

DYNAMIC RESPONSE OF A GUARDRAIL SYSTEM BASED ON PRESTRESSED CABLES

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Abstract

Road safety is a major global concern nowadays. Within the road infrastructure, bridge sectors are the most dangerous in terms of the incidence and severity of accidents. Engineering practice is to reduce their gravity by installing safety barriers with a very high level of protection, type H4b. There are however situations in which these protection systems actually and up reducing the level of safety for road users by limiting visibility.

This paper studies the possibility of adopting an innovative safety barrier solution based on modern, more efficient materials such as prestressed high-strength steel reinforcement. Scaled model of 1:20 tests and numerical simulations are presented for a guardrail system made up of high strength cables and plastic hinge supports.

1. INTRODUCTION

Nowadays, road safety is a pressing issue in all countries of the world. Road accidents are one of the main causes for serious injury and loss of life to humans, with around 19,400 deaths in Europe alone in the year 2025. Limiting the gravity of accidents in the field of transport infrastructure represents a challenge in the from both a social and economic point of view.

Within the road infrastructure, bridge sectors are the most dangerous in terms of the frequency of accidents and their consequences, which very often lead to serious injuries and even loss of life. The conventional solution to increase the level of safety is to install safety barriers with a very high level of protection type H4b, which, in accordance with Romanian AND 593 and European SR EN 1317/1-5 can be made of steel or out o concrete, called “New Jersey” guardrails. These usually have a dual role, to protect structural elements of the bridge from

collisions with vehicles and to protect road users by dissipating impact energy and stopping vehicles before they fall off the bridge or ricochet back.

History has shown that if installed properly, the barrier solutions used have had acceptable results in the event of impacts, but there have also been situations in which their very presence has led to accidents, by limiting visibility or narrowing the roadway due to insufficient space on existing, older bridges.

Since the early days of steel guardrail systems, the quality and strength of building materials have evolved greatly. There are much more efficient construction materials available nowadays like high-strength steels, carbon fibers, nylon, etc, none of which are used in approved safety barrier solutions. Furthermore, there are many passive and semiactive energy dissipation systems that can mitigate impact energy, other than the plastic deformations methods currently used. Incorporating such efficient materials and devices in guardrails systems would most likely increase the overall level of safety and comfort for traffic participants.

In the next chapters, this paper will study a novel guardrail system made up of high strength cables and plastic hinge supports. Scaled model of 1:20 tests and numerical simulations are presented.

2. NECESSITY FOR IMPROVEMENTS IN THE FIELD

This chapter will present three situations in which current guardrail models and regulations cannot ensure all safety, strength and visibility criteria.

2.1. Intersection between National Road DN2 and county road DJ 203C

A typical "T" intersection between a secondary road and a very busy road, where there was no way to ensure both optimal visibility and safety conditions for drivers. A compromise had to be made by locally reducing the level of protection provided by the guardrail from H3 to H2, in order to increase visibility.



Figure 1. Low impact level guardrail in the intersection between National Road DN2 and county road DJ 203C

2.2. Grant Bridge, over Grivița Bd, Giulești Bd. and 8 railway lines in Bucharest, after retrofitting works

The Grant Bridge recently underwent a series of retrofitting procedures. During the latest interventions on the structure, high impact resistant H4b guardrails were installed, replacing the older, less resilient model, in accordance with the regulations in force. The large dimensions of the guardrail, corroborated with the lack of acceleration/deceleration lanes and the curvature of the bridge in plan view, make entering the flow from the side shoulders very difficult and dangerous. This situation existed before, but the much smaller guardrail reduced the magnitude of the phenomenon. Since reopening to traffic in march 2024, there have been numerous incidents of light accidents on the bridge.



Figure 2. Grant Bridge Shoulder view when entering the traffic flow

2.3. Domnești bridge over Bucharest ring road and railway

The atypical shape of the passage supporting a roundabout makes it very difficult to ensure visibility conditions at the entry into the flow, while also ensuring a very high level of impact protection, in accordance with all regulations. The solution adopted was to ensure satisfactory visibility conditions by locally reducing the level of protection of the safety barriers from H4b to H3.



Figure 3. Domneşti bridge local guardrail impact level decrease

The situations presented above are only a few recent examples of protection barriers issues that need to be addressed. It is clear that there are certain situations for which current guardrail models and norms are not sufficient.

3. PROPOSED GUARDRAIL SYSTEM

3.1. Design approach

In trying to develop an alternative guardrail solution, several materials were considered. Concrete guardrails tend to be more massive and opaquer compared to their steel counterparts, so they are not a viable solution here, only metallic systems. High strength steel cables are very compact and resilient structural elements as long as they are subjected to tensile stresses and would fit very well in the design of the guardrail system. Prestressed carbon fiber plates could also be a solution, but they are relatively new in the field and still need more testing, so they were not considered in the paper.

Steel guardrails work by absorbing the impact energy and mitigating it through plastic deformations. After a crash, most of the components adjacent to the point of impact cannot be reused and need to be replaced. This study proposes to increase the efficiency of the parapet by incorporating passive energy dissipation devices in the design, while also ensuring optimal visibility by reducing the size of the damper and frequency of the stilps.

