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Numerical Analysis of an Intercity Bus Structure: A Simple Unifilar Model Proposal to Assess Frontal and Semifrontal Crash Scenarios

Abstract

To improve the safety of the intercity bus structure against impact scenarios and to reduce the injuries and death in traffic accidents it is crucial in a country with continental dimensions like Brazil, where the road transport matrix is fundamental in the traffic of people and goods. In this context in the present article, a numerical model of an intercity bus was built with elastoplastic beam implemented in a commercial software Ls-Dyna. This model was submitted to different frontal and semi frontal impact crash scenarios. With this model were analyzed different accidents which happened in the Brazilian highways, it was also simulated a frontal impact test and the results obtained were compared with the experimental results. Finally two numerical approaches were compared, they are: a simple model made with lumped masses and non-linear springs series connected, and the elastoplastic beam model. The different comparisons carried out let us validate the intercity bus model created using elastoplastic beam elements and propose to use this model as an effective tool to search for more efficient bus structural configurations against impact scenarios.

Keywords

Finite element method, intercity bus, frontal and semi frontal impact scenarios.

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1 INTRODUCTION

The intercity transport in Brazil, country with continental dimensions, is crucial for its social and economic development. The jump in the economic development that happened in Brazil in the last years has been translated in a sensible increase in the intercity buses that circulate in the Brazilian railways, but this increase in the traffic was not accompanied by the increment in the capacity and in the improvement of the highways. These facts have motivated a sensible increment in the number of accidents involving intercity buses, the majority of these accidents with a great number of victims. This problem could be minimized improving the quality of the highways and also turning the intercity bus structures safer against impact scenarios.

The structural capacity of the vehicle to absorb the kinetic energy that results from an impact and to maintain the integrity of the occupants is called the "crashworthiness" or IAC (Impact Absorber Capacity), wherein this quality must be maximized by means of the adequate spatial distribution of the flexibility in the structure analyzed. The intercity bus is formed of uniaxial elements and metallic tin panel, metallic foil and joints among the different structural components. These structural components linked absorb the larger part of energy during the impact event.

The vehicle capacity to absorb the impact energy IAC is governed by four basic principles (Sánchez, 2001):

- Controlling of the tolerance level applied over the vehicle occupants;
- Providing the ways to absorb the impact energy maintaining the level of safety in the survive occupant space;
- Maintaining the occupant in the survive space during the collision avoiding the occupant ejection;
- Protecting the occupant against the risk after the collision.

There are international norms that rule the IAC vehicles and airplanes. Brazilian norms in this topic were not found. The Brazilian industry that manufactures the bus truck has found difficulties to export its products due the necessity to adequate its structures to these international norms. In the process of the exportation, it is necessary that the structure is homologated by an official regulatory agency that justifies the adequacy of the product to the norms required at the destination country.

The crash analyzes of the vehicle structure design has high priority in the vehicles industry. This problem is dynamic and implies to consider the interaction of several types of effects that let us arrive to the global non-linear response at the collision. The plastic deformation of the vehicle structure when the impact happens is considered an excellent absorption mechanism of the vehicle kinetic energy. By means of an adequately design the vehicle structure could serve as an economical and efficient element to attenuate the impact effect over the vehicle occupants during the collision.

The search for information throughout the assessment of damage caused in the intercity bus structures involved in road accidents and the number of victims, allowed us to perceive what happens in a frontal or semi-frontal impact collision.

Among the several types of accidents involving buses, the most dangerous are the frontal collisions and rollovers. When the transit of the road demands the over passing maneuver due to the road only having two lanes, the probability of frontal and semi-frontal collision increases in a sensible way. This problem is typical in Brazilian roads.

The structural arrangement of a bus structure is basically composed of a truck that is joined to the chassis. Figure 1 shows the main parts that make up the structure of a bus. In the Figure 2 the damage happened in buses due to frontal impact in Brazil illustrating the gravity of the problem (Dias de Meira Junior, 2010).

The frontal region of the bus is the responsible for the impact energy absorbed during the collision as it is possible to conclude observing the photos presented in the Figure 2. In this way models that study the performance of buses against frontal impact could be carried out studying in detail only the vehicle frontal part.

