NRA).

Following initial evaluation, gabions were envisaged as a possible alternative safety barrier design. The capacity of blending with the natural landscape and the cost which is comparable with low-cost barriers already in use (steel cable and steel w-beam) made them a potential choice for a novel low cost barrier for scenic National Secondary Roads (Design speed 85 km/h).

Gabions are modular structures made of steel wire mesh laced together and filled with locally sourced stones. To date gabions have been extensively used as retaining wall structures to provide soil reinforcement and embankment protection. Analytical, experimental and numerical analyses of gabions in these applications have been performed. Hearn et al. [11] was the first to propose a multibody model in the case of a dyke-type structure subjected to impact. However, very few dynamic tests are available, among these Lambert et al. [15], Betrand et al. [6] and Nicot et al. [19] on rockfall embankments and Soudé et al. [23] on geocell-reinforced walls subjected to localised impacts.

In Nepal, gabion units have been used as roadside crash barriers since at least the 1990s to avoid median crossings and provide protection from cut slopes [13, 24]. However, there is no evidence that this gabion barrier is effective in reducing occupant injuries and it has not been crash tested according to either the European Standard EN1317 [9] or the U.S. standard [17]. The gabion barrier reported in this paper is a modular chain of gabions laced end-to-end together by selvage wire, see Figure 1. The gabion unit dimension is 1.0x0.75x0.75 m (L x W x H). The height of the gabion barriers is limited in order to avoid restricting the driver's view. Commercially available gabion units were used to reduce costs.

The barrier working mechanism is mixed: similar to concrete barriers, the impacting vehicle is slowed down because of the momentum exchange with the barrier. On the other hand, the gabion units connected on the front face only should behave as a chain and redirect the vehicle into the road lane as a steel w-beam or cable guardrails would do.

The potential of the gabion barrier was assessed through three stages:

1. A MADYMO multibody (MB) model of the TB31 crash test of the gabion barrier was built to investigate the optimal gabion unit length and vehicle-barrier interaction. Published [2, 4] and new experimental input data were used to input the model.
2. Several sets of 1:4 scaled crash tests were carried out to investigate the gabion-vehicle interaction.

3. A full scale TB31 crash test of the gabion prototype was performed at the UK Transport Research Laboratory (TRL).

The paper is structured as follows: a description of the “EN1317 requirements” for a new safety barrier design is first given. Then the assessment of the gabion barrier prototype is reported in the “Multibody modelling of TB31 crash test”, “Scaled TB31 crash test” and “Full scale TB31 crash test” sections followed by “Discussion” and “Conclusions”.

EN1317 requirements

For a N1 containment level barrier, which is generally the minimum containment level for barriers in Europe, the EN1317 Standard prescribes a TB31 crash test, which involves a 1500 kg vehicle impacting the barrier at 80 km/h at an angle of 20 degrees.

The barrier Working Width is used to measure the required deadspace for the barrier and the Exit Box criterion dictates the trajectory of the vehicle after it leaves the barrier; vehicle roll-over is not allowed. The Acceleration Severity Index (ASI) measures the acceleration at the Centre of Gravity (CG) of the vehicle. The Theoretical Head Impact Velocity (THIV) is used for to evaluate the possibility that the occupant’s head strikes the vehicle interior.

Multibody modelling of TB31 crash test

The multibody software MADYMO was used to model the TB31crash of the gabion barrier. Multibody simulations have already been proved reliable in simulating vehicle-barrier impact scenarios [5, 10, 14, 22] and are particularly suitable for mass based systems such as concrete barriers which have a working mechanism based on momentum exchange between the impacting vehicle and the barrier. The vehicle-gabion interaction and the optimal gabion unit length were the focus of the multibody analysis. The MB model is composed of a vehicle system, a barrier system and a ground system. The vehicle model was previously validated using the results of experimental data of two concrete barrier crash tests [2].

Gabion unit

Compression, shear and bending tests of gabion units were carried out at the University of Bologna [1] and mesh tensile tests were carried out by Bertrand et al. [7]. Static FE modelling of a single gabion unit by Lin et al. [16] has also shown that it is appropriate to use the apparent total moduli G and E of a gabion to capture the compound deformation behaviour of wire mesh and filling stones. Based on these published results a Timoshenko beam representation of a gabion beam was previously built and validated [4].

The multibody model of the gabion was thus built on the assumption that a gabion unit behaves as a Timoshenko beam. To reproduce this mechanical, each unit was modelled by assembling a variable number of rigid body gabion sub-units using shear and tensile springs, see Figure 2a.

A sub-unit length of 0.4 m was chosen and four different gabion lengths were modelled: 0.8 m, 1.2 m, 2.0 m and 2.8 m; each composed of 2, 3, 5 and 7 sub-units respectively. Sub-units were assigned mass and inertia based on a gabion section of 0.75x0.75 m, packing ratio of 65% and gabion unit mass per unit of volume of 1755 kg/m^3. Three contact surfaces were assigned to each sub-unit: one hyper-ellipsoid for modelling the contact between two neighbouring barrier units or sub-units and two planes for modelling the barrier-vehicle interaction: one parallel to the gabion front face and one parallel to the gabion side face (see Figure 2b). This side plane surface was used to model the possible impact of the vehicle on the gabion corner due to relative displacement of the units, and the frictional forces acting along the barrier front face. A friction coefficient was also set on the surfaces parallel to the barrier front face.

All the force-penetration curves characterizing the contact between the gabion sub-units were obtained by multiplying the experimental stress-strain results [1, 4] by the contact area (for the force) and by the element length (for the penetration). The gabion-vehicle contact curves were obtained in a similar way based on estimated area of contact. The contact curves are reported in Figure 3.

Gabion lacing connection

Three tensile tests using an Instron 5589 were carried out to assess the force deformation characteristics of the lacing system connecting the front faces of the gabion units. The tests consisted in pulling of two adjoining laced panels apart. Woven mesh PVC coated panels 500 mm wide, having mesh opening of size 80 x 100 mm and 2.7 mm wire diameter were used. The edges of the panels, ending with a selvage wire, were laced using 2.7 mm PVC coated wire. Each of the two panels was connected to a clamp designed to restrain the mesh and stop the side edges from contracting (see Figure 4a). An Instron 5589 machine was used for applying the loading.

