Dynamic Actions on Bridge Slabs due to Heavy Vehicle Impact on Roadside Barriers

Guido Bonin, Alessandro Ranzo

University of Rome "La Sapienza"
Via Eudossiana, 18
00184 Rome, Italy
guido.bonin@uniroma1,it
alessandro.ranzo@uniroma1.it

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Abstract. In Italy, during the past years the use of roadside safety barriers has changed: the number of installed devices increased and also did their stiffness and resistance. This change was necessary because the early barrier design was inadequate to contain and redirect the heavy vehicles. The change of barrier design led an increase of stiffness and resistance; consequently the action transferred by the device to the structure increased. The request of resistance on the bridge slabs can be too high, because the peculiar action of the roadside barriers was not adequately taken into account in the oldest bridge design codes. Additionally, characterizing the actions transferred to the bridge slab is difficult due to the dynamic nature of the vehicle impact on roadside barriers. Given the impossibility to perform a full scale laboratory test for every different bridge deck, the use of computational mechanics applied to dynamic impact/interaction problems is one of the best way to establish these actions in the project phase. The aim of this research is to use a 3D Finite Element Model of the bridge slab-barrier-vehicle system to perform a numerical simulation of the impact, according to the procedure used for the roadside barrier homologation crash test, described in the European standard EN1317.

1 INTRODUCTION

1.1 The adoption of concrete barriers

In the late 80's in Italy there was a strong need of enhancing the road barriers: some accidents showed that the old steel barriers were really too low and structurally inadequate to contain the heaviest vehicles. Sometimes the truck hit the median barrier and, not contained, overran in the adjacent carriageway colliding with the vehicles running in the opposite direction. As a consequence a period of great changes for these safety devices started.

One of the first changes was the adoption of concrete barriers with New Jersey shape; these barriers were often mounted in pair in the median and sometimes they became stiffer by filling the space between them with soil.

These devices solved almost completely the median overrun problem and quickly became the standard median in all the roads. Soon they began to be used also as a protection for the lateral obstacles (piles, structures) and a new kind of concrete barrier was built explicitly for the bridge decks: it was higher than the median and had a circular steel beam on the top.

1.2 The new test guidelines and the rise of steel barriers

In the February of 1992 a new ministerial decree was published in Italy[1], defining the rules for road barriers design, test and homologation.

The decree specified the requirements for the devices to be tested with a full scale crash test, with conditions and vehicles assigned according to the required containment level.

In the 90's the steel barrier producers greatly improved their products and gained the major part of the market share. The new steel barriers are generally higher, more complex and stiffer than the old guard rail. Many of the new barriers are modular and have height and number of components growing with the containment level.

1.3 Very High Containment barriers

The new guideline define the containment level categories, based on the lateral kinetic energy of the test vehicle; the top category is H4 (H4a and H4b), "very high containment level". The required containment level for H4a is 572 kJ and the test is done with a 30 ton 4 axles rigid vehicle hitting a barrier with a 20 degree angle and 68 km/h speed.

1.4 Barrier installation

The median and lateral concrete barrier are not restrained to the ground: their shape give them the redirection capabilities and some energy is dissipated through the heavy mass and high friction between concrete and road pavement.

The lateral and median steel barrier posts are partially embedded in soil, to give adequate restraint: the post rotates (during elastic phase) and then a plastic hinge is created just below the pavement surface level, where the bending moment is maximum.

The bridge barrier, either the concrete and the steel ones, are fastened to the bridge deck with steel anchor bolts, that transfer to the structure shear and bending moment. It is necessary, on bridge decks, to reduce the lateral displacement of the barrier to prevent the vehicle from falling down the bridge; this requirement makes the barrier stiffer and this leads to higher actions transferred to the structure that can cause local structure faults. These faults can be dangerous for the vehicles on the bridge and for the eventual traffic or structures overpassed by and surrounding the bridge.

1.5 A new design tool: computational mechanics

The 1992 Italian decree and later the EN 1317 (European standard on Road Restraint Systems) gave to the roadside device designer and producer a guideline for the evaluation test and not a real design standard. The real device design, intended as structural project, is often missing.

This is due to the difficulty in performing an accurate structural calculation with the standard simplified rules, because these structures carry their loads during a crash event, so the large deformation and plastic behaviors have to be considered.