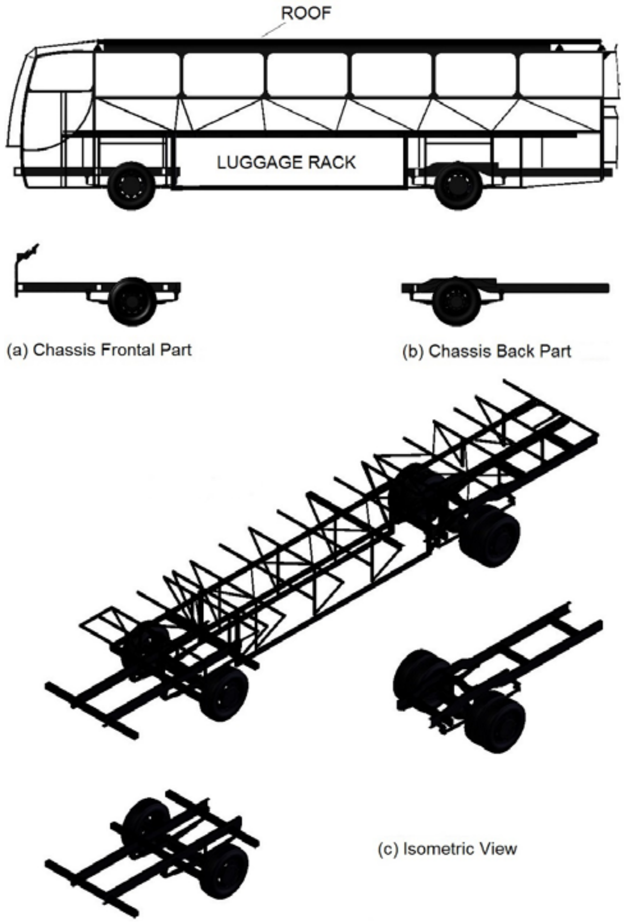


Figure 1: Intercity bus Chassis and Truck.

Figure 2: Bus accident (frontal Impact). (Dias de Meira junior, 2010)

According to the last transport statistical yearbook published by the Brazilian Agency of road transport (ANTT, 2007), it is possible to observe the significant number of road accidents after the year 2006 as indicated in the Table 1. Also notice a considerable increment in the number of victims, in the accident that involved buses. It is important to mention that this information was not updated after 2007.

Year	2004	2005	2006	2007
Number of dead victims	225	173	201	288
Number of injured victims	1109	1014	1032	1687
Total number of victims	1334	1187	1233	1975
Mortality rate	0.16	0.14	0.16	0.14
Total number of accidents	371	358	567	632
Accident index	0.25	0.24	0.43	0.47

Note: the mortality rate - dead victim's number/ total number of victims.
Accident index: total number of accidents/ distance [km] travelled by the bus fleet x (10^6).

Table 1: Accident evolution. (ANTT, 2007)

The structural assessment against the impact scenarios could be made by mean of physical test or with the aid of computational models. The most used numerical technique for these types of problems is the Finite Element Method (FEM). The frontal impact severity involving buses is discussed in Bjornstig et al. (2008). Notice that there are several analyses carried out using finite element models where the vehicle structure is represented in detail. This numerical tool is applied in massive way in the analysis of the crashworthiness in cars, due to the fact that the safety level is, in this case, linked with an attractive parameter used when the vehicle is acquired by the users. This relation is less direct in the bus case. As example of this kind of analysis of crashworthiness applied in buses, it is possible to reference Kwasniewski et al. (2009), in this paper the author models the bus rollover after the lateral impact with another vehicle using an elaborated finite element model. We also point out the work developed by Kang et al. (2012), where the bus structure performance in a rollover test is analyzed, to carry out this study the authors using the finite element method employed shell elements.

The proposal of the present work has as focus to implement a simplified model (beam elastoplastic element) to simulate the bus behavior against accident scenarios. The premise of the models to be simple was followed to be able to apply this same model jointed in an optimization algorithm and in this way develop improvement in the bus structures against impact situations.

The numerical model was implemented in the commercial Finite Element package Ls-Dyna (2010), this software integrates the motion equation that results from the spatial discretization made with the Finite Element technique, and used to explicit the scheme of integration in the time.

In the mentioned context, the capacity of a very simple numerical model of intercity bus to represent different crash scenarios is shown in this work.

2 PENDULUM TEST

In Brazil, aspects linked with traffic safety, and specifically the technique specifications that must be satisfied in case of buses are not adequately regulated. As example of this issue, it is possible to mention that in the Brazilian transit code it is presented briefly the strength conditions that the bus structures must present when solicited in frontal impact scenarios (Lazzari, 2001), and when, it is necessary to determine parameters for frontal and semi-frontal impact, this code recommends to make the pendulum impact test over the structure. In consequence, this test assesses the structure strength against this kind of solicitation. On the other hand the Brazilian National Transit Council by mean of the resolution n° 210 (CONTRAN, 2009) provides the weight and dimensions for the vehicles circulation. For these and other several reasons the National Enterprises that work in the truck bus manufacture do not find in the Brazilian standards an adequate technical support to make the bus structure when they must account for the safety against impact crash scenarios.

The resolution 316/09 of the Brazilian National Transit Council (CONTRAN, 2009) demands that after two pendulum tests are carried out, no bus part of the structure tested could present permanent longitudinal strain higher than 200 mm. The Figure 3 illustrates the execution of the pendulum test. An impact mass of 1010 kg with a pendulum spin radius of 4.75 m impact against the front of the bus structure. In the case presented in the figure permanent displacement in the bus frontal part was 123.2 mm.