The force-displacement curves are shown in Figure 4b and in Table 1the maximum load per meter and corresponding displacement are reported. A consistent pattern in terms of slope, peak and maximum elongation was observed; failure was always preceded by a high elongation and the connections were not sensitive to individual wire failure. The experimental curves obtained were used to calibrate the MB gabion spring connections working in tension only. The force-displacement law used for the springs is plotted in Figure 4b.

Experimental gabion/ground friction coefficient

In order to evaluate the friction behaviour between gabions and different ground surfaces a set of tests were performed, see Appendix A. Coulomb friction coefficients between 0.31 and 0.7 were measured. In the MB model the value obtained for the tarmac (μ=0.46) was used.

Simulations

To investigate the vehicle-gabion interaction and in particular the possibility that the vehicle would penetrate into the gabion and spin out, a range of gabion-vehicle friction coefficient (from 0 up to 1.6) were used. Three sets of numerical simulations were run. Each simulation set differed by the number of the transversal barrier surfaces interacting with the multibody vehicle, see Figure 5. The following simulation sets were run:

(1) Transversal surfaces included for each gabion sub-unit (YES model);
(2) Transversal surfaces not included for each gabion sub-unit (NO model);
(3) Transversal surfaces only included for the first sub-unit of each gabion (CORNER model).

Each model was run for the four gabion lengths and for five vehicle-barrier friction coefficient values: $\mu = 0$, $\mu = 0.4$, $\mu = 0.8$, $\mu = 1.2$, $\mu = 1.6$.

Multibody model results

In Figure 6, the ASI, THIV, Exit Box and barrier deflection values obtained for the *YES*, *CORNER* and *NO* models of gabions with different unit lengths and coefficients of friction are presented. Necessary conditions for passing the crash test are ASI $\leq$ 1 (score A) or ASI $\leq$ 1.4 (score B); THIV $\leq$ 33 km/h and barrier displacement inside the 2.1 m wide stripe (working width class 7).The solid bars in Figure 6 indicate appropriate vehicle redirection during simulation (Exit Box successful) while hollow bars indicate that the vehicle did not stay inside the Exit Box (Exit Box not successful) due to the vehicle spinning out (the car rotated around the contact point with the rear of the vehicle moving away from the gabion wall) or rolling over. The following comments can be made:

- The YES model (with orthogonal barrier surfaces per each gabion sub-unit) generally gives the highest ASI and THIV. The CORNER model (with orthogonal barrier surfaces at the start of each gabion) gives the second highest values and the NO model the lowest. Departure from this trend (for example for gabion size 2.8 m and friction equal to 0.0, Figure 6a) results because the peak ASI score could correspond to the primary impact (front corner of the vehicle) or to the secondary impact (vehicle back).
- ASI and THIV increase with increasing vehicle-barrier friction ~~force~~ coefficient.
- The relationship between barrier maximum displacement and friction coefficient has for the NO and CORNER models a minimum for $\mu = 1$ and $\mu = 0.4$-0.8 respectively, while the YES model is increases with the coefficient of friction. However, the three models differ only for the intensity of the total vehicle-barrier force in the direction parallel to the barrier, that is the sum of the longitudinal force due to friction and the normal contact force due to the planes perpendicular to the barrier face (absent in the NO model).
  For this reason it is reasonable to assume that all the three models show a same pattern and that the YES model, having the highest total longitudinal contact force is minimised for a coefficient of friction lower than zero.
- Vehicle spin-out occurs for friction coefficient higher than 0.8 in the YES model, 1.0 for the CORNER model and 1.2 for the NO model. The vehicle also

spun out in the CORNER model for a gabion length of 0.8 m and friction coefficient of 0.8.

- When the vehicle spins out, very high values of barrier deflection occur.

In Figure 7 the ASI values results of Figure 6 are grouped in terms of gabion unit length. Surprisingly the comparison shows that the predicted response of the gabion barrier is not strongly dependent on the gabion unit size. The same can be stated for THIV, barrier deflection and vehicle Exit box. These results indicate that the barrier behaves as a chain and that, for the sizes investigated, the mass activated does not significantly depend on the unit length. The CORNER model, having orthogonal barrier surfaces only at the beginning of each gabion, brings out the interaction between the relative size of vehicle and gabion units but no clear conclusions can be obtained.

Overall, the many simulations showed a consistent range of results with the probability of passing the TB31 crash test depending mainly on the intensity of the longitudinal contact forces between the barrier and the vehicle: the multibody model results indicate that for a friction coefficient between 0.4 and 0.8 the test could be successful. However, the local interaction between the vehicle and the barrier determines the effective friction behaviour and this remains a significant uncertainty in the modelling.

Scaled TB31 crash tests

Test set up

To study the dynamic deformation of the gabion chain under the impact of the vehicle and, in particular, the risk of vehicle spin out or roll over, a number of scaled impact tests were carried out.

A length scale factor S_L in the range of 1:5 and 1:4 was used. Scaled gabion units made with component materials similar to the full scale ones were used to investigate the interaction between the vehicle and the mesh and between the mesh and the filling. Geometry, mass and inertia of vehicle and barrier are reported and in Table 2 the corresponding length scale factor values are summarised. A total of 7 scaled gabions (3.5 m) connected on the front face only, as in the full scale test, were used for making the barrier. The gabion barrier was free to slide on the floor.

Since the investigation was mainly aimed at understanding the gabion deformation, a rigid scaled vehicle was used (see Figure 8). The scaled vehicle was obtained by modifying a steel framed piano-skate with four steel-rubber wheels. The frame was modified using a timber profile to obtain the desired size and mass and to avoid the presence of sharp corners, see Figure 8a-b. An impact speed of 50 km/h was decided for practical and safety reasons. A HYGETM Dynatest 500 Crash Simulation System was used to accelerate the vehicle. The tests were recorded using a high speed camera (Fastec Imaging - Hi Spec 5).

Four kinds of scaled gabion specimens, see Figure 9, were manufactured using both a full scale woven gabion mesh and a thin mesh. Different stone sizes were used as well in an attempt to find a compromise between using full size materials and avoiding scaling issues. For test specimens B, cobblestone bricks (200x200x50 mm) were used as filling material. However, the mass of each gabion unit was unmodified (between 19 and 21 kg) due to a lower density of the material. In Table 3 the mesh and stone size and the void ratio (volume of void divided by volume of gabion cage) of each set of tests are reported.

Scaled Test results

The results of the scaled tests are reported in Table 3. Each test was considered successful if the barrier redirected the vehicle and unsuccessful if the vehicle spun out or rolled over.