The requested performance for these devices is also one of the major causes of the calculation difficulties: the barrier has to contain a heavy vehicle (heavy mass vehicle test) but there is also a control on the impact severity (done with a light car test). The designer could be inclined to make the device stiffer to satisfy the heavy vehicle test, but that has to be balanced with the results on the light vehicle.

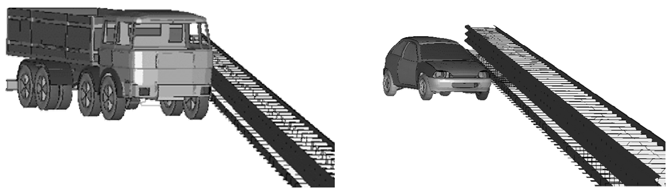

Figure 1 - The two required tests for a high containment barrier

Therefore in the past only simplified calculations were performed, but the real behavior of the structure during the test remained unknown.

The situation changed when the growing speed of computers made possible the use of Finite Element codes specifically developed for impact simulation: these codes were born initially for military applications and ran on very expensive supercomputers.

These Finite Element codes made it possible to test design changes before the execution of a full scale crash test. This test will become in the future only the final confirmation of the computational mechanics simulations' results.

This is a valuable tool, because with the simulation is possible to test situations difficult to recreate in the reality (or simply too expensive or dangerous), getting from the analysis the complete stress-strain history of each part involved in the impact.

The main drawback to this application is the complexity of the code, that still needs highly trained engineers and, for some particular situation, additional research is needed.

All the calculations reported in this paper were performed using LS-DYNA v.950d, a nonlinear explicit finite element code. The current version of this code has a material model database, which counts more than 200 constitutive laws and is expanding to fulfill all the application needs, but often particular applications needs fine tuned user defined materials, valid only within limited conditions.

2 FINITE ELEMENT MODEL

This paper focuses on the evaluation of the actions transferred to a bridge deck when an heavy vehicle hits one of the newest very high containment steel barriers.

To do this it was built a model to reproduce the crash test for a H4a steel bridge barrier, mounted on a simulated bridge deck.

The complete model counts about 50,000 elements and is composed by three sub-models: the bridge deck, the barrier and the vehicle.

The typical run time to analyze a 1300 msec event, using the complete model, was 180 hours.

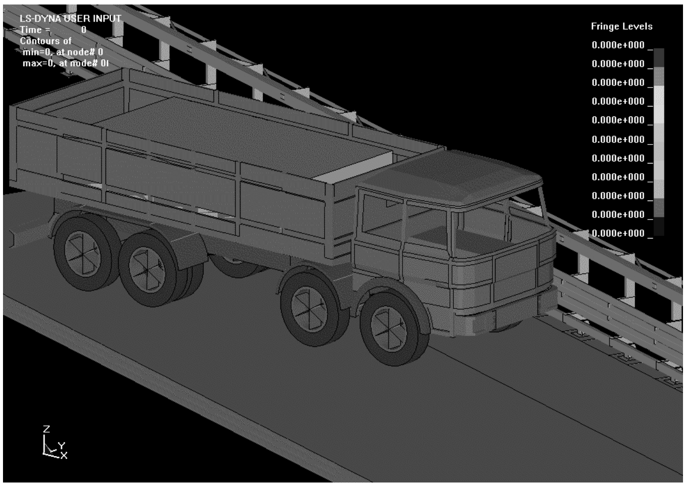

Figure 2 – FE model of bridge barrier crash test

2.1 The vehicle model

The vehicle model was built at the University of Rome – Area Strade. In the past, because of the unavailability of the vehicle model and the long run times, it was used a simplified vehicle model, with few elements, no suspension system and rolling tires and no correspondence to any real vehicle.

This choice was good for some kind of barriers, in particular the concrete barriers, but when the device got more complex, the analyses with simplified vehicle models showed that much of the real test behavior was lost.

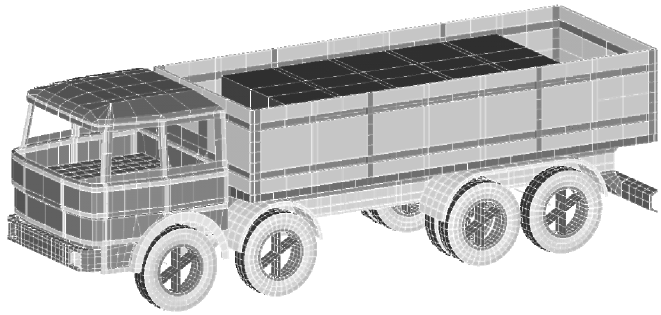

Figure 3 - FIAT IVECO F180NC vehicle model

The vehicle is a reproduction of a FIAT IVECO F180NC 4 axle vehicle with a total mass (ready for the test) of 29,600 kg. The model reproduces the rolling tires and the suspension system of the real vehicle. It was validated with the reproduction of crash tests on concrete and steel barriers, showing a good correspondence between the real test and the simulation.