The Figure 4 shows the most solicited points during the pendulum test, being that this test submits the bus over stress condition much lower than the situation that happens during an accident of frontal impact with allowed velocity by the traffic codes. The energy that is given over the bus structure in a pendulum test is 47.1 kN.m, and in an accident where a bus impact against the rigid obstacle at 13.89 m/s (50 km/h) given to the bus structure an energy of 1600 kN.m (nearly 34 times higher). This affirmation could be verified comparing the Figures 2 and 4, where we notice that the displacement produced in the bus structure that suffered frontal impact is higher than in the one where the pendulum test was applied.

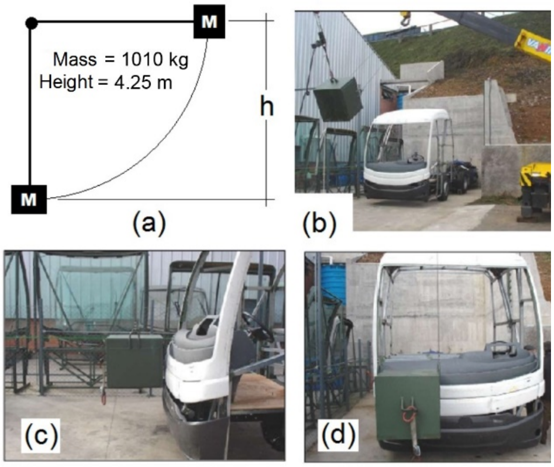


Figure 3: Pendulum Test.

Figure 4: Pendulum Test: points with more solicitation.

3 NUMERICAL MODEL DESCRIPTION

We present here the characteristics and boundary conditions used in the numerical model implemented in the Finite Element Package Ls-Dyna (2010).

The masses of the components that do not add stiffness in the structure will be considered as lumped masses positioned as indicated in Figure 5. With the aim to define this masses, were used the information furnished by the enterprise that makes the truck, was adopted a chassis Scania with a mass of 5330 kg, being 1030 kg in the front part and 4300 kg in the back. For the truck added to the chassis was adopted a total mass of 13020 kg, considering a bus with 44 seats, 12 m of total length, with air conditioner and bathroom, also are computed the additional masses due to doors and windows. These values of mass do not account for the passengers and luggage mass. Considering the bus with total load with an additional mass of 3080 kg, that corresponds to 44 passengers (70 kg per person as mean), plus 1000 kg to consider the luggage, for this reason when the bus has its capacity full it will be a mass of 17100 kg.

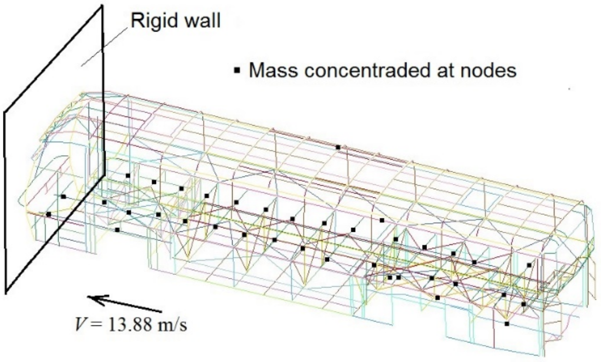


Figure 5: Numerical Model.

The longitudinal members used in the chassis were the C Profile (80 x 200 x 6 mm). For the tubes that compose the roof structure (Figure 1) was adopted a thickness of 2.6 mm and for the other tubes and in the capsule profiles, was adopted tubes with 2.0 mm of thickness. More details about the profiles used could be presented by Dias de Meira Junior (2010).

The model presented in Figure 5, is built by 5502 nodes and 2566 beam elements that use the Hughes – Liu theory (Ls-Dyna, 2010).

In the present work were used two kinds of materials, as shown at follow:

(1) For the models presented in section 4 and 5 the material used is steel NBR 7008 ZAR 230, that in this work was considered as elastoplastic with linear hardening, wherein can see in the table 2 the parameters details.

(2) For the model presented in the section 6 the material used was a steel NBR 7008 ZAR 380. In this case was considered an elastoplastic material also with linear hardening. Moreover, in this case the details about the parameters used could be presented in the table 2.

Properties	Material (1)	Material (2)
Type	NBR 7008 ZAR 230	NBR 7008 ZAR 380
σo (MPa)	230	380
σu (MPa)	310	460
E (GPa)	210	
Et (MPa)	730	444
D	40.4	
Q	5	
ν	0.3	
γ (kg/m³)	7850	

Table 2: The material properties considered for the FEM model.

For the materials described in (1) and (2), commonly used in the bus manufacture industry, the constitutive relation in the plastic range is sensitive to the deformation rate as cited by Schaefer (1998).

The Cowper and Symonds law, presented in Jones (2001), suggests the following expression to account for the dependence between the plastic parameters of the constitutive equation and the strain rate.

$$\frac{\sigma 0'}{\sigma 0} = 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{1/q} \tag{1}$$

Where σ'_0 is the dynamic yielding stress for a determined value of $\dot{\varepsilon}$, σ_0 is the static yielding stress, D and q are material constant. For the steel here modeled was adopted D=40.4 s^{-1} and q=5 parameters that produce a good concordance with experimental data (Jones, 2001).