The proposed crash barrier consists of adjacent high strength cables 20cm apart, each made up of one Y1860 S7 15.2 strand. Three cables are proposed in order to maximize efficiency for a larger number of vehicles heights and to reduce shear cutting of the car body. The cables are attached to a fixed anchorage at the end of the guardrail in the direction of movement, and a shock absorber at the beginning, with a shear key to unlock it during a crash. The cables are held in

position by articulated fixings attached to steel stilps with bolts, 5 meters apart in the longitudinal direction.

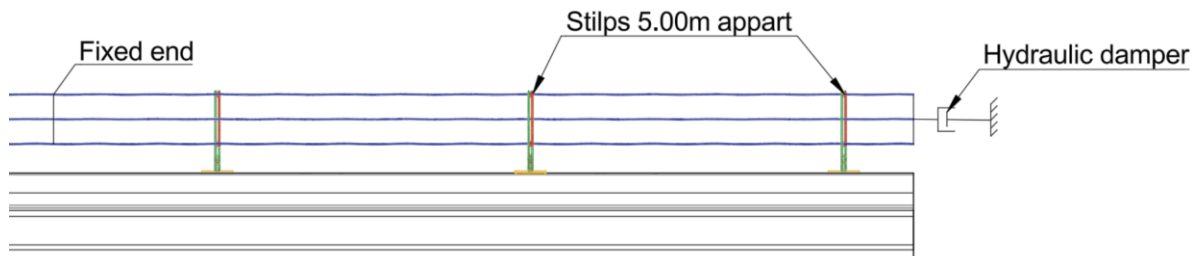


Figure 4. Guardrail elevation sketch

In order to minimize damage, the stilps are attached to the superstructure with a friction hinge made up of two bolts and circular ovalized holes. The base of the friction hinge is attached to the structure with chemical anchorages.

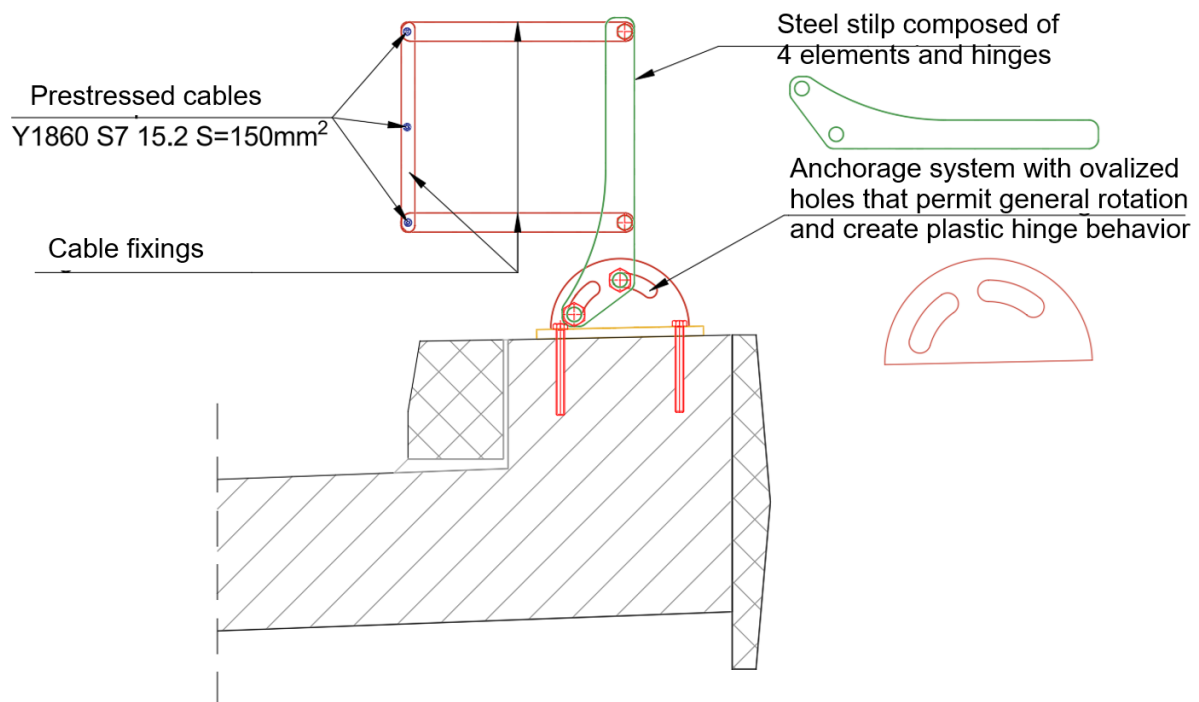


Figure 5. Guardrail cross section sketch

3.2. Expected performance

In order to ensure adequate behavior and linear geometry, the cables must be prestressed at about 45% to 50% of their tension limit. The shear key at the start of the barrier will need to withstand this force and about 5% more to account for lesser incidents.

During small impacts, the flexibility of the cable and the stilps should allow small displacements to occur and stop the vehicles by friction with the cables and energy dissipation in the friction hinges of the stilps. Only minor damage is expected to appear both in the stilps and the vehicles themselves. The system should maintain usability without external intervention.