The main part of the structure was modeled with 4 nodes shell elements; the material is elastic-plastic with failure (based on a maximum strain).

2.2 Barrier model

The barrier model. reproduces a three rail steel bridge barrier, with a containment level of 572 kJ (H4a). The barrier has a maximum height of 1.5 m and the post spacing is 1.333 m.

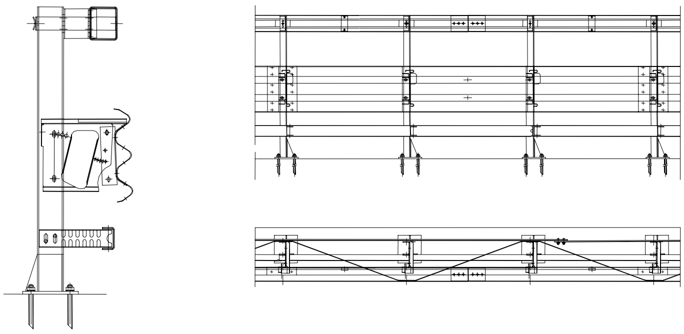

Figure 4 – Side, front and top view of the bridge steel barrier used for the analysis

The barrier model is 78 m long.
The posts are mounted (welded in the real barrier) on steel plates fastened with steel anchor bolts to the bridge deck. In the model there is a central part (40 m) that reproduces the real installation of the device, with 4 beam elements for each plate connected to the bridge deck model. The remaining posts are connected to steel plates, which have 4 nodes fully restrained.
All the nodes on the barrier have the additional condition to avoid penetration of the bridge deck and pavement surfaces.
The barrier model is built with 4 nodes shell elements and the material model is elastic-plastic with failure.

2.3 Bridge deck model

The bridge deck was modeled to reproduce accurately the real restraining conditions of the barrier in the impact zone.
The test should be done in the same condition found on the road, so a bridge barrier should be tested on a simulated bridge deck, in order to give the device the correct restraint and behavior.

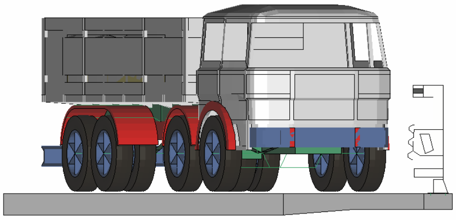

Figure 5 - Bridge deck model (cross section view)

The modeled deck is reinforced concrete slab, 42 m long and 6.5 m wide. The cross section is composed by a 4 m wide uniform height part and a cantilever slab, with thickness varying from 310 mm to 230 mm. The barrier is mounted on the thinnest extremity.
Unfortunately the new LS-DYNA material model specifically suited to be used with roadside crash tests was not available at the moment of this analysis [11], so the deck is modeled with 8 node solid (brick) elements and the material model used to perform the simulation is elastic with failure.

2.4 EN 1317 TB71 test specifications

The model was built to perform an EN 1317 TB71 test, that is the standard test performed for H4a barriers.
The vehicle is a 4 axles rigid Heavy Goods Vehicle (lorry) that has to fulfill some requirements on the main dimensions, mass and Center of Gravity location.
The vehicle impacts the barrier with a constant speed of about 68 km/h with a 20 degrees angle that, with a mass of about 30,000 kg, have a lateral kinetic energy higher than 572 kJ.

3 RESULTS

The actions transferred from the barrier to the bridge deck are basically shear (longitudinal and transversal) and bending moment (around longitudinal and transversal axis); due to the strength of the posts, the plates and the anchor beams, there is also a risk of local concrete crush. Our main objective was to evaluate shear and bending moment.

