Concrete Roadside Safety Barriers – Development of Impact Loads Models

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Abstract: The design of a safety barrier – bridge deck system implies the knowledge of both the deck and the safety barrier behavior for a situation when a road vehicle collides with the barrier. The European codes for designing are doubtful about this subject, especially for the safety barrier case. Therefore, the development of numerical models that allow the study of the consequences of a vehicle collision on the barrier and the deck are of significant matter. Above all, this models must allow the understanding of the materials nonlinear constitutive relations influence and the effect of a dynamic load associated with a vehicle collision.

Considering a set of loads that fully simulates a real collision, and also taking into account the proposals of the European Standards, it was possible to conclude that the nonlinear relations of the materials lead to a rearrangement of the internal stresses, mobilizing larger regions of the barrier and the deck. The dynamic effect is not relevant due to the multiple modes of vibration of the structure - consequence of its inner characteristics, such as the mass and the stiffness - which means that for this case the dynamic coefficient is close to one.

The collapse of the structure was also studied and it was possible to conclude that even for this case the permanent damage is strict to the barrier, not being transmitted to the deck. Such result was obtained as a consequence of the vertical reinforcement that was adopted for the barrier.

Keywords: Safety Barrier – Bridge Deck System**,** Dynamic Impact**,** Dynamic Coefficient**,** Load Degradation

1 Introduction

For some road structures, such as bridges, it is very important to keep a vehicle in the road after a collision. For that purpose, one should use safety barriers. Concrete barriers are less deformable than steel railings, and must be structurally connected to the bridge deck. This means that not only the safety barrier has to be design but also the bridge deck needs to be design taking into account the loads transmitted by the barrier due to a vehicle collision. The European Standards concerning road barriers (EN 1317 – Part 2 [1]) do not suggest any design loads, they only define performance classes and testing criteria. On the other hand, the North American Standards (AASHTO [2]) suggest design forces and the location where those loads shall be applied, but presents no information regarding the load degradation along the barrier - or any length of control for its connection with the deck - nor any suggestion about the dynamic effect that an impact load has over the structure. That way, in order to fully understand how a vehicle impact should be taken into account when designing a safety barrier and a bridge deck, a finite element model was built and a combination of loads representing a vehicle collision was defined with the aim of developing project models for this kind of structures.

2 Modelling

The model of the bridge deck and safety barrier was developed using the finite element program ABAQUS [3]. In this program, the concrete elements were defined as solid (C3D8R) and the reinforcement elements as truss (T3D2), having all the elements a general dimension of 100 mm. About the model, it was considered a section of the deck with a length of 12 m. It was also admitted that the part of the deck considered in the model works as a cantilever, assuming that its connection with the main cross section of the bridge prevents it from moving and rotating. All the other borders were defined as free ends. Figure 1 shows the model defined in ABAQUS and the boundary conditions admitted for the analysis.