During high impact incidents, the shear key is expected to break and the impact energy to be mitigated by the shock absorber acting on the vehicle by means of the cables. Because of inertial forces limitations, an estimated longitudinal displacement of about two meters or more is expected to be necessary for the vehicle to come to a complete stop. Transverse displacement is expected to be minimum because of the high tension in the cables. Displacement is also expected to occur in the friction hinges of the stilps, and the cables tension will be lost after impact. After the accident, some stilp elements might need replacement, but most are expected to maintain usability and just require repositioning. Minor damage is expected to occur in the cables, but they will need to be retensioned and a new shear key be installed.

4. NUMERICAL SIMULATION OF THE CRASH TEST

4.1. Finite element model

To simulate the impact, a three-dimensional finite element model of the guardrail was created, for a 40m long section of the barrier. The cables were modeled as a single line meshed with several 5cm long bar-type elements, each with two joints and 6 degrees of freedom at both ends. As boundary conditions, the cable is blocked at one end, connected to a shock absorber at the other, and special connections to the stilps, that only resist to axial force between the two.

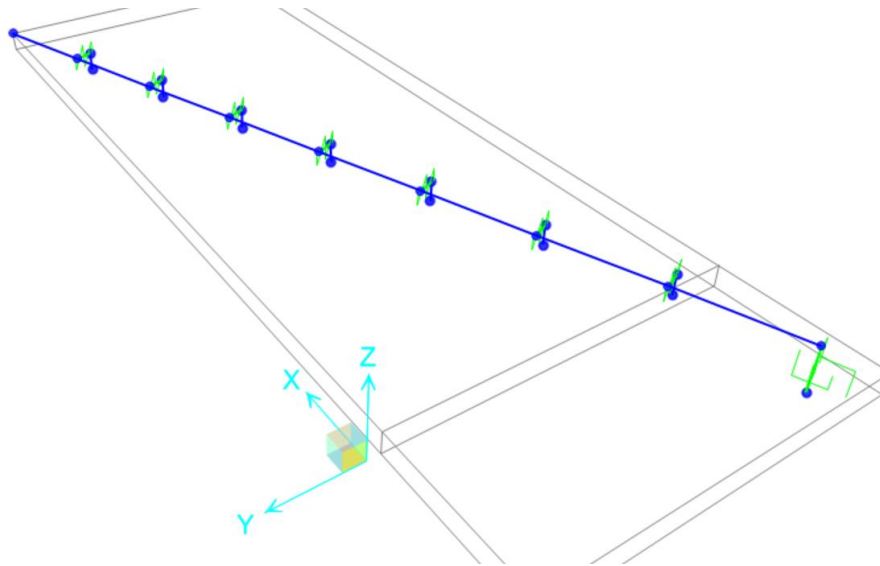


Figure 6. Finite element model general view

The stilps were also modeled as bar elements, but with plastic joints at their base with previously calculated characteristics.

4.2. Input and analysis parameters

The vehicle was modeled as a concentrated mass of 38.00 tons, and the impact speed was introduced through an acceleration of 1666.67 m/s^2 acting for 0.01s in order to reach a speed of 60 km/h, as prescribed in the norm.

The analysis consists of two stages:

- Prestressing the cables to a value of $0.45 \times f_{pk} = 840 \text{ Mpa}$
- Performing time-history analyses with direct integration, geometric nonlinearity and material nonlinearity at a 0.01s step

4.3. Theoretical results

Deformation, speed and acceleration of the vehicle are the three parameters analyzed in the study, as well as compliance to the norm regarding containment level and working width class of the barrier. The last two are presented in [fig. 7].