The bus input parameters presented here will be used in the following section, two types of materials are used following the specifications indicated in Table 2. Specific conditions of each study, such as impact velocity, are described in the description of each application.

Additional information about the bus model calibration and about the convergence analysis was presented in Dias de Meira Junior (2010).

4 PRELIMINARY STUDY: A BUS STRUCTURE SUBMITTED TO FRONTAL IMPACT AGAINST A RIGID OBSTACLE

In the present section a model of a typical intercity bus structure composed by beam elements submitted to impact conditions is shown, focusing on understanding its structural behaviour.

The bus structure was impacted with a velocity of 13.89 m/s (50 km/h) against a rigid wall, as was indicated in Figure 5. The material parameter used was presented in Table 2 and called Material 1.

The mean element length was 200 mm, and the process time in a PC I7 with 8 GB of RAM was in this simulation 15 minutes.

In the Figure 6 are presented two configurations obtained during the simulation, at t=0.12 s and t=0.3 s.

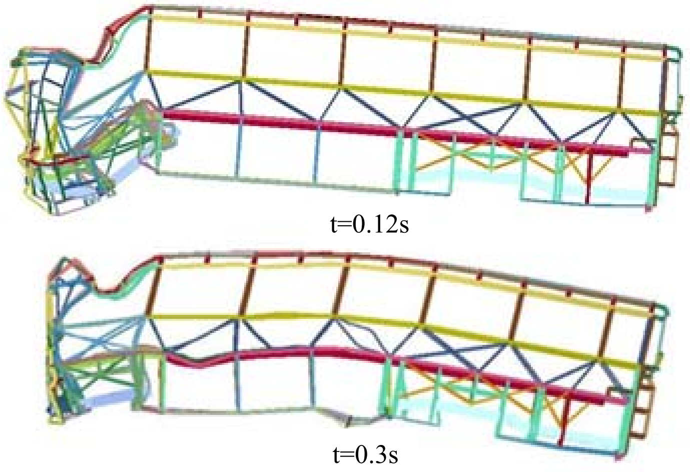


Figure 6: Bus frontal impact against a rigid wall at V=13.89 m/s (50 km/h). Configuration at 0.12 s, and 0.3 s (see also the Fig.8)

In the Figure 7 it is possible appreciate two pictures that show the final configuration of buses after frontal impact. In both cases the impact velocity was in the range (10-15 m/s). Notice the similarity in the level of damage between the numerical configuration of these pictures and the Fig. 6.

Figura 7: Final configuration of real accidents where frontal impact happened at velocity in the range of (10-15 m/s).

As it is evidenced in the Figures 8 to 10 in this time the bus numerical model has practically stopped. Notice, that in this configuration the frontal part of the structure suffers an accentuated deformation, and the driver safety will be totally compromised. In the Figure 8 it is presented the frontal displacement *d* during a simulated process.

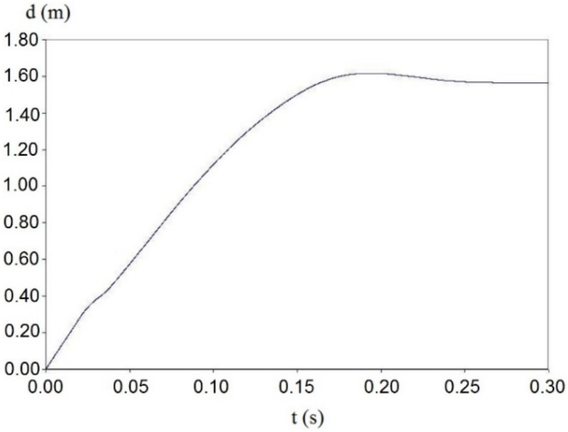


Figure 8: The frontal displacement in the bus structure (d[m]) during the simulation of the frontal impact crash.

At 0.3 s the frontal part of the bus suffers a total displacement of approximately 1.6 m. The Figure 9 presents a deceleration that happens in the vehicle during the simulation, also notice that the peak value of the deceleration is around 7 g. The Equation 2 lets us compute the mean acceleration during the impact as computed by Huang et al. (2005).

$$a_m = \frac{v^2}{2g\Delta L} \tag{2}$$

where v is the translation bus velocity, g the gravity acceleration, and ΔL the total displacement that the bus suffers. For the problem in study, the velocity is 13.89 m/s and using a displacement of 1,6 m it is possible to arrive to a mean deceleration of a_m=6.15 g, this value is coherent with the plot presented in Figure 9. Up to Huang et al. (2005), a pulse is considered low when it is around 18 g and is considered high for values around 87 g.