Specimens A were manufactured with full size stone and mesh. For four out of six specimens A the vehicle spun out because of the vehicle front corner being caught by the gabion mesh or a stone sticking out of it. The high speed videos showed the stone filling being pushed longitudinally along the gabion unit until constrained by the mesh. This effect was particularly enhanced by the high void ratio and by the stone and the mesh size which were large in relation to the vehicle. None of the tests failed due to snagging at the laced joints.

Specimens B were manufactured with cobblestone bricks, had a low void ratio and a more regular barrier surface. The vehicle was successfully redirected in five out of seven tests. For the two tests in which the vehicle spun out, the vehicle was trapped by the mesh due to an indent on the timber profile caused by a previous test. The high speed videos of the successful tests showed an almost pure shear deformation of the gabions with the bricks sliding one over the other in direction perpendicular to the barrier during the impact, see Figure 10.

For both Specimens C and D small stones were used to decrease the void ratio and avoid a single stone stopping the vehicle as in tests A. In spite of this these gabion specimens were too deformable and unable to redirect the vehicle. In all the C and D tests, see Figure 11, the vehicle spun out and in some cases the deformed gabion worked as a ramp for the vehicle. The mesh was torn during the impact in tests D.

Full scale TB31 crash test

Test set up

A gabion barrier was constructed and crash-tested in the UK Transport Research

Laboratory (TRL) according to EN1317 procedure for N1 barriers. The gabion barrier prototype was constructed by a professional gabion producer (PhiIreland) using 60 gabions each having nominal dimensions 1x0.75x0.75 m. Woven mesh PVC coated with 80x100 mm opening made using 2.7 mm wire was used for manufacturing the gabions. Stone infill was 15 cm in size. Internal connecting wires limited lateral deformation. Consecutive units were tied together on the front face only using the standard lacing system. The front face was architectural finished to obtain a flat and regular impact surface.

A 2003 Rover 75 Saloon car, with mass 1500 kg, was used for the test and a velocity of 83.9 km/h and a 20 degree impact angle were recorded during the test see Figure 13a.

Test results

The crash test resulted in a failure due to rollover of the vehicle and excess of working width. Gabions 18 to 20, see Figure 13a, were completely opened by the impact. Gabions 21-23 were displaced rearwards. Maximum displacement of gabions was 3.4 m from the rear face of the system, see Figure 13b.

In Figure 14 and Figure 15 time histories of the acceleration and angular velocity of the CG of the vehicle are reported. ASI and THIV were equal to 1.3 and 43 km/h respectively. In Figure 12 a sequence of high-speed video still shots with the impact and roll over of the vehicle is shown.

The vehicle-barrier impact mechanism can be described as follows:

- The vehicle impacted the gabion and partially pocketed into it.
- The crushed front of the vehicle tore the mesh on the front face of the barrier.

- The pocketing and the following breaking of the mesh and deformation of the gabions caused the front of the vehicle to lift up and ramp on the barrier.

The mesh on the back of the gabions and the connections between the units did not fail and were able to contain the vehicle inside the exit box. However, the containment occurred with a mechanism of rollover for the vehicle.

Discussion

A gabion barrier is a mixed design, partly mass based and partly tension based. The interaction of mass and stiffness in this barrier design is complex and the gabion impact behaviour could not be predicted directly based on the comparison with either concrete or steel beam barriers respectively. However, the combined results from both the scaled and the full scale TB31 crash test showed that a chain/beam made of gabion units is not a suitable safety barrier solution.

The preliminary modelling and scaled tests showed the potential for successful redirection of the vehicle. However, the vehicle-barrier interaction is strongly influenced by local deformation occurring on the gabions or on the vehicle, and the preliminary analysis therefore also showed a significant risk for the vehicle to penetrate into the barrier and spin out. Overall, among the four different scaled specimens only the gabions with low void ratio were able to redirect the vehicle (test B). The test set D, which was the most similar to the full scale crash test in terms of scaled mesh stiffness and strength, showed the same kind of vehicle-barrier interaction as the full scale crash test with the vehicle ramping over the barrier and the mesh being torn apart.

The two main issues shown by the full scale test are a low strength of the mesh which was torn by the crushed front of the vehicle and a low barrier stiffness which did not redirect the vehicle. Connections on the gabion back face would have probably increased the barrier stiffness but would not have prevented the tearing of the mesh on the front face.

A high barrier contact stiffness, a low gabion void ratio (between 30% and 35%) and a stronger mesh could reduce the probability of this failure occurring. However, these are not trivial changes and it is unlikely that minor design changes would significantly alter the overall barrier behaviour. A comparison between a standard w-beam barrier manufactured with AASHTO M180 steel and cross-sectional area of about 1270 mm^2 shows an axial strength about 20 times higher than that of the mesh used for the gabion design (mesh section: length 0.75 m, opening dimension 80x100, wire diameter of 2.7 mm). Although this axial strength is only partially used during an impact, the comparison shows that enhancing the gabion front face strength and stiffness would require significant changes which would increase costs and appearance considerably.

The multibody model was used to optimise the gabion unit mass and size through a range of possible vehicle-barrier scenarios represented by the three contact models (YES, NO, CORNER, see the Multibody modelling section). The experimental ASI=1.3 and THIV=43 km/h values recorded were matched only in simulations with very high barrier-vehicle contact and friction forces. The YES model simulations of gabion units of 0.8 and 1.2 m and barrier-vehicle friction coefficient 1.6 gave ASI and THIV scores respectively of 1.25/1.29 and 43/44 km/h. The barrier maximum displacements of these simulations (3.5 m and 3.0 m respectively) also matched the experimental value of 3.4 m. However, the vehicle rollover, partially due to the low vertical stiffness of the barrier, did not occur in any simulations.

In Figure 14 and Figure 15 the accelerations and yaw rate from simulation YES, gabion length 0.8 m and friction coefficient 1.6 are superimposed on the experimental time histories; In Figure 16 the vehicle MB positions at time steps of 0.1 s are plotted on top of the high-speed video camera still shots. From the comparison of the vertical vehicle acceleration it can be seen that the model was not able to capture the vertical motion of the car while the longitudinal trajectory was correctly captured.