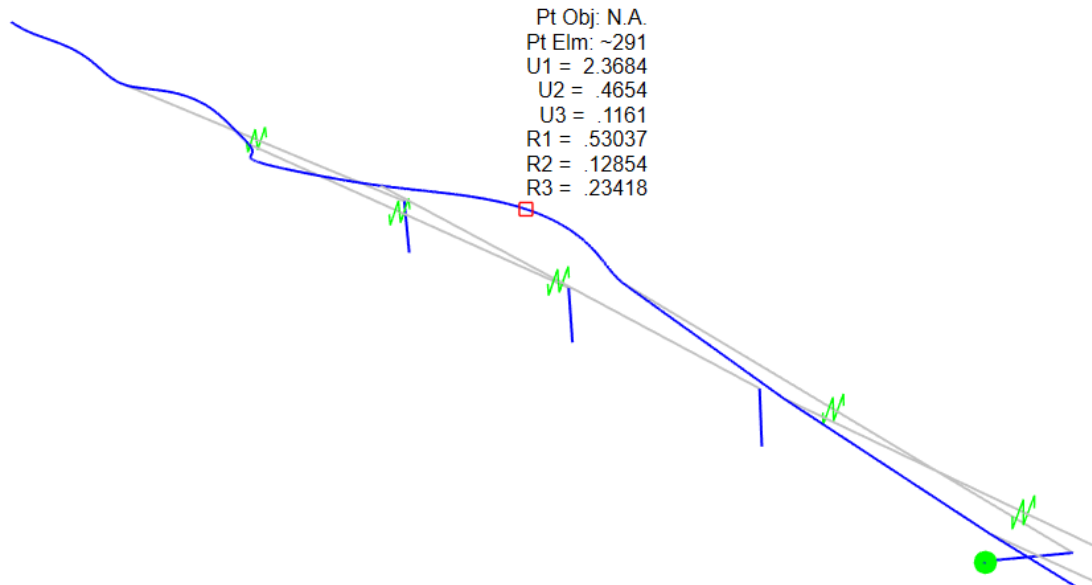


Figure 7. Deformed guardrail after impact

As can be seen in the picture above, the total displacement along the cable is just under 2.50m and transversely it is just under 50cm. The shape of the deformed cable is not symmetrical, and depends on the internal stresses after the impact. The section in front of the vehicle shows an arbitrary shape corresponding to what probably is a detensioned cable, while the section behind the vehicle describes an almost straight line between the shock absorber and the point of impact, indicating high tension. The panel between the adjacent stilps of the impact point shows a curved cable, indicating a little bending overlapping the high axial stresses.

The mass of the object stopped by the guardrail corresponds to a H4b high containment level and the transverse displacement corresponds to a W3 working width class, both of which are acceptable for this situation.

For a more detailed presentation of the dynamic response of the cable, displacement, speed and acceleration variation graphs are provided in the images below.

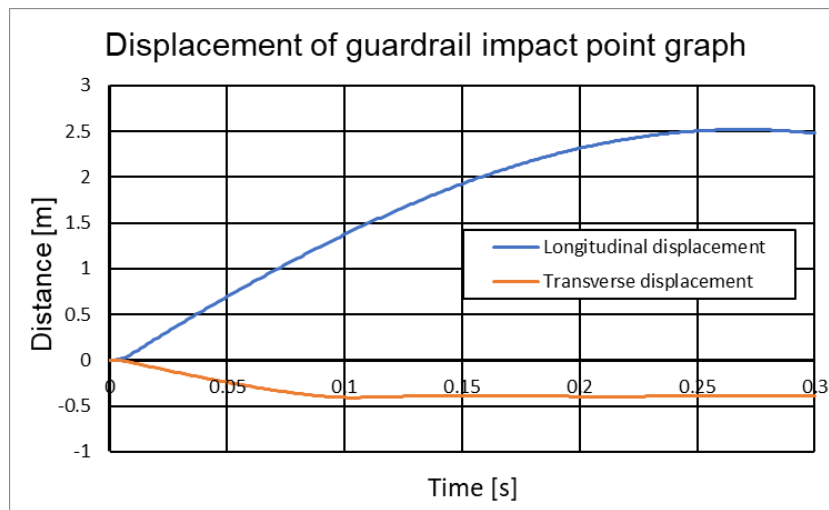


Figure 8. Displacement response of the point of impact

The displacement graph shows a total time of the impact incident of just 0.28 seconds. The values in the longitudinal direction indicate a steep rise at first and then an asymptotic trending to a maximum value of about 2.50m, followed by a small comeback tendency of about 10-15cm probably because of remaining tension in the cable. The vertical displacement increases to a value of about 40cm in the first 0.1s, and the maintains this level throughout the test. This indicates a wave like behavior of the cable as it deforms in the longitudinal direction.

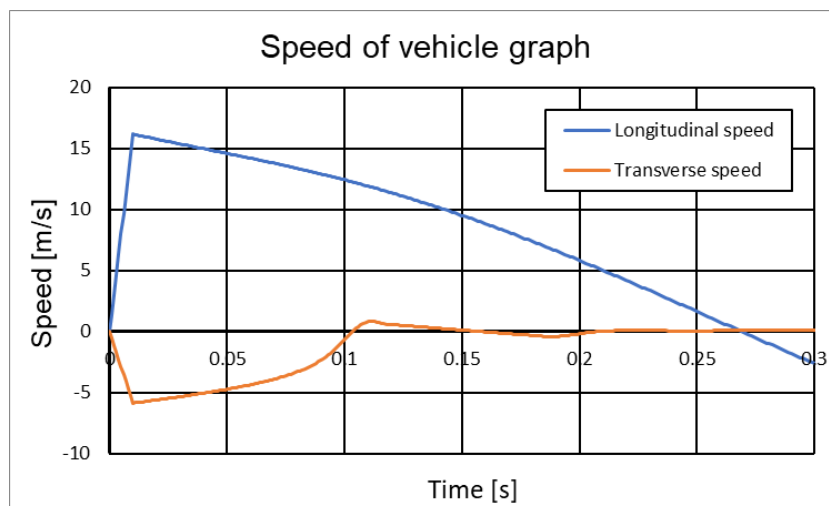


Figure 9. Speed variation of the vehicle before and during impact

Regarding the speed variation, in the longitudinal component, the graph shows a steep increase during the first 0.01s of acceleration up to a peak value of 16.67m/s (60km/h) and then a constant decrease throughout the incident, probably because of the shock absorber working. The transverse component of the speed

vector indicated an initial negative value of 6m/s that quickly turns to zero in about 0.1s and then stays constant throughout the simulation.