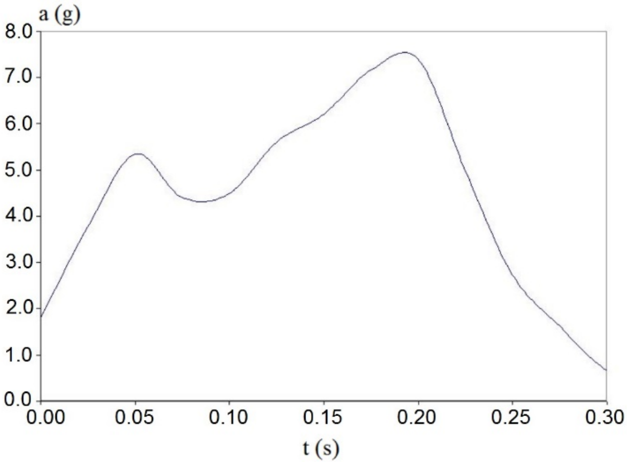


Figure 9: Deceleration evolution in the bus frontal part (a[g]) during the process simulated.

Finally, in the Figure10 it is presented a energy balance vs time. Notice that it is necessary a time of 0.3 s to absorb all the kinetic energy that the bus has during the impact event.

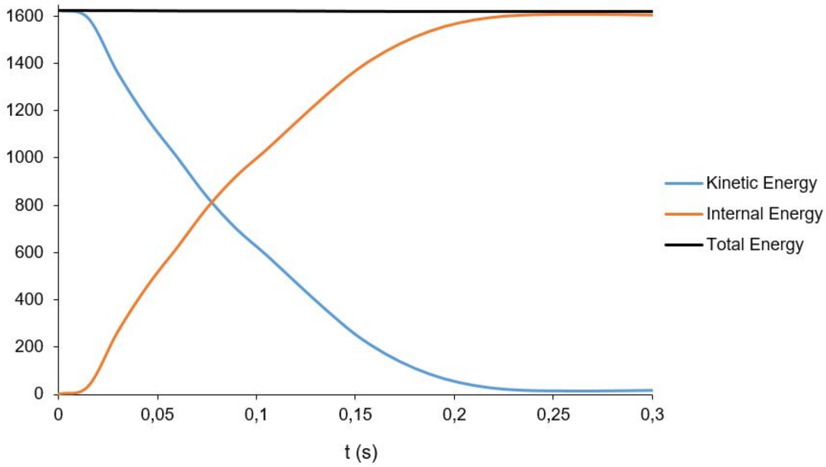


Figure 10: Energy balance during the process simulated in [KNm].

5 SIMULATION OF ACCIDENTS THAT HAPPENED IN BRAZILIAN ROADS

In this section are presented simulations of accidents that happened in Brazilian roads. As it was not possible to count on all the necessary data of the accident conditions, the main problem was to obtain the quantitative parameter that allows the characterization of the accident conditions. For this reason some parameters were estimated and this fact prejudices the comparison with numerical results.

Following the simulation of two real accidents are presented, one where frontal impact happened, and in the other case semi-frontal impact.

5.1 Frontal Accident Simulation

Next, the accident that happened on 22/10/2006 at Raposo Tavares road SP-270 (Dias de Meira Junior, 2010), is analyzed. This event was presented in schematic form in the Figure 11.

In this case it was also used the material parameters presented in Table 2 as Material 1 (elastoplastic material with linear hardening).

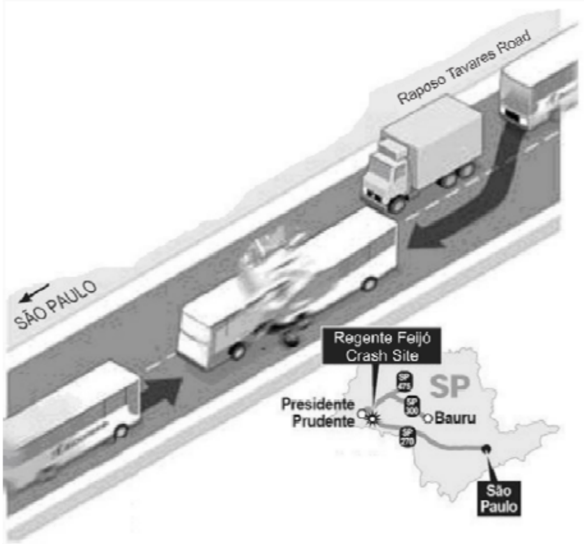


Figure 11: Raposo Tavares Accident layout.

According to Newspaper São Paulo State in 01/22/2006 (Dias de Meira Junior, 2010), one of the buses coming from Presidente Prudente city with 13 passengers and the other bus coming from Bauru city with 38 passengers, collided frontally. Thirty-two people died and twenty-one were injured with different levels of gravity.