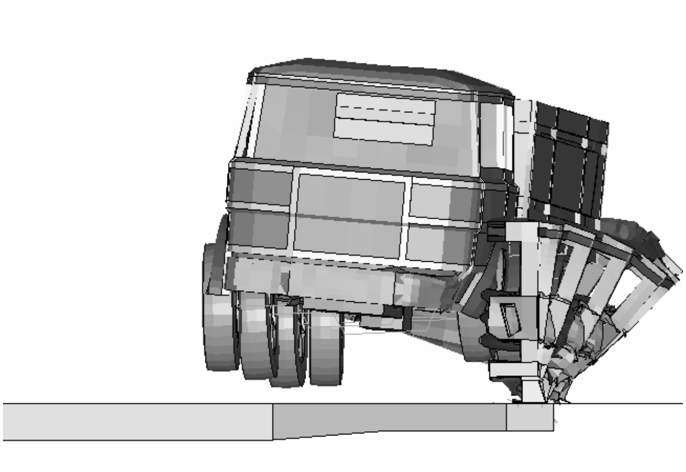

Figure 6 – Computational mechanics model, side view (maximum dynamic load time step)

The anchor beams are the elements that connect and transfer actions from the barrier to the deck, so all the actions are calculated starting from shear and axial forces of the beam elements connected to the plate and to the bridge deck.

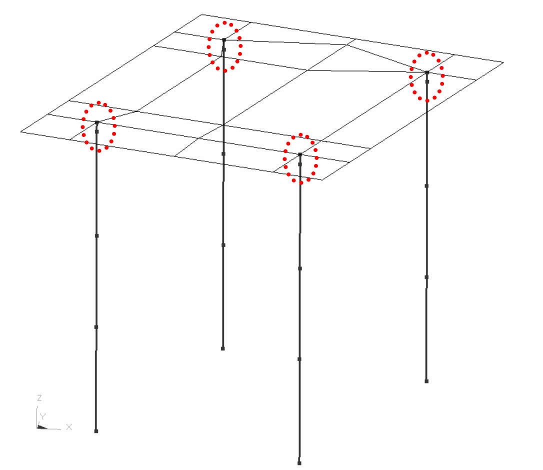

Figure 7 - Beams used to evaluate actions

These forces vary dynamically during the test, so it is possible to represent the results with a diagram that shows the time history of each action.
The actions are calculated with an interval of 10 msec, that is a compromise value to cut out high frequency actions that have no practical significance.
During the simulation there was no element failure in the bolt connection, while there was some minor failure in some shell element of the spacers.

3.1 Shear forces

Shear forces are calculated for each group (post) by summing the single beams shear forces (longitudinal and transversal component).

The following diagrams show the longitudinal and transversal forces for each time step of the simulation, in the most loaded post.

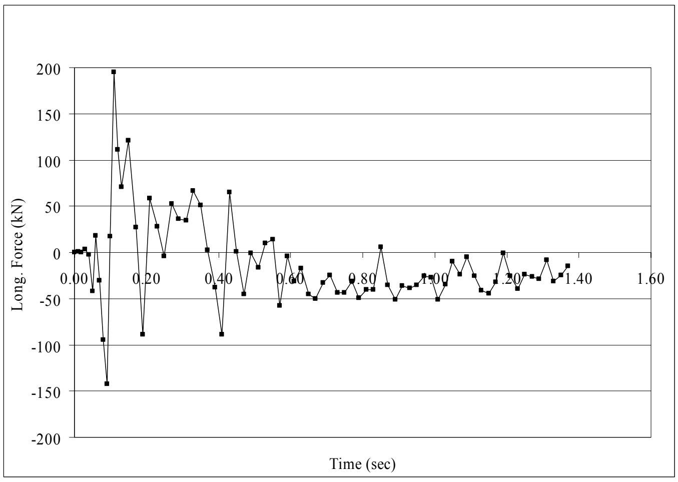

Figure 8 - Longitudinal force time history (post 8)

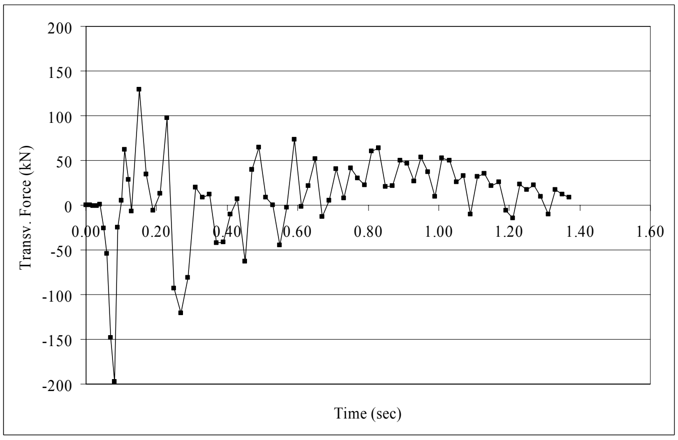

Figure 9 - Transversal force time history (post 8)

Maximum and minimum values of shear force computed for each group of anchor beams are reported in the following table.