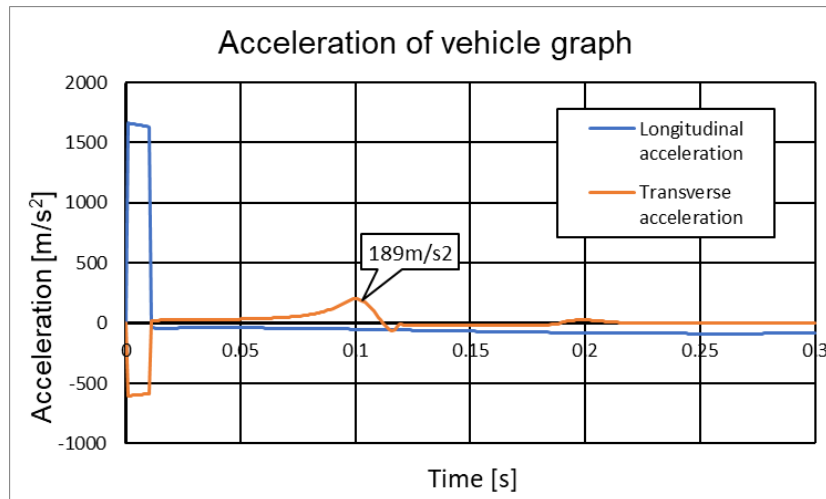


Figure 10. Acceleration variation of the vehicle before and during impact

The acceleration graph shows an initial huge value of over 1650 m/s² which should be neglected because it is the theoretical initial impulse used to achieve the desired velocity.

The relevant part that should be considered is afterwards, where results show an almost constant negative longitudinal braking acceleration of 78m/s², and a narrow increase in transverse acceleration with a peak value of 189m/s² around the 0.1s threshold.

The longitudinal acceleration value of just under 8g is not comfortable but tolerable for the human body since it only lasts for about one third of a second. The transverse value of almost 19g is much more dangerous event for the limited time of under 0.05s. This however is not likely to occur in a real incident because of deformations that the chassis of the car would undergo first.

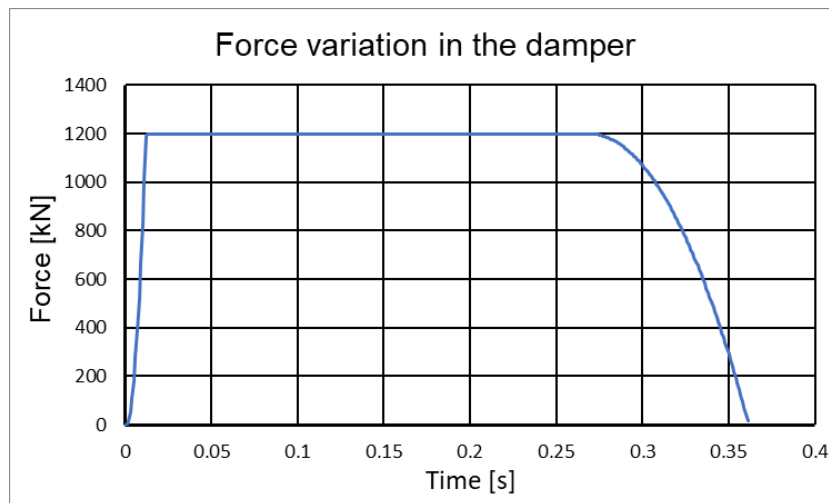


Figure 11. Force vs time variation in the shock absorber

The behavior of the shock absorber perfectly matches its constitutive law. Neglecting the first 0.01s, the force developed maintains a constant value of 1200kN for the first 0.25s, and then sharply decreases to zero as the speed of the vehicle is reduced in the last part of the analysis

5. SCALED MODEL

5.1. Principle of the model

A physical model of the barrier was created with a scale of 1:20. This model cannot account for a full-scale crash test, since the norm does not permit this approach, but it can be used to demonstrate the principle behind the idea.

A 2.10m barrier was created consisting of 6 stilps installed at a distance of 35cm each and two $D=2$ mm high strength steel cables. The functional crash area estimated for this design is around 1.50m, in order for the results to not be influenced by the end constraints.