Next it is shown the frontal impact simulation using the model presented in the section 2. The aim of this simulation is to show the model capability to represent an event of this type. To adjust this model, fundamental information as structural characteristic of the buses involucrate in the accident, and technical information that allows to determine with more precision the accident condition, for example the shape of the marks in the asphalt and the final position after the accident, were not available. Despite this lack of information a parametric study was carried out, modifying the collide velocities. It was also considered that the bus structure used in all the simulation defined in section 3 is representative of the buses involved in the accident.

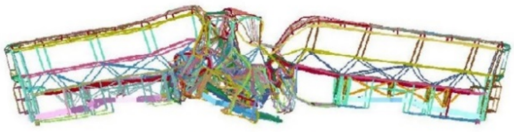
Initially the simulation with two vehicles colliding in the same velocity was made. The Figure 12 presents the results obtained for equal velocities in the interval to 13.89 m/s to 33.3 m/s (50 km/h, 120 km/h) for each bus. Account for that the velocity of both vehicles must be added due to the buses advance in opposite direction of movement, in the present parametric study the impact velocity changes from 27.78 m/s to 66.67 m/s (100 km/h, 240 km/h).

V = 13.89 m/s

V = 16.67 m/s

V = 19.44 m/s

V = 22.22 m/s



V = 27.78 m/s

V = 33.33 m/s

Figure 12: Impact simulation at different velocities.

The Figure 13 presents how the impact velocity changes in function of the bus frontal displacement.

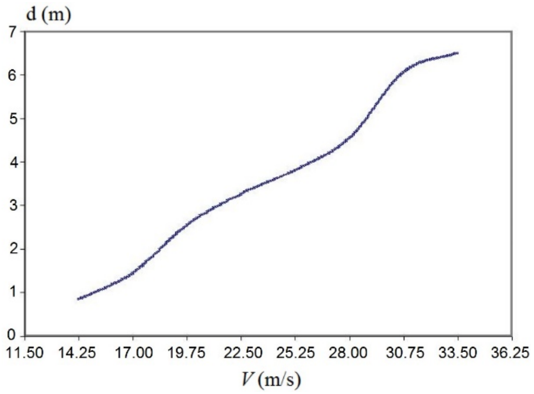


Figure 13: Impact velocity vs displacement measure in the frontal part of the vehicle obtained with the numerical model.

In Figure 14 the final configuration of other situation of frontal impact is studied (one bus is moved at 25 m/s (90 km/h) and the other at 36.11 m/s (130 km/h). The impact was so hard that one of the buses entered until the middle of the other vehicle, around 6.95m of total displacement, as it is possible to see in the Figure 14. All the occupants that were in the first part of the vehicle died.

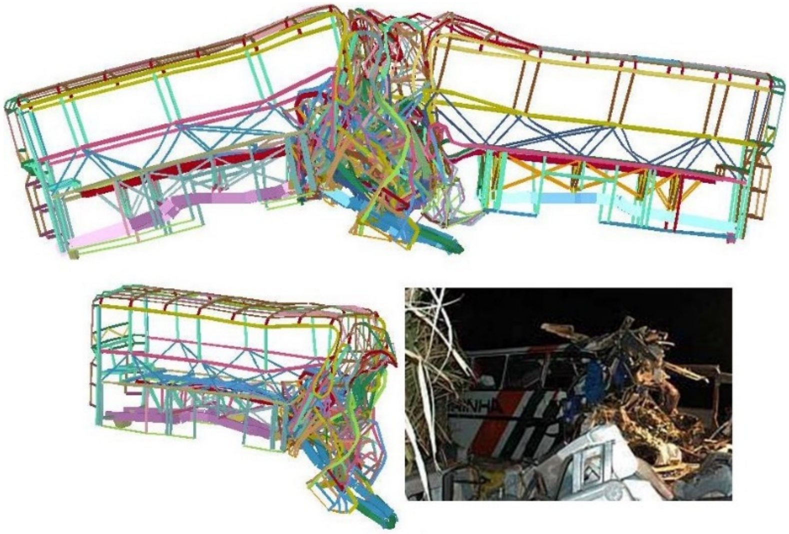


Figure 14: Qualitative assessment in the accident: Raposo Tavares Road in 2006.

Assessing the Figures 12 and 14, it is possible conclude that the beam model has been shown coherent with the accident that happened at Raposo Tavares Road in 2006, despite of not being able to carry out a complete model calibration.

5.2 Semifrontal Impact Simulation

In the present subsection the numerical analysis of an accident of semi-frontal impact is simulated. In this case the “open tin effect”, where the bus structure has removed part of its lateral due to the impact with other vehicle, is studied. This kind of accident is very common in the Brazilian roads because the great majority of them are simple way roads. It is very common this kind of accidents involving trucks and buses. In Goedel et al. (2015) this kind of accident was studied with similar kind of numerical model here used.

In this case was used an elastoplastic model with linear hardening called Material 1 in the Table 2. The Figure 15 presents the real bus final configuration after the accident that happened in July 2008 in the BR 386, this figure shows clearly the “open tin effect”.