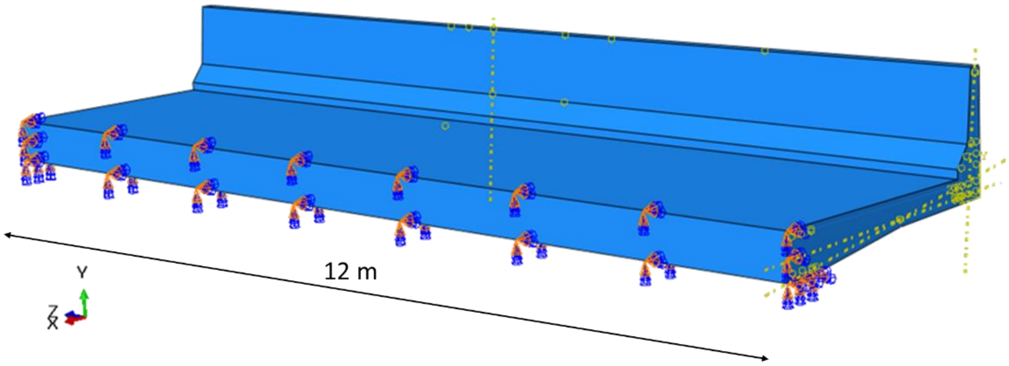

Figure 1 - Model and boundary conditions defined in ABAQUS

It is now important to mention that this work follows the one developed by Mendes [4], who concluded that the consideration of a dynamic factor leads to an increase in the materials resistance. When a material is subjected to an impact load it suffers an increase of resistence, beeing that increase of resistance called dynamic factor. Since a vehicle collision shoulbe considered as an impact load, both the steel and the concrete resistance are afected by a dynamic factor, calculated according to the Model Code 2010 [5] for the concrete and according to Malvar et al. [6] for the steel. The final constituive relations for these materials are presented in Martins [7]. Besides this, it is also possible to define the damping associated with the system. Considering a damping of 2% and the eigenfrequencies of the structure given by ABAQUS, the Rayleigh damping coeficients – α (dependent on the mass) and β (dependent on the stiffness) – were calculated and are presented in Table 1.

Table 1 - Rayleigh damping coefficients

α	4,72
β	$5,69 \times 10^{-5}$

3 Loading Definition

It was already mentioned that in order to simulate a real situation it is needed to define a set of loads that represent a real vehicle collision with the safety barrier. In order to define that set of loads both the standards' recommendations and the results of one to one scale tests were considered.

First of all, it is important to state that this analysis comprehends static and dynamic loads. The static loads include the own-weight of the structure, the weight of the pavement and the weight of the car. While the weight of the pavement is applied as evenly distributed in the deck, the weight of the vehicle is divided by its four wheels, considering each one of them with an area of 40×40 cm^2, as indicated in the Eurocode 1 – Part 2 [8]. The dynamic actions on the structure correspond to the impact of a vehicle into the barrier. Defining this action implies the knowledge of the maximum value of the force that is generated by the impact, the total time of the impact and the location where that force must be applied. The maximum value of the force cannot be calculated by regular expressions, as it depends on several parameters, like the stiffness of the vehicle and the barrier, the angle of collision and the vehicle impact speed, among others. Considering the results achieved in one to one scale tests with a Toyota Echo conducted by Jiang et al. [9] the maximum impact load was defined with the value of 250 kN. These tests were also suitable to understand how the force increases and decreases during the impact. The force starts at zero, then grows until its maximum value and then decreases again until being null. This process is linear and symmetric and most of the tests suggest that its total duration is around 0,4 s. The adopted shape for this force can be seen in Figure 2.

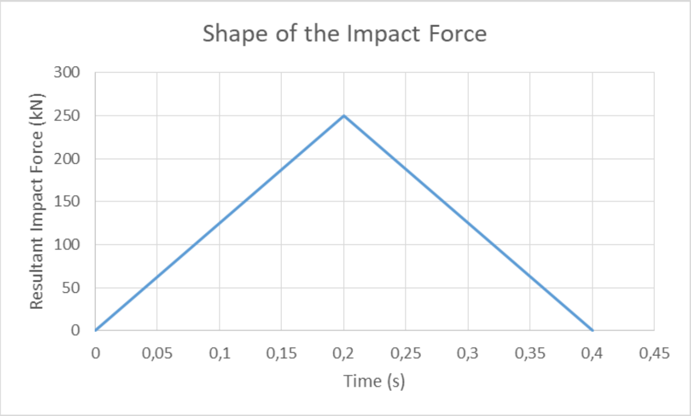

Figure 2 - Shape of the impact force associated with a vehicle collision into the barrier

About the place where the impact force should be applied, the recommendations of the European Standards lead to bigger forces in the base of the barrier, which means bigger forces transmitted to the bridge deck. For this simulation the impact force was applied according to Eurocode 1 – Part 2 [8] which indicates that the load associated with collision forces on vehicle restraint systems must be applied 100 cm above the bottom of the barrier and it must be distributed along a line of 50 cm.

4 Analysis of the Case Study

4.1 Permanent Damage

As it was explained in the previous sections, the simulation of a vehicle collision into a safety barrier is made through a finite element model developed in ABAQUS and considering a set of loads that fully describes its effect. In order to understand the effect of the collision on the deck, the analysis was divided into three stages. The first one corresponds to the time before the collision, when only the static forces are acting. The second one is associated with the time when the impact force is acting and, as shown in Figure 2, has a total duration of 0,4 s. The third stage starts when the impact force is no longer in action. This means that comparing the results of the first and the third stage allows to identify where the permanent damage is. For that, Figure 3 and Figure 4 show the normal stresses in the deck (along the xx direction) for the first and the third stage, respectively.