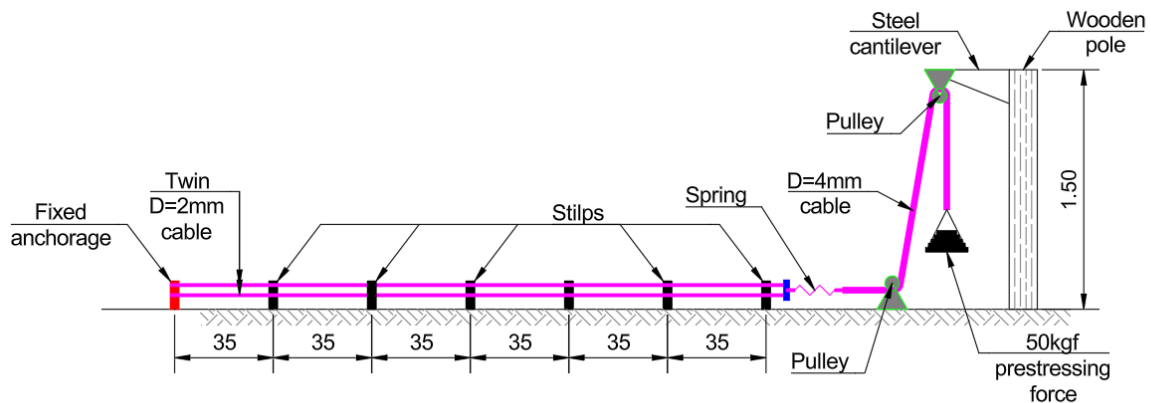


Figure 12. Sketch of the scaled model

The two cables are attached to a steel passive anchorage at one and an active one at the other. The active anchorage is made up of a system of pulleys, a stronger D=4mm cable and a weight of 50 kgf used to apply tension. The link between the stronger cable and the two smaller ones is made up of a stiff spring added to account for the initial shock and not damage the other components.

This prestressing system is also used to mitigate impact energy like the viscous damper would. Any movement of the cables under crash conditions will lead a lifting of the 50kg mass, thus transforming kinetic energy into potential and absorbing the impact.

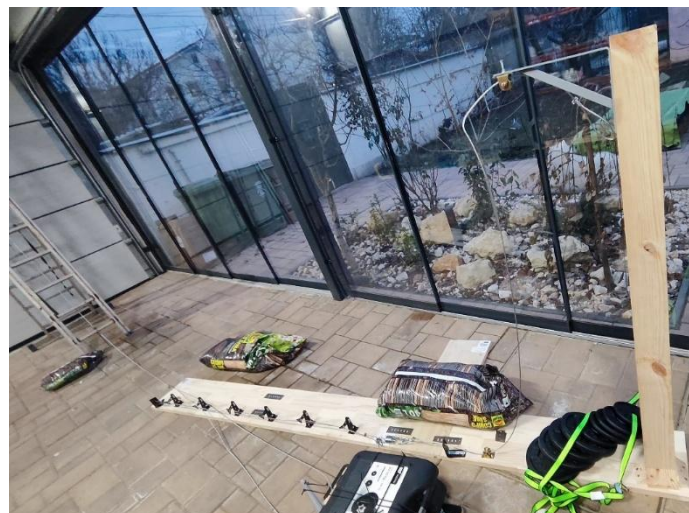


Figure 13. Actual footage of the model

5.2. Scaled model components

5.2.1. Stilps

A 3D plastic filament printer was used to create the stilps. Some alterations were done to the base model to accommodate for some shortcomings of this approach. The stilp is made up of one base, two vertical straps, one cantilever and one cable holder. Pictures of the theoretical model and the actual one can be found in the pictures below.

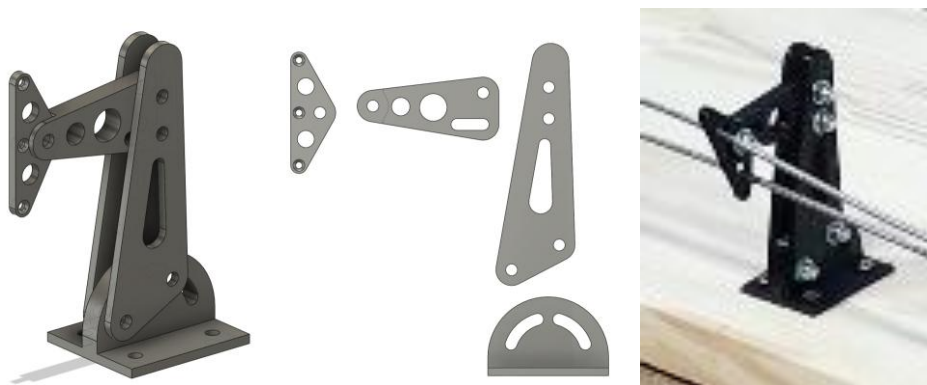


Figure 14. Scaled stilp design

The pieces of the stilps were attached to each other using M4 bolts and nuts. Each stilp is attached to a wooden base plate with 4 M4 bolts, 20mm long.