The expertise report number 14625/2008 of the Brazilian general expertise institute presents the main information that allows to characterize the accident (Dias de Meira Junior, 2010). The Figure 16 illustrates the condition in which the impact between the bus and the truck happened.

Figure 15: Accident at BR 386 in July 2008. (Dias de Meira Junior, 2010)

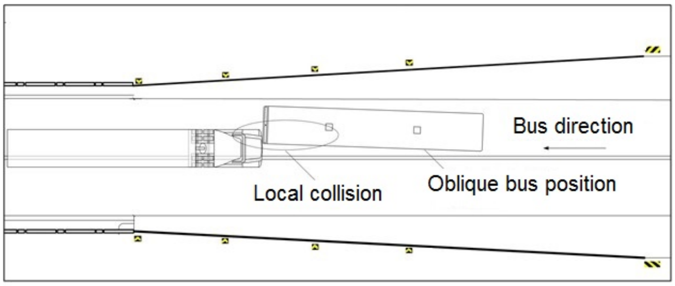


Figure 16: The accident lay out. (Dias de Meira Junior, 2010)

In the Figure 17 the final configuration obtained with numerical model where were represented two buses, one with double the stiffness, to represent the truck involved in the accident. In the Figure 17 the model of bus that represented the truck is on the left and the initial boundary condition of this vehicle was 33.3 m/s (120 km/h), the velocity of the other bus was considered 25 m/s (90 km/h) with a inclination of 1°.

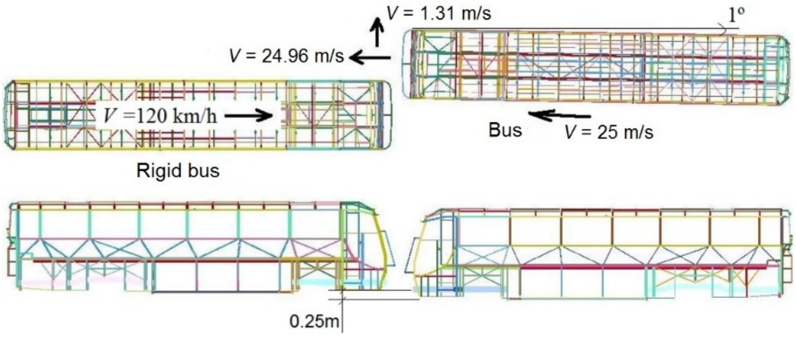


Figure 17: Initial boundary conditions considered in the numerical simulation. Rigid bus represent the truck.

In the Figure 18 an image sequence in different times of the collision event is shown. In the Figure 19 is visualized the damaged simulation, that could be compared with the real final configuration.

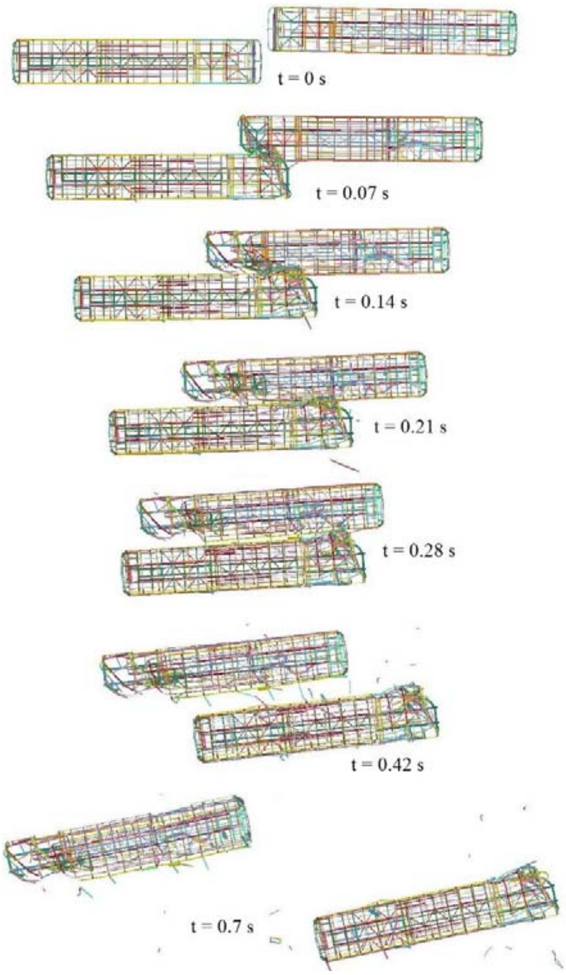


Figure 18: Sequence of images during the simulation of impact.

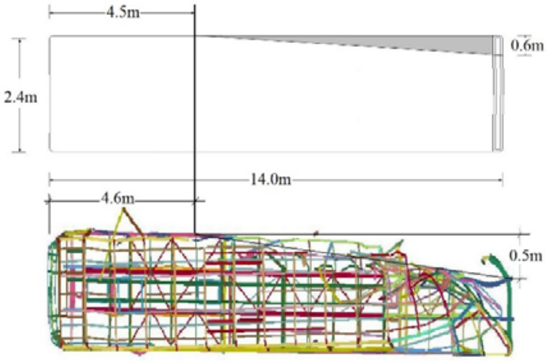


Figure 19: Opening tin effect, comparison between the real and numerical model.