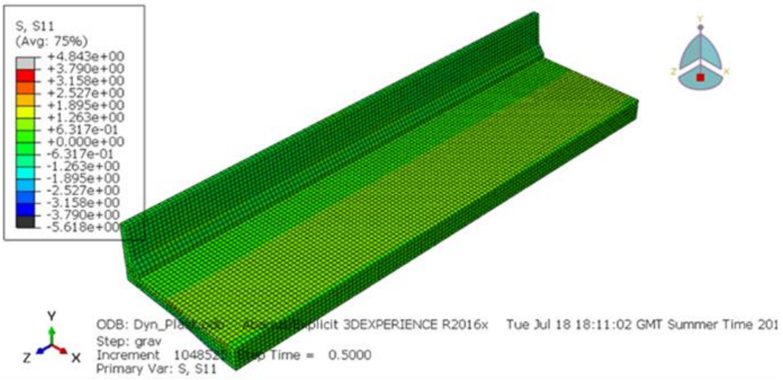

Figure 3 - Stresses along the deck at the end of the first stage

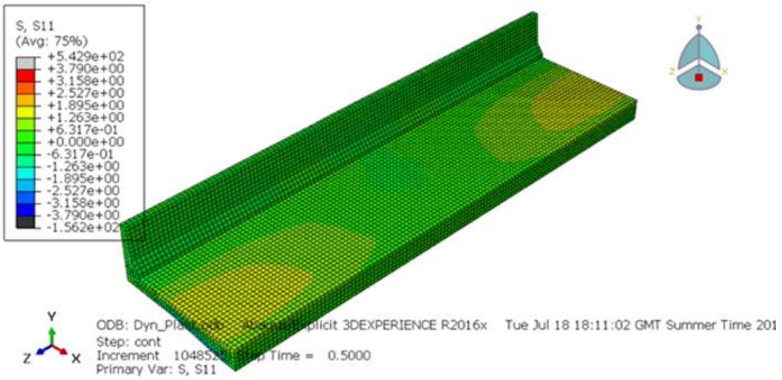

Figure 4 - Stresses along the deck in the third stage

Comparing both pictures it is possible to note that the stresses in the deck are not the same before and after the collision of a vehicle. However, there is no permanent damage in the deck. The highest tensile stresses in the deck occur when the impact force takes its maximum value (in the middle of the second stage). As it can be seen in Figure 5, there is a part of the deck - represented in grey colour - where the maximum stresses are higher than the concrete tensile resistance. Nevertheless, this only happens at a very superficial level and all the reinforcement in the deck is still in elastic condition. The opening of cracks is not significant and the deck is able to recover its shape when the impact force is no longer acting.

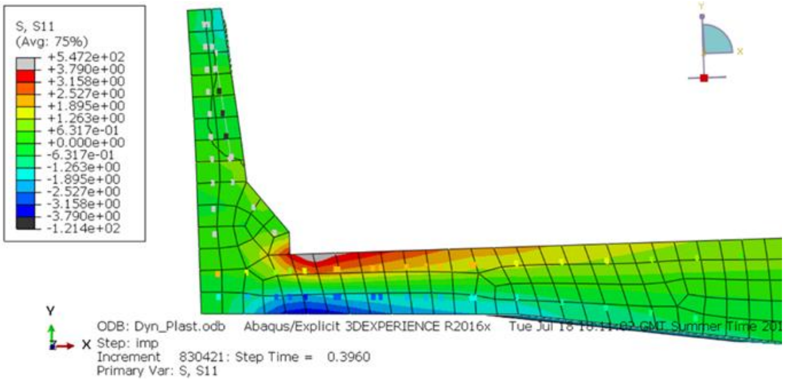

Figure 5 - Normal stresses in the deck (in MPa) for the time when the impact force has its maximum value

So, it is known that there is no permanent damage in the deck, yet its initial and final stresses are not the same. This information indicates that there is probably permanent damage in the barrier. Figure 6 represents the principal strains in the reinforcement. All the reinforcement remains in elastic condition but the one in the middle of the barrier. In that region, some of the reinforcement is already in yielding state, which means that the barrier is no longer capable of recovering to its original shape. The crack width was also calculated, according to the indications of the Eurocode 2 – Part 1-1 [10], which led to a value of $W_k = 0{,}41$ mm.