Conclusion

This paper describes the modelling and crash testing of a novel gabion based roadside safety barrier design according to the EN1317 European standard. Tensile tests on gabion lacing methods showed that the lacing failure is always preceded by a high elongation and that this connection system is not sensitive to individual strand failure. Moreover a method for scaling a mass-based barrier crash tests has been presented and four different sets of scaled crash tests have been carried out. A good match between the scaled and the full scale crash in terms of vehicle-barrier interaction and barrier deformation patterns was obtained. Gabion barriers are already used in some regions as roadside barriers but this study, which resulted in the vehicle rollover in a full-scale EN1317 TB31 crash test, showed that they do not provide good occupant protection. Given that the low gabion stiffness and strength are the main issues it is unlikely that a minor design change would significantly improve the barrier behaviour.

Appendix A: gabion drag tests

A set of drag tests was carried out to determine the coefficient of friction of gabions on different surfaces. The surfaces tested were gravel, rough concrete, painted concrete, dry soil lab, soil site, grass site, tarmac site and wet soil site. A 300 mm cubed stone filled welded mesh gabion of 48 kg mass was used for the testing. The Gabion was tested by wrapping a harness around the gabion and attaching it to a winch. A load cell was interposed between the gabion and the winch. The friction coefficient for each surface was obtained as the average value of the ratio between the horizontal drag force and the weight of the gabion. The results are reported in Table 4.

Acknowledgment

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Figures

Figure 1. Gabion barrier: a) photo and b) working mechanism.

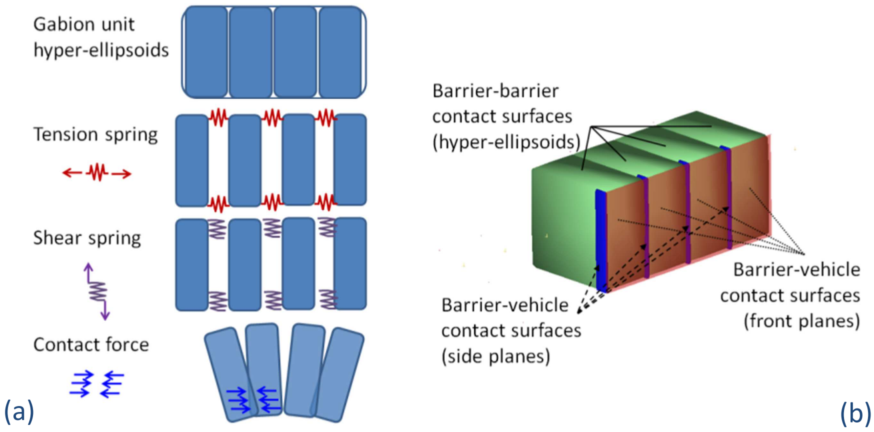

Figure 2. MB gabion composed of four sub-units: a) scheme of the spring and contact connection between the hyper-ellipsoids; b) Barrier-barrier and barrier-vehicle contact surfaces.

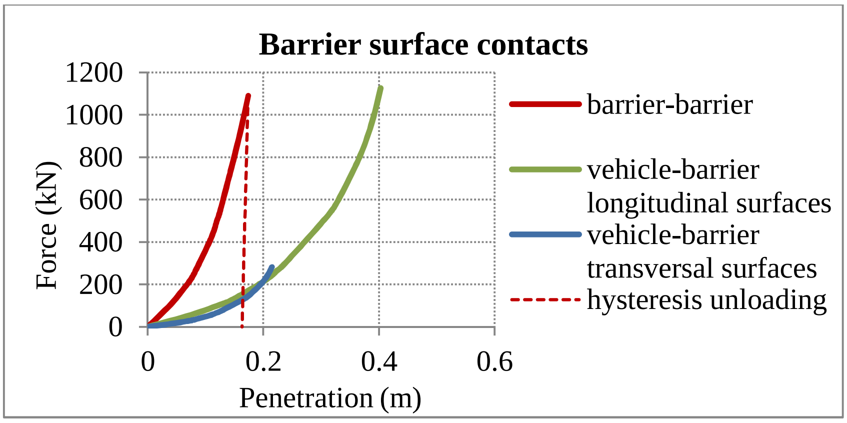

Figure 3. Force – Penetration curves for the contact surfaces modelling the barrier-barrier and barrier-vehicle interaction.

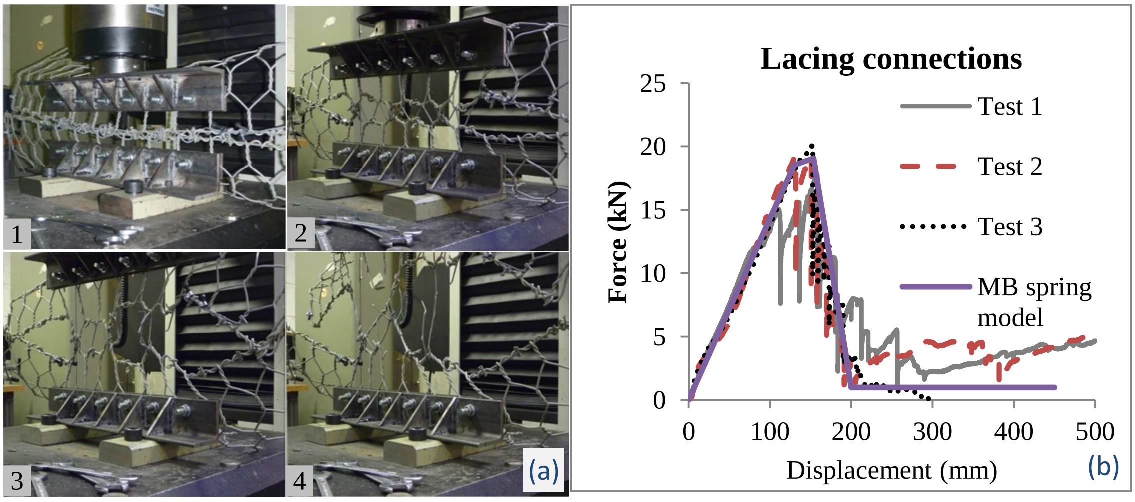

Figure 4. Lacing connection test:

a) Test photos up to failure for test 1; b) Experimental force – displacement.