	Transversal shear		**Longitudinal shear**	
Post	*min* *(kN)*	*max* *(kN)*	*min* *(kN)*	*max* *(kN)*
5	-137	118	-103	80
6	-119	113	-164	111
7	-138	121	-170	151
8	-198	129	-142	195
9	-110	117	-144	73
10	-101	83	-120	89
11	-104	137	-72	134
12	-95	118	-66	128
13	-74	114	-97	143
14	-82	117	-116	85
15	-75	74	-101	49

Table 1. Maximum and minimum shear forces for each post

3.2 Bending moments

For every the two pairs of beams, bending moments are calculated around the transversal and longitudinal axis of the plate welded to the post.

Also the bending moments are variable during the test and are reported in the following diagrams for the most loaded post.

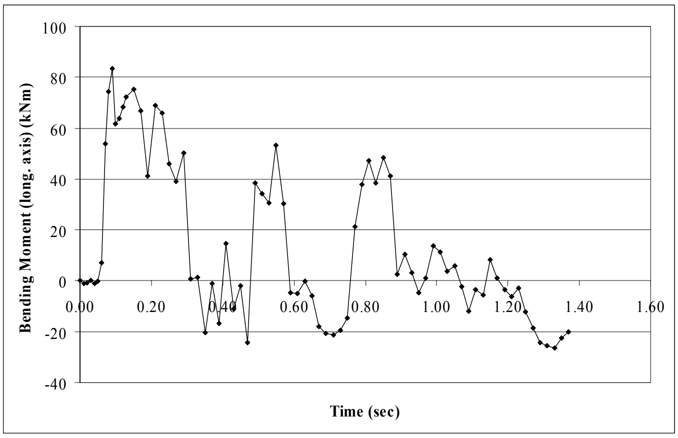

Figure 10 - Bending moment around longitudinal axis (post 10)

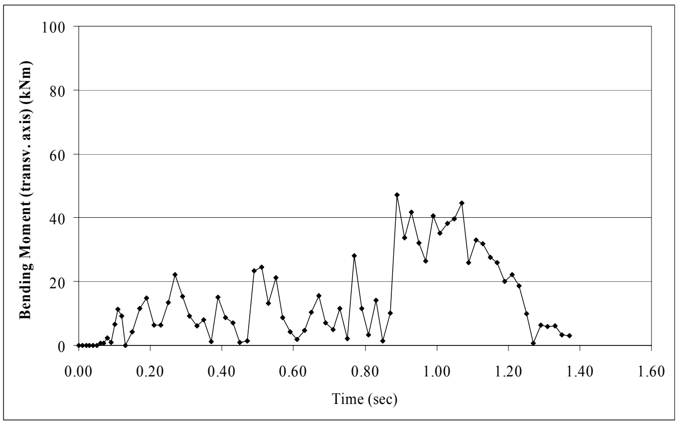

Figure 11 - Bending moment around transversal axis (post 10)

It is to notice that (correctly) the bending moment is only positive in the transversal axis.
The results for the other posts are summarized in the following table.

	Bending moment *(around long. axis)*		**Bending moment** *(around transv. axis)*	
Post	*min* *(kNm)*	*max* *(kNm)*	*min* *(kNm)*	*max* *(kNm)*
5	-24.80	43.06	-0.41	28.65
6	-33.84	44.87	-0.09	23.08
7	-23.17	50.17	-9.03	16.88
8	-31.26	38.73	-3.28	24.67
9	-36.93	77.90	-5.69	30.41
10	-26.57	83.32	-0.05	47.11
11	-63.62	74.30	-18.18	32.13
12	-46.92	72.74	-0.12	24.05
13	-30.49	63.03	-7.41	32.86
14	-24.04	23.30	0.00	27.35
15	-19.49	15.19	0.00	28.26