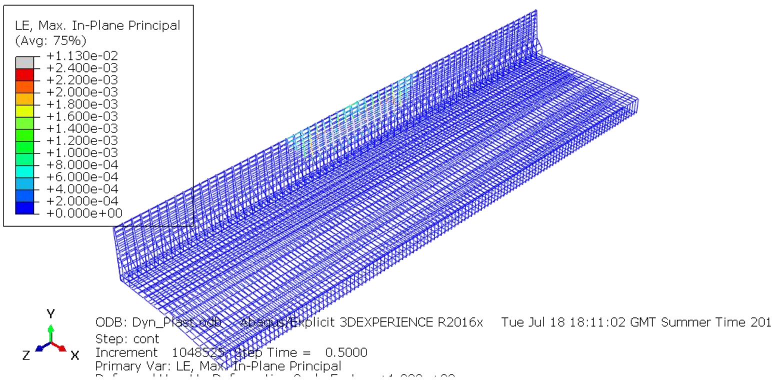

Figure 6 - Maximum principal strains in the reinforcement

It is now possible to conclude that the reason why the stresses in the deck are different in the first and in the third stage is due to the fact that in the third stage, besides all the loads that are applied to the structure in the first stage, there is also an imposed deformation - applied along the border between the barrier and the deck – that results from the permanent damage in the barrier.

4.2 Ultimate Load

The ultimate load capacity of the barrier was calculated based on the Yield Line Method. Figure 6 shows that only the vertical reinforcement yield. If there is no yielding of the horizontal reinforcement, it means that a horizontal yield line is not formed in the base of the barrier. This way, it is possible to assume that the mechanism of collapse formed is the one presented in Figure 7.

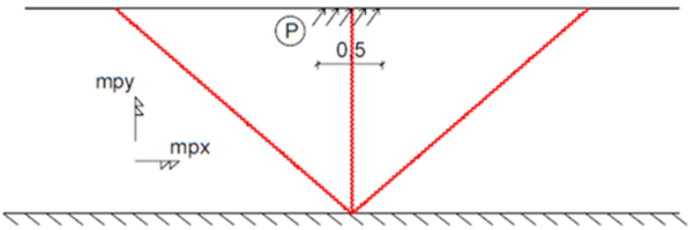

Figure 7 - Mechanism of collapse formed in the barrier

Solving the equilibrium equations that result from the mechanism shown in Figure 7, a maximum load of 345,18 kN was achieved. On the other hand, the maximum load obtained through an iterative analysis using ABAQUS led to a value of 350 kN, which is very close to the value calculated analytically. So, a new simulation was carried out, but instead of considering a force of 250 kN it was considered one of 350 kN. The maximum principal strains in the reinforcement for the ultimate load are shown in Figure 8.

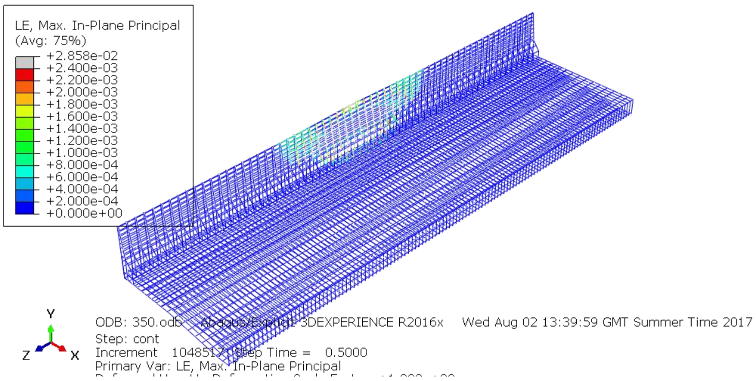

Figure 8 - Maximum principal strains in the reinforcement for P=350 kN

Once again, it is noticeable that the reinforcement in the deck remains in elastic condition, whereas the amount of reinforcement in barrier already in yielding condition has increased. It is now possible to conclude that, even for the maximum load, there is no permanent damage in the deck. This situation is essentially due to the amount of vertical reinforcement adopted for the barrier, which prevents the formation of a horizontal yield line close to the connection between the barrier and the deck. This conclusion is very important because it allows to state that if the damage remains strict to the barrier, then one can assume that for design purposes the barrier can be modeled as a cantilever. It is important to mention that the Yield Line Method can be applied because the collapse of the structure is due to bending. The shear resistance at the bottom of the barrier was calculated by Martins [7], being its value higher than the acting transverse load.