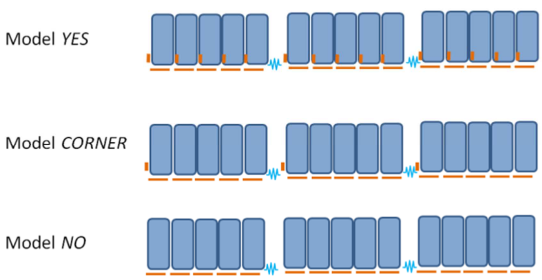

Figure 5. Top view of a MB gabion composed of four sub-units:

contact surfaces for modelling the barrier-barrier and barrier-vehicle interaction.

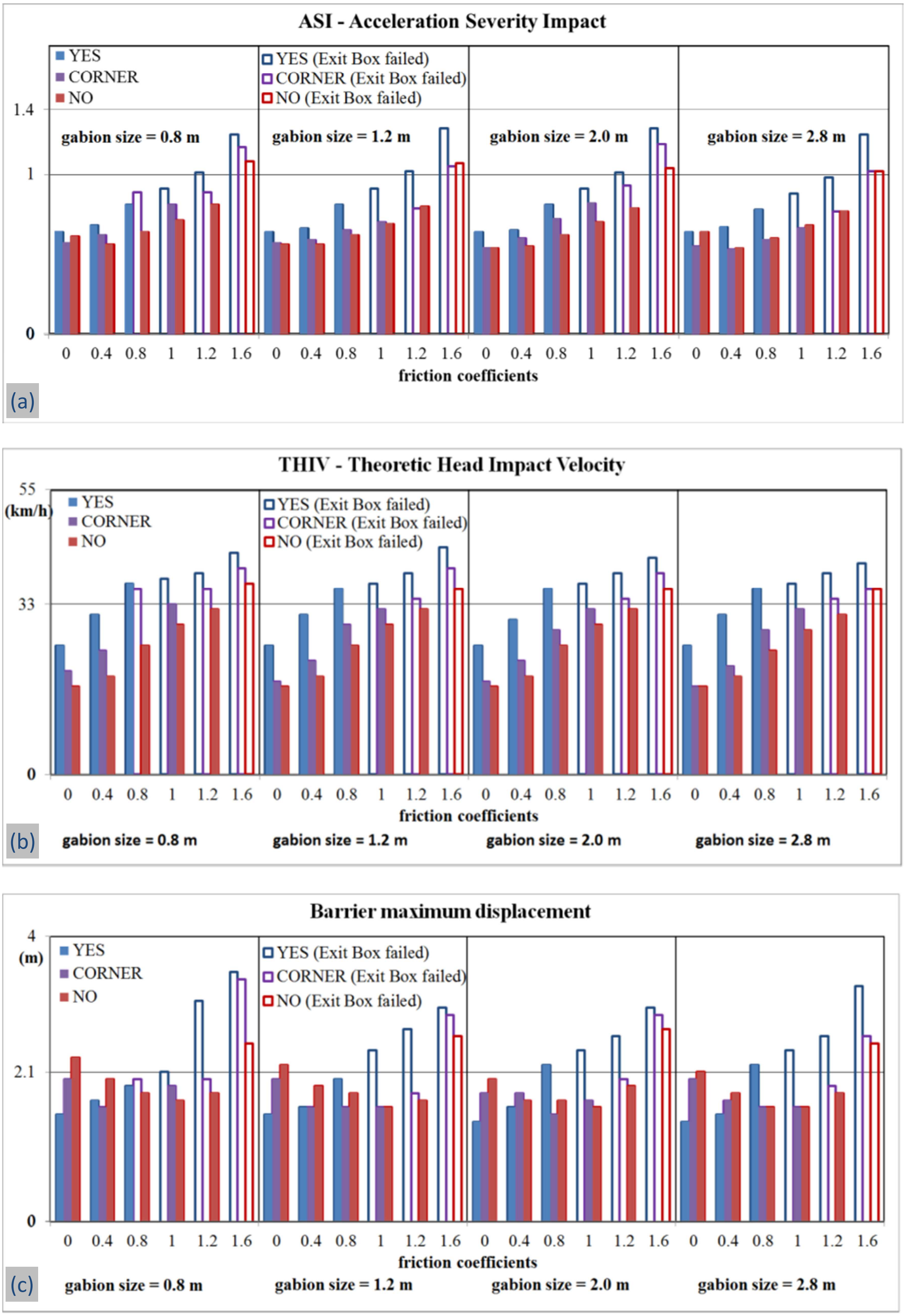

Figure 6. a) ASI; b) THIV and; c) Barrier displacement results of YES, CORNER and NO models for different values of gabion length and vehicle-barrier friction coefficient (results grouped by MB model).

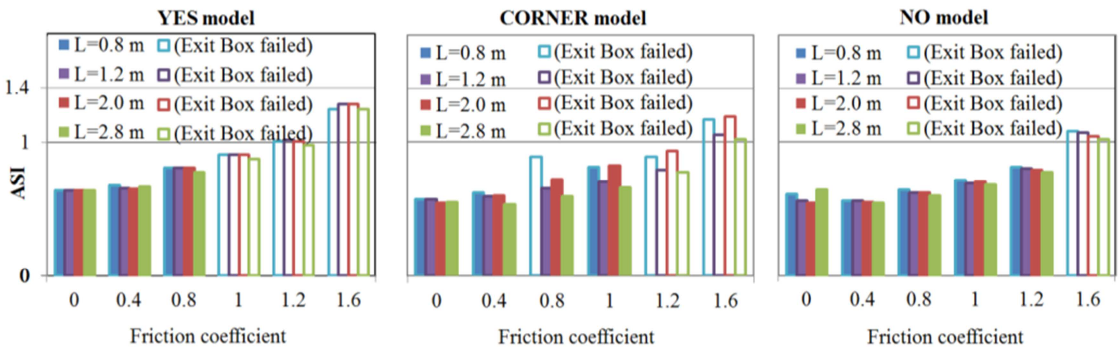

Figure 7. ASI results of YES, CORNER and NO models for different values of gabion length (L) and vehicle-barrier friction coefficient. Results are grouped by unit length.