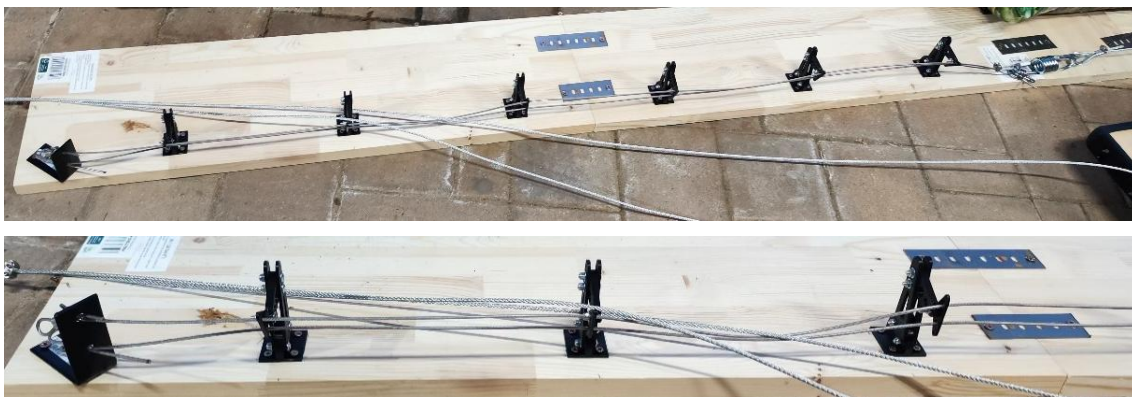


Figure 15. Installed stilps and anchorage on the wooden base plate

5.2.2. Pole

The pole was created from a 5x15cm section, 1.50m long wooden bar. This also has wooden reinforcements installed on all sides at the base level and a 30cm long steel cantilever attached at the top.



Figure 16. Installed stilps and anchorage on the wooden base plate

After installing the pole on a separate base plate, pulleys and the cable were also attached. A textile strap and a hook were used to attach the 50kg weights and prestress the system cables of the system. Bags of earth and bolts fixed to the ground were added as a precaution for general stability of the test frame.

5.2.3. Impact vehicle

The impact vehicle is composed of a 60x40cm wooden plate with 4 wheels attached at the bottom. The following components were added on the plate, in order to facilitate better impact conditions and measurements:

- a steel hook was added at the front in order to pull the cart to the desired speed
- a three directional accelerometer was mounted for test results
- two 25kg weights were added to simulate the scaled mass
- a plastic bumper bar to simulate damage and deformation of the vehicle chassis
- wooden wedges and plastic strips were added to fix all components on the plate



Figure 17. Scaled vehicle

5.3. Scaled crash test

Kinetic energy of the impact was the main parameter considered for similitude theory comparison. Considering the scale of 1:20 and a total weight of the impact vehicle of 56kg, the required test speed was determined using the following formulas:

$$\text{Actual kinetic energy: } E_{C_actual} = \frac{M \cdot v^2}{2} = \frac{38 \text{ tonnes} \cdot (60 \text{ km/h})^2}{2} = 5277,78 \text{ kJ} \quad (1)$$

$$\text{Scaled kinetic energy: } E_{C_test} = \frac{\frac{M}{20} \left(\frac{v}{20}\right)^2}{2} = 659,72 \text{ J} \quad (2)$$

$$\text{Test speed: } v_{test} = \sqrt{\frac{2 \cdot E_{C_test}}{M_{test}}} = \sqrt{\frac{2 \cdot 659,72 \text{ J}}{56 \text{ kg}}} = 4.854 \text{ m/s} = 17.5 \text{ km/h} \quad (3)$$

The required speed was induced in the cart by an additional system of cables, pulleys, an “A” frame metal stair and a 100kg mass falling from a height of 70cm.

Only one test was done due to damage to a part of the stilps. Keyframes of the test are presented in the following pictures, showing moments prior to impact, initial collision with the cables, collision with the stilps and position of the cart when it stopped.

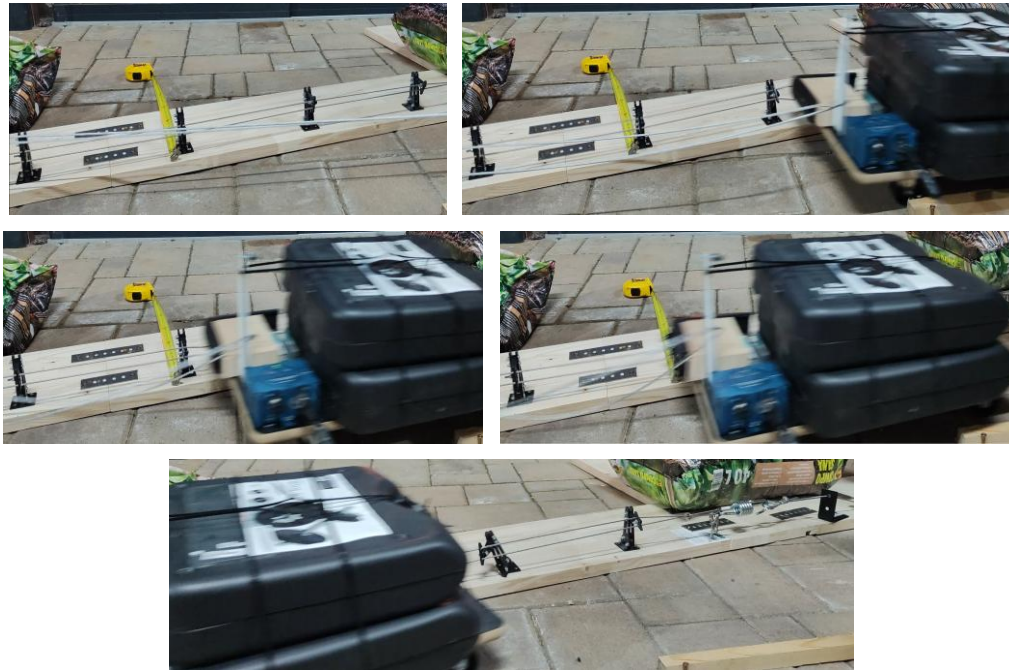


Figure 18. Crash test in keyframes

5.4. Scaled model results

Although some damage to the stilps occurred, the test can be considered a success. It took about 1.10m of impact length for the cart to come to a complete stop, with a maximum transverse displacement of about 8cm. The transverse displacement matches a W4 working width class, which is higher than anticipated but still within acceptable limits according to the norm.