4.3 Load Degradation

The first assumption for the design of a safety barrier – the one that it works as a cantilever – has already been proved. It is now time to understand how the loads associated with a vehicle collision degrade along the barrier. This analysis will enable the definition of a length of control for the forces generated in the base of the barrier. With that goal, graphics showing the distribution of the bending moment and the axial force – the axial force in the deck corresponds to the shear force at the bottom of the barrier - along the cross section of the deck that is closest to the barrier, were developed. The aforementioned graphics were obtained based on the stresses along that cross section. For the main simulation – the one in which the impact force is 250 kN – the bending moment and axial force distributed along the cross section between the barrier and the deck are presented in Figure 9 and in Figure 10.

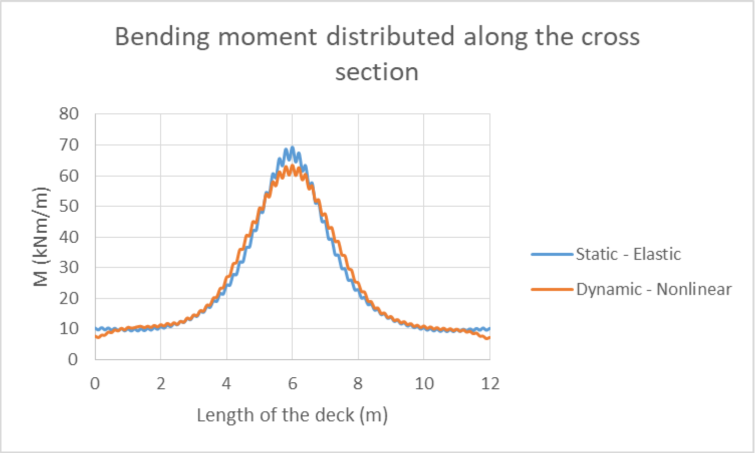

Figure 9 - Bending moment distributed along the cross section of the deck that is closest to de barrier

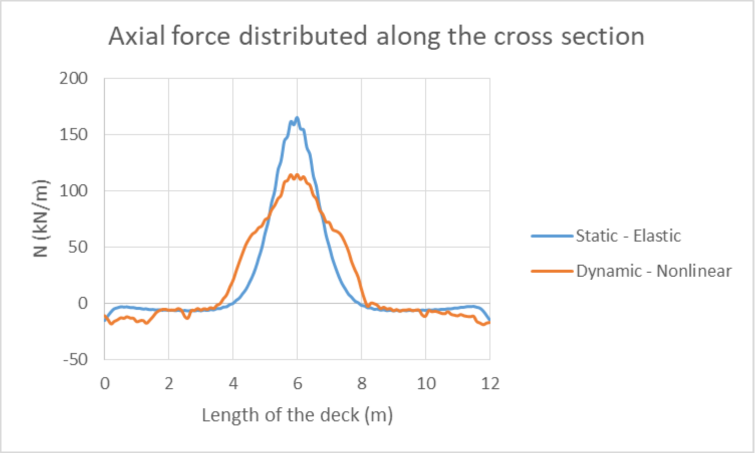

Figure 10 - Axial force distributed along the cross section of the deck that is closes to the barrier

Notice that in both figures the forces are compared with the ones that result from a Static-Elastic analysis. A Static-Elastic analysis corresponds to a simulation in which all the loads are applied as static and the materials are defined as elastic. A comparison between the results of these two graphics for both simulations leads to a very relevant conclusion. It can be seen that in the Dynamic–Nonlinear analysis the maximum force is lower, but it spreads along a greater length, being that more noticeable for the axial force case. This situation outcomes precisely from the fact that, in an elastic analysis, the tensile stresses in the central part of the deck – where it connects with the barrier – would be higher than the resistant stresses of the concrete. This implies that, in a nonlinear analysis, the central part of the cross section can no longer equilibrate higher forces and so adjacent parts are mobilized to equilibrate those forces. In other words, the nonlinear relations of the material lead to an internal redistribution of the forces. It is these internal redistribution, noticeable in Figure 9 and Figure 10, that helps understanding how the forces degrade along the barrier.