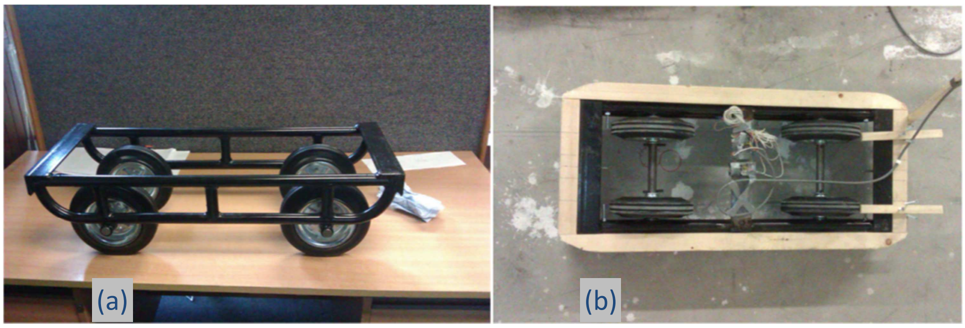

Figure 8. a) Steel frame; b) Steel frame with timber profile.

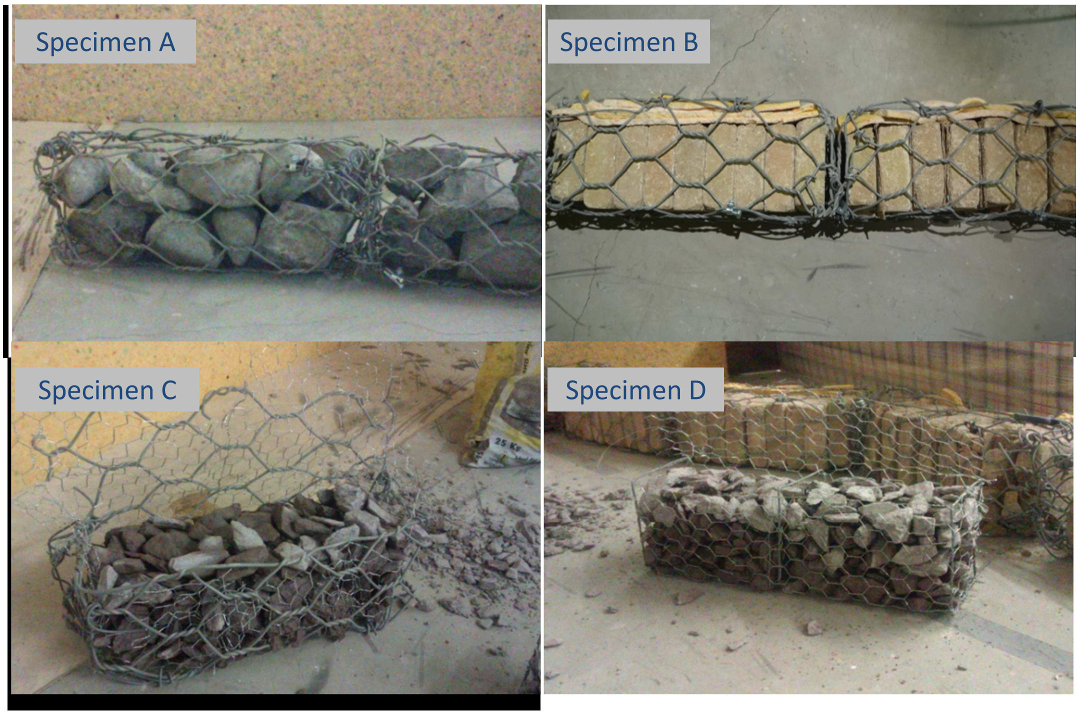

Figure 9. Gabion specimen types A-B-C-D.

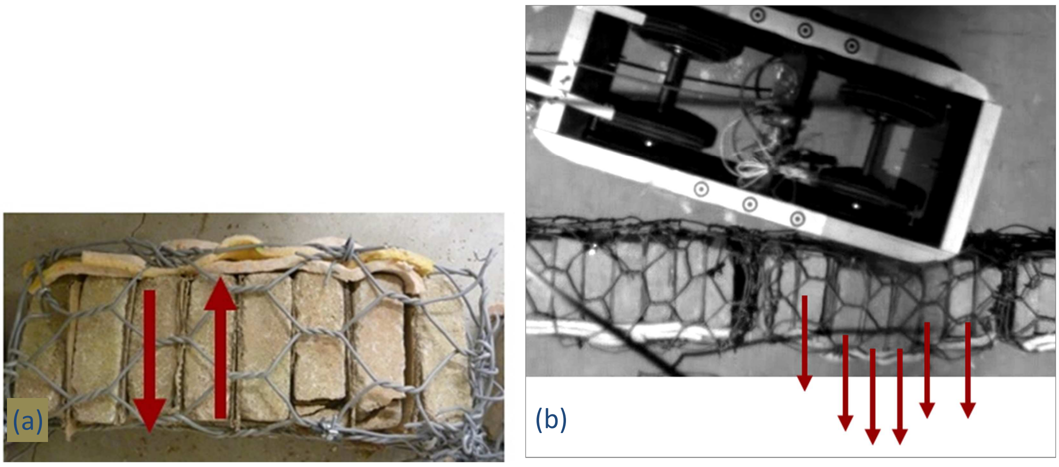

Figure 10. (a) Gabion specimen type B. (b) Interaction with the scaled vehicle.

Figure 11. Gabion specimen type D at 60 ms from the impact start.