Table 2. Maximum and minimum bending moment for each post

3.3 Discussion of results and comparison with design standards

The analysis of the actions due to an heavy vehicle impact on a roadside barrier involves the bridge design and the barrier design.
The new stronger and stiffer barriers affect bridge decks design and calculation, as it is possible to see analyzing the bridge design standards.
In Italy the current design standard was published in 1990 [4] and specifies, on paragraph 3.11, that for the actions on parapets can be used a horizontal static force of 45 kN, at 0.60 m over the road surface, plus a static force of 30 kN applied on 4 posts maximum.
The currently published Eurocode 1 part 3 [5] recommends a 100 kN static force, horizontal and transversal, applied 100 mm below the top of the barrier or 1 m above the road surface and acting on a line 0.50 m long. There is also a recommendation that the structure supporting the barrier should resist an accidental load effect 1.25 times the maximum characteristic local resistance of the vehicle parapet (e.g. the anchor bolt).
The new draft Eurocode 1 part 2 [6], that will supersede the current ENV 1991-3:1995, severely raise the actions due to collision with restraint systems. In paragraph 4.7.3.3 the draft Eurocode has the same recommendations, but there are now 4 classes of horizontal forces, ranging from 100 kN (that is now the minimum) to 600 kN. There is a clear reference to the European roadside hardware design standard, but it is no direct correlation between the higher classes of the Eurocode and the high containment classes for the EN 1317.
In the following table there is a summary of the values suggested by the design standards and the results of the computational mechanics model. The loads from design standards are calculated for a barrier like the one used in the computational mechanics model, 1.50 m tall.

	Shear force *(kN)*	**Bending moment** *(kNm)*
Italian DM 1990	52.5	31.5
ENV 1991-3:1995	100	140
prENV 1991-2 - Class A	100	140
prENV 1991-2 - Class B	200	280
prENV 1991-2 - Class C	400	560
prENV 1991-2 - Class D	600	840
Computational mechanics	*198*	*83.32*
TTI Lab tests (static)	218	113.73
TTI Lab tests (dynamic)	484.86	252.47

Table 3. Comparison between design standard values and computational mechanics results

The bending moment results of computational mechanics are lower than the values included in the Eurocodes, but the load is applied in a very different way. The Eurocode load has to be applied on a line 0.50 m long in a single position, that represents the worst possible action for that kind of load and has to be determined with the influence line method. The Eurocode says that the load "may be applied 100 mm below the top of the selected vehicle restraint system or 1,0 m above the level of the carriageway or footway,", but it is not clear if the load has to be applied on the barrier or on the deck itself. This is a key point, because if the force is applied on the barrier, the action will be transferred to the deck by many posts, with lower, distributed stresses on the deck.

The load resulting from computational mechanics is applied on a single post, and the other posts carry, in the same time, a similar load. These shear forces and bending moments are the real loads acting locally on the bridge deck.

As a comparison it was also added some laboratory test[9], conducted in different condition and with different barrier and bridge deck. During the static tests a variable static force was applied to a fixed height of 0.521 m (20.5 in) carrying the structure to failure; during the dynamic tests a bogie vehicle impacted the barrier and the force applied to the structure was measured.

In the static tests the maximum shear force was 218 kN (49.1 kips) with a maximum bending moment of 113.73 kNm (49.1 kips at 20.5 in).

In the dynamic tests the maximum shear force reached was 484.86 kN (109 kips) with a maximum bending moment of 252.47 kNm (109 kips at 20.5 in).

4 CONCLUSIONS

There is no doubt that in the oldest design standards the loads were smaller than necessary to support the new devices. This is probably the key point of the problem: when a new high containment barrier is installed over an existing bridge, surely designed with old standards, there is always a risk of a local deck failure and therefore also barrier malfunction.

The draft Eurocode seriously takes in account this issue and raises the loads, that in some cases can be very tough to face for the designer, in particular for old bridges.

The computational model presented and the draft Eurocode recommendations confirm that a barrier installation over a bridge is a complex operation that sometimes needs additional resistance from the deck, that has to be partially redesigned.

The analysis was carried on only with one particular type of barrier and one particular bridge deck, but these two components can vary very much. The barrier can be made in various shapes and with different materials, but with those with high containment and low lateral deflection always transfer high actions to the bridge deck. The bridge deck can be really different from case to case and the heavy vehicle impact to the barrier can seriously damage it, particularly the older designs.

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LIST OF FIGURES

LIST OF TABLES