Figure 19. Scaled guardrail after crash test

During the test, two of the stilps actually broke at the level of the base plate piece. Upon closer inspection, it was found that the rupture mechanism was of share force, basically tearing apart two adjacent layers of filament. It is highly

improbable for this to happen in real life if the stilps would have been made of steel. The rupture mechanism is related to the limits of 3d filament prints that are known to have poor layer adhesion. Aside from this, there was minimal to no damage on the cables, anchorages, or on the cart itself.

The total horizontal accelerations were calculated by using the square root of the sum of squares method, based on the recorded values during the test and are presented in the graph below. There is a lot of background noise probably related to imperfections of the runway, but a total of three spikes can be observed. The first one relates to the final positioning of the cart prior to the test, the second correspond to the induced acceleration and the third one corresponds to the actual impact.

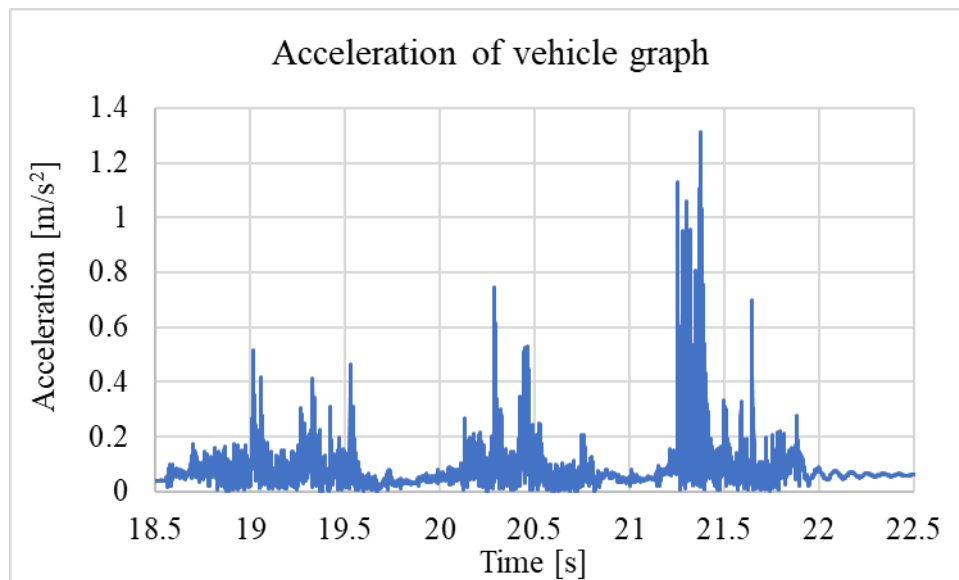


Figure 20. Acceleration variation of the vehicle before and during impact

The maximum acceleration recorded is of 1.33 m/s^2 , which indicates to a full-scale value of 26.6 m/s^2 , so around $2.6g$, much lower than predicted. The large difference when compared to the simulation is related to friction or lack of it to be more exact. In the theoretical simulation, there is no slipping between the vehicle and the cable itself, while in scaled test little to no friction could be interpreted between the bumper plate and the cables.

6. CONCLUSIONS

The field of road safety barriers is very strict and well-regulated with an abundance of expectations to be met, but despite this there are some limitations with situations for which there are currently no solutions provided (e.g. visibility

in acceleration/deceleration lanes, higher impact angle than prescribed in standard tests in turnabouts).

Considering today's technology and construction materials, much more efficient safety barrier models could be made than those existing on the market, both in terms of safety and durability.

The solution proposed in this paper has proven to be effective in stopping the vehicle following the impact, indicating a fairly low level of degradation of the structural systems and at the same time greatly increasing visibility.

There were some inconsistencies between the theoretical simulations and actual test results, but the overall results seem to match. The variations were probably caused by material limitations and lack of some small details in the scaled model.

Although the results of the impact analysis are promising, they are not sufficient to move to the next stage of production. Although the vehicle was stopped in similar conditions both in the simulation and the test, some of the objectives of the test barrier were not achieved. The impact length was too long, and the efficiency of the semi-active energy dissipation mechanism was very low due to a fair amount of slipping between the test cart and the barrier. Furthermore, two of the stilps were completely destroyed and couldn't have been used in later tests, which was supposed to be one of the secondary objectives.

Further, more detailed analyses of the behavior of the structural elements at the local level should be carried out and full-scale impact test (crash test) should be performed, in order to move on.

Another important limitation of the barrier model which would need to be solved regards to costs, which are expected to be much higher than current conventional models. Solutions must be sought to reduce the production costs of the presented system, in order to make it more economically feasible

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