According to the widely used standards, this length of control should be determined considering a load degradation angle of 45º. For this case, where a 250 kN force is applied along 50 cm and 100 cm above the bottom of the barrier, it is easy to find out that the forces transferred to the deck would be a bending moment of 100 kNm/m and an axial force of 100 kN/m, both applied in a length of 250 cm. However, Figure 9 and Figure 10 reveal a different scenario. According to those figures, the bending moment takes the maximum value of 65 kNm/m (applied along 385 cm) and the axial force takes the maximum value of 115 kN/m (applied along 220 cm). It is interesting to notice that the standards' recommendations are for the design of members subjected to transverse load, hence the results of the simulations for the axial force in the deck are very close to the ones from the standards. Since there is usually no specific information regarding the bending moment, one could assume that its degradation is the same as the axial force, but it is not, it is actually smoother. This way, based on the length of controls mentioned above, it is now possible to calculate different angles for the load degradation and suggest a project model for the design of the barrier and the deck due to a vehicle collision. That model is presented in Figure 11, in which P represents the impact force and M and N the load degradation lines for the bending moment and axial force, respectively.

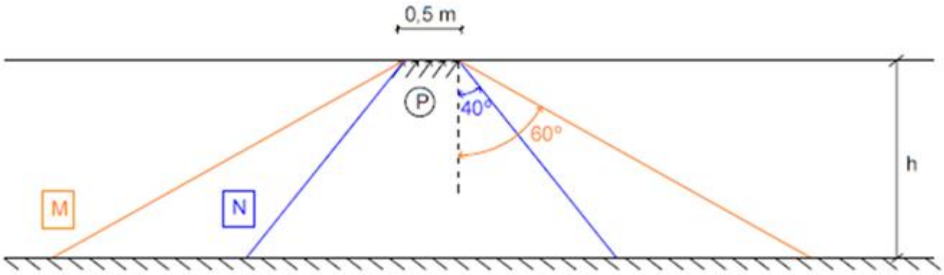

Figure 11 - Suggested model for the design of roadside safety barriers

4.4 Dynamic Coefficient

It is now known how the forces associated with a vehicle collision degrade along the barrier and how they are transmitted to the deck. It is also known that, for project purposes the barrier can be considered as clamped in the deck. In order to fully understand how a vehicle collision affects the structure it is now important to analyse the dynamic effect of an impact force over the barrier. In other words, an analysis has to be made with the aim of finding out the value of the dynamic coefficient.

For that purpose, several simulations were carried out using a Dynamic-Linear model. A Dynamic-Nonlinear model was not suitable for this analysis since it allows an internal redistribution of stresses which would lead to misrepresented results. The main focus was to understand if different durations of the force application would lead to different dynamic coefficients. So, total durations of 0,1 s, 0,2 s, 0,4 s and 0,8 s – according to the shape presented in Figure 2 - were tested using the Dynamic-Linear model. The forces generated in the cross section of the deck that is closest to the barrier were once again calculated and compared with the ones got for a Static-Linear analysis. These results are presented in Figure 12 and Figure 13. As it can be seen, there is no difference in the forces transmitted to the deck regardless of the load application time. It is also noticeable that those results are the same as the ones for the Static-Linear situation. It means that there is no amplifying effect of the impact force over the structure or, in other words, the dynamic coefficient is equal to one. The reason for that has to do with the fact that this is a multi-degree of freedom structure, which implies that there is more than one mode of vibration contributing for the response of the structure for this impact load, and also with the fact that the force is applied and removed in a short period of time. This fact leads to a mitigation of the dynamic effect over the structure.