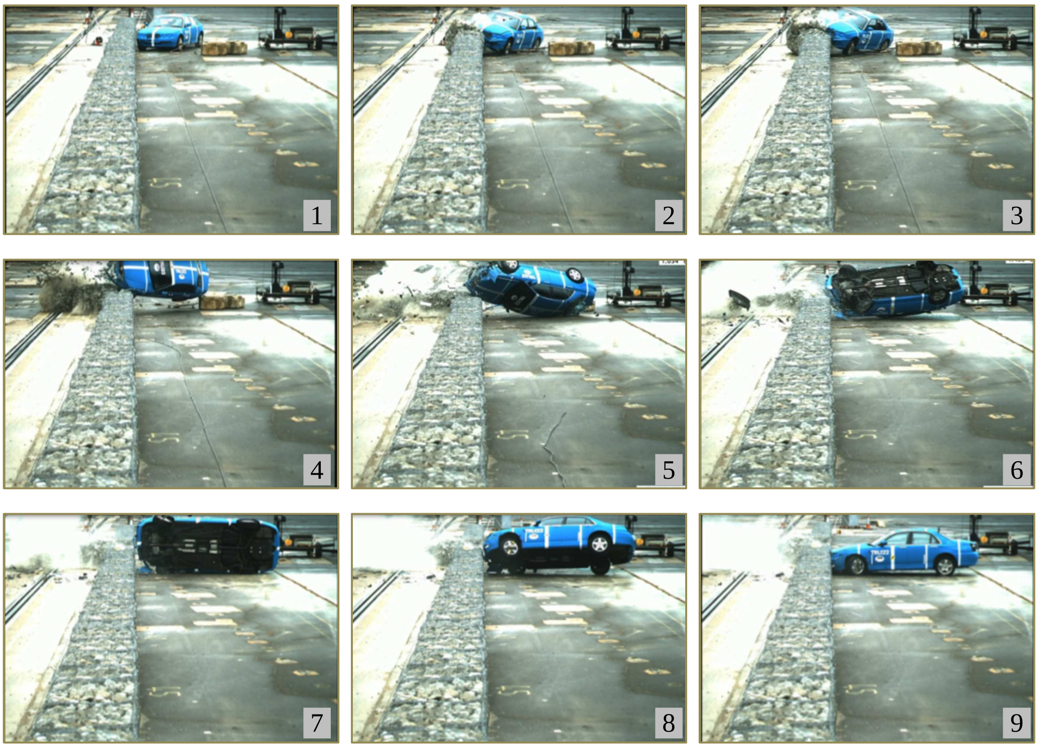

Figure 12 TB31 crash test: Sequence showing the impact and roll over of the vehicle.

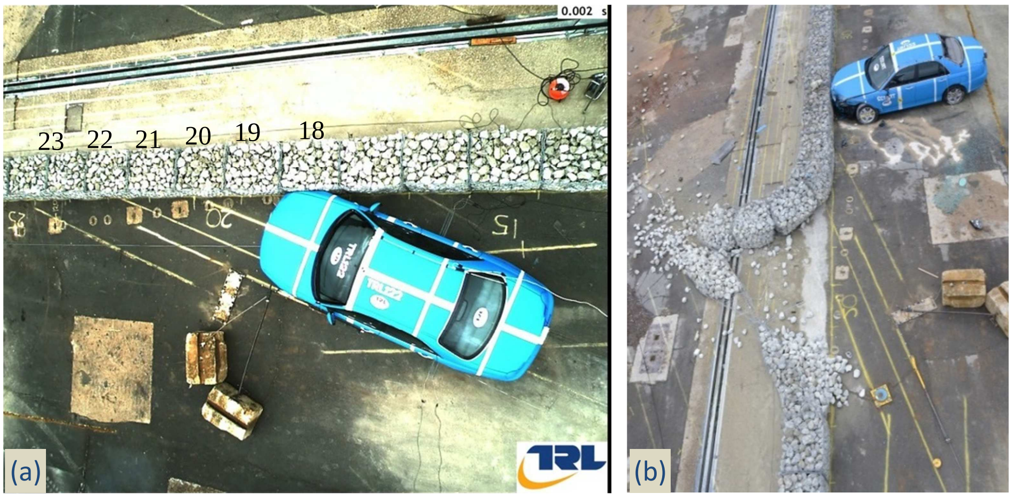

Figure 13. TB31 crash test:

a) Snapshots of the barrier; b) Vehicle before and after the impact.

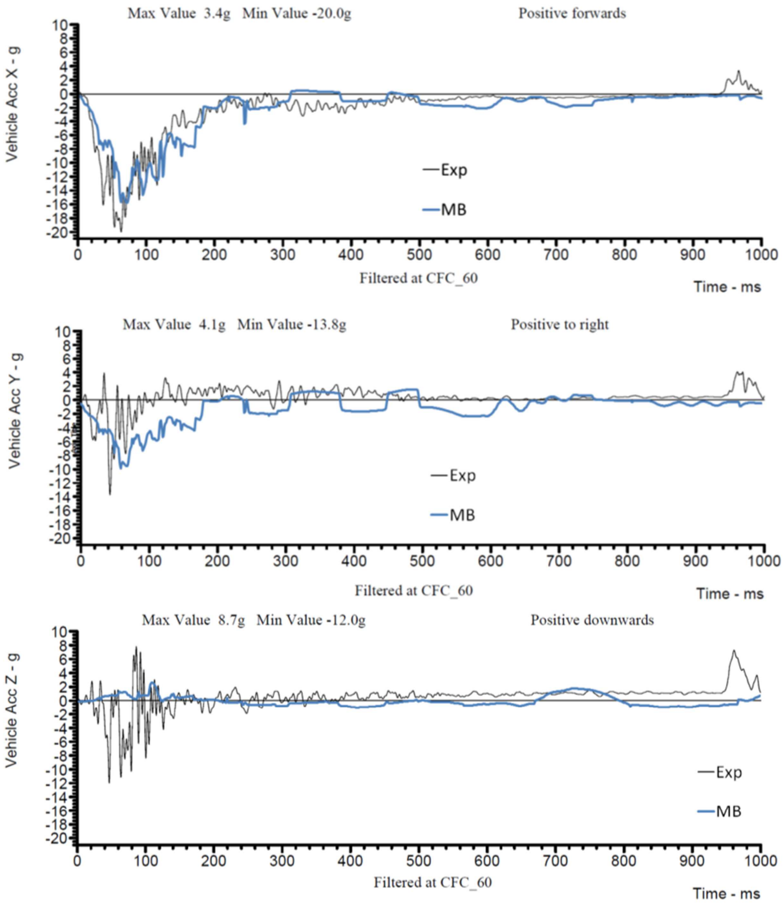

Figure 14. TB31 gabion barrier crash test: Time histories of the acceleration of the vehicle and corresponding accelerations from MB simulation of YES model, gabion length 0.8 m, friction coefficient 1.6.

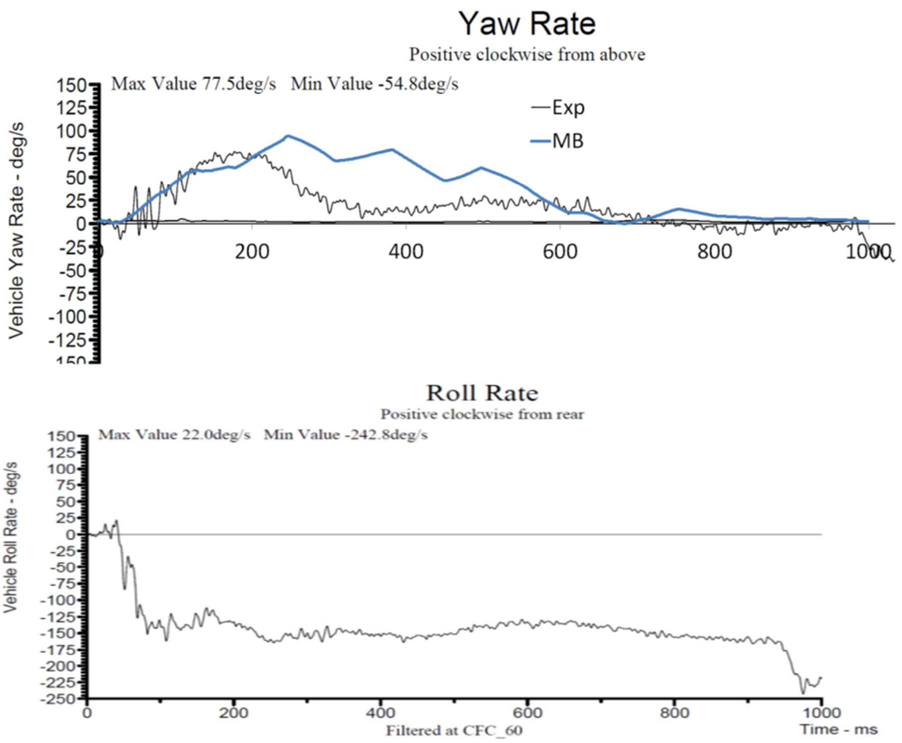

Figure 15. TB31 gabion barrier crash test. Time histories of the angular velocity of the vehicle: Along the longitudinal axis (roll) and along the vertical axis (yaw) with corresponding yaw rate from MB simulation of YES model, gabion length 0.8 m, friction coefficient 1.6.

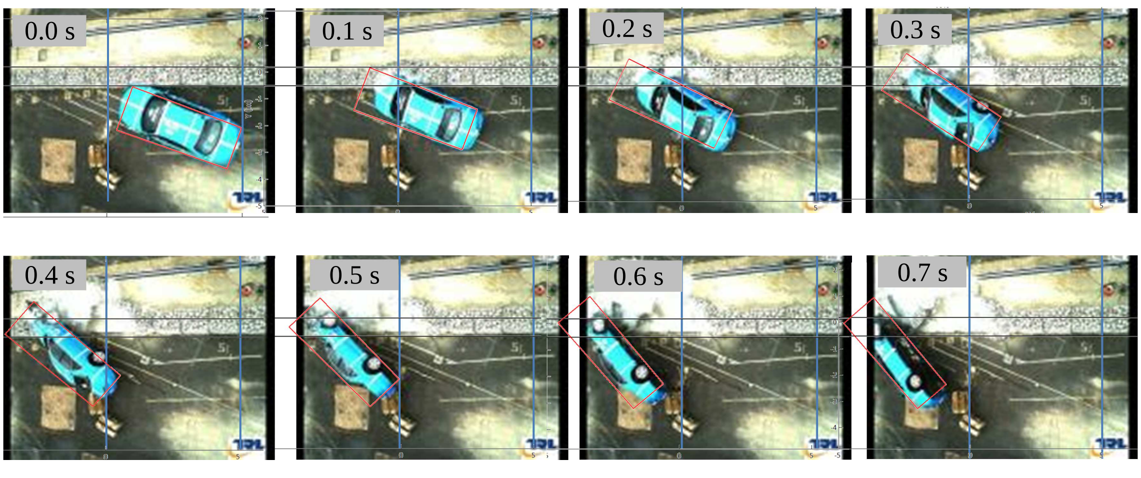

Figure 16. TB31 crash test: Sequence showing the impact with superimposed vehicle position from MB simulation.

Tables

Test	Displacement at max force (m)	Max force per meter of lacing (kN/m)
1	0.158	35.6
2	0.150	38.6
3	0.152	40.2
Average	0.153	38.1
Standard Deviation	0.004	2.4

Table 1. Lacing test: Maximum load and elongation.

Element	**Full size**	**Scaled**		**Length scale factor**
	Length L_f	Length L_{sc}		$S_L = L_f/L_{sc}$
Gabion unit length	2.0	0.45-0.50	m	4.4-4.0
Vehicle length	4.0	0.87	m	4.6
Vehicle Width	1.7	0.386	m	4.4
Vehicle CG height	0.49	0.114	m	4.3
Vehicle Bumper height	0.5	0.159	m	3.1
Vehicle Bumper width	0.1	0.09	m	1.1
Vehicle Wheelbase	2.8	0.434	m	6.5
Vehicle Track	1.51	0.18	m	8.4
	Mass M_f	Mass M_{sc}		$S_L = \sqrt[3]{S_M} = \sqrt[3]{M_f/M_{sc}}$
vehicle	1500	19	kg	4.3
gabion unit	2000	20-34	kg	4.6-3.8
	Inertia I_f	Inertia I_{sc}		$S_L = \sqrt[5]{S_I} = \sqrt[5]{I_f/I_{sc}}$
Vehicle Inertia I_x	2700	0.31	kg m^2	6.1
Vehicle Inertia I_y	540	1.23	kg m^2	3.4
Vehicle Inertia I_z	2760	1.46	kg m^2	4.5
Impact speed	80	50	km/h	/
Impact angle	20	20	deg	/
Scaled vehicle wood class	/	D40 - D50	/	/

Table 2. Geometry and length scale factor of the scaled vehicle and gabion barrier.

Test set	Mesh opening size (mm)	Stone sizes (mm)	Void ratio	Mass (kg)	Total number of tests	Vehicle redirected (number of tests)	~~Spinning~~Spin-out or Roll over (number of tests)	Mesh torn
A	80x100x2.7	120	45%	27	6	2	4	No
B	80x100x2.7	bricks	~~30~~10%	20	7	5	2	No
C	80x100x2.7	50	30-35%	32-34	2	0	2	No
D	25x35x0.5	50	30-35%	32-34	4	0	4	Yes

Table 3. Scaled crash test specimen details and results.

Ground/gabion friction coefficient		
Surface	Average	Standard Deviation
Tarmac site	0.46	0.07
Dry soil Lab	0.69	0.05
Rough Concrete	0.61	0.02
Wet soil site	0.69	0.05
Gravel	0.69	0.13
Soil Site	0.73	0.06
Grass Site	0.65	0.05

Table 4. Gabion/ground experimental friction coefficients for different ground surfaces

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