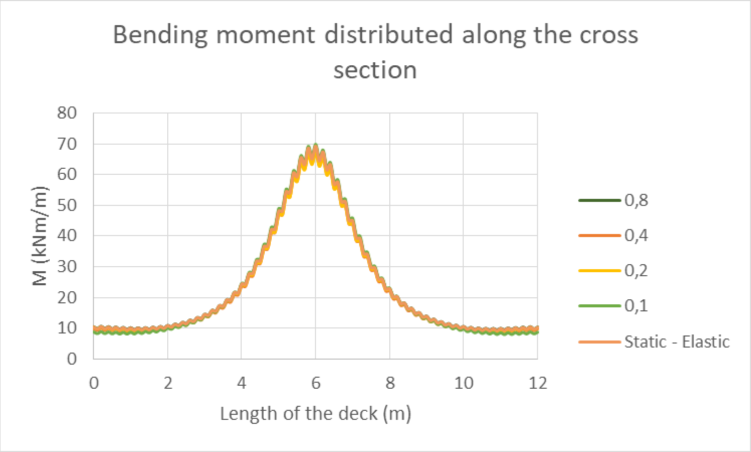

Figure 12 - Comparison of the bending moment for different times of load application

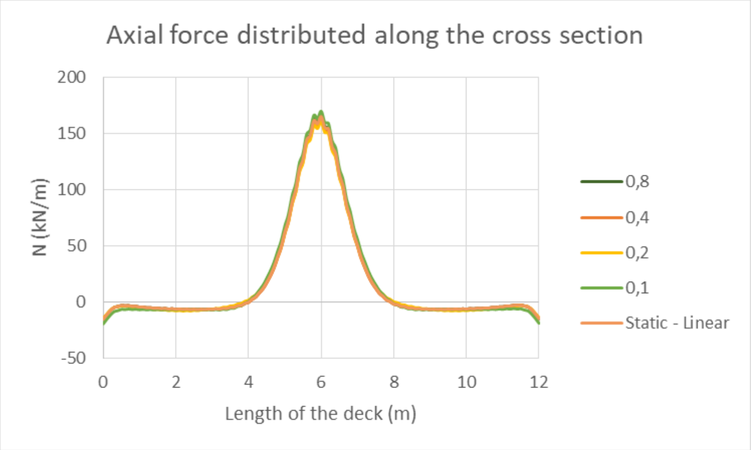

Figure 13 - Comparison of the axial force for different times of load application

Since it was possible to conclude that when the impact force is defined as linear and symmetric – as in Figure 2 – there is no dynamic effect over the structure, it is important to evaluate the influence of different shapes of the impact force on the dynamic effect. For that purpose, Martins [7] simulated the impact force as a trapeze and as an half-circle. Those results were also compared with the ones from the Static-Linear analysis, leading to the conclusion that the dynamic coefficient was still equal to one.

Besides that, it was also relevant to study the influence of considering the damping of the structure. That way, two more simulations were made, one with a model without any damping coefficients and another in which the damping was defined through the Rayleigh damping coefficients presented in Table 1. Once again, both simulations led to the same results in terms of forces transmitted to the deck. So, as it has already been concluded analytically by Biggs [11], when modeling an impact force there is no difference in considering or not the damping of the structure.

4.5 Conclusions

For design purposes, since there is no transmission of damage between the barrier and the deck, the barrier can be considered as clamped in the deck. This situation is mainly due to the amount of vertical reinforcement adopted for the barrier. The edge of the deck can also be assumed as clamped.

About the loading, it is not mandatory to adopt a maximum force of 250 kN. Although most of the one to one scale tests suggest that this is a good approximation of the real force that is generated when a vehicle collides into the barrier, other values can be assume. Nevertheless, the European Standards recommendations, by comparison with the work done by Mendes [4], lead to a worse case scenario, so they should be taken into account. It means that a load applied close to the top of the barrier and distributed along a length of 0,5 m represents a good model of considering a vehicle collision.

About the length of control at the connection between the barrier and the deck, the simulation made allowed to state that the load degradation is not the same for the bending moment and the axial force. A length of control for the axial force can be determined assuming a degradation of 40º/45º – which is very similar to what is recommended by the standards – and for the bending moment it can be determined assuming a degradation of about 60º.

Concerning the dynamic effect, the dynamic coefficient always takes the value of one, regardless of the duration or shape of the load application. Such fact is connected with the several modes of vibration contributing for the same response of the structure. It is important to mention that this conclusion should only be applied for this structure, or structures with a similar range of frequencies, since a different barrier and deck system may present different modes of vibration. It was also concluded that the consideration of damping coefficients makes no difference in the analysis.

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