In the Figure 19 it is illustrated the final configuration of the numerical model and the real bus, the region that was open in the numerical simulation was indicated to facilitate the comparison between the numerical and real configurations.

In the comparison between the real and numerical results, the capacity of the beam model to simulate an accident where happened semi-frontal impact is shown.

In Goedel et al (2015) a parametric study about the main variables involved in the semifrontal crash scenarios are made, comparing real accident information and numerical simulations.

6 NUMERICAL ANALYSIS OF BUS CRASH TEST

In the present section are simulated a bus crash test carried out by the TRC (2010) using the numerical beam model. It is also used a model made with masses and stiffeners connected in serial way. This model was proposed by Riera (1980). The material used to model the structure was steel NBR 7008 ZAR-230, called Material 2 in the Table2.

6.1 The Numerical Simulation of the Bus Crash Test

The crash test was carried out by the TRC (2010) and the film of the this test is a public domain on the web. The Figure 20(a) illustrates the test impact done and the Figure 20(b) shows the final configuration obtained in the simulation.

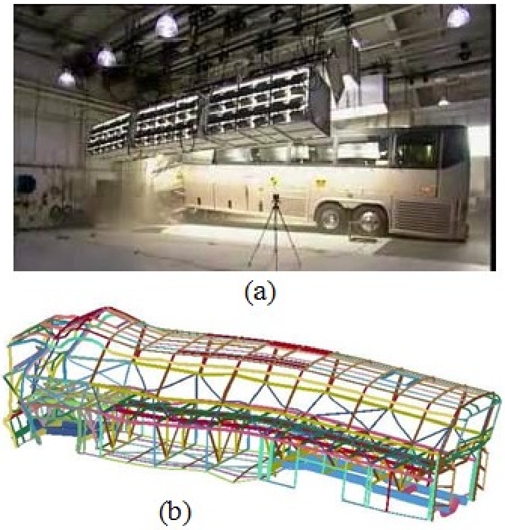
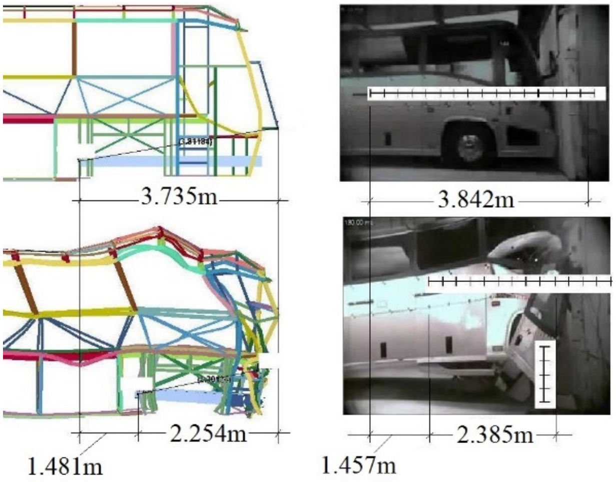


Figure 20: Impact test. (a) Crash Test TRC (b) final configuration obtained by the numerical model.

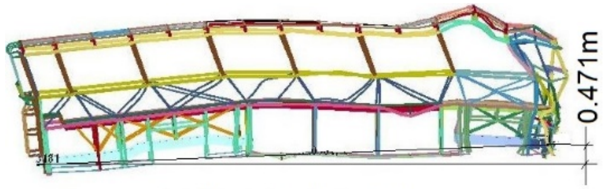
In the Figure 21 the comparison between the real and numerical deformed configurations at 180 ms of simulation are shown. It is possible to observe that the correlation between both results is very good. The displacement in the vehicle front was 1.481 m and the displacement measure in the same point in the real configuration was 1.457 m, the percent difference between the real and numerical results in terms of this parameter was 2 %.



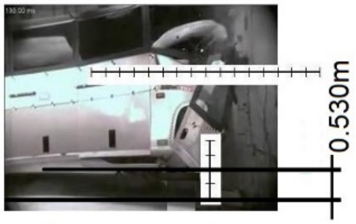
(a) Bar numerical model (b) TRC test configuration

Figure 21: Real and Numerical comparisons in terms of deformed configuration at time 180 ms.

In the Figure 22 the comparison of the vertical bus displacement at 180 ms in the real test and in the numerical simulation is presented. Notice that in the crash test of the TRC the vertical displacement was approximately 0.530 m and in the numerical model this displacement was 0.471 m. In this query the difference in percentage found was 11 %.



(a) Numerical model



(b) Crash test

Figure 22: Vertical displacement – Comparison.

In the Figure 23 for several time intervals different images during the TRC test are shown. And in Figure 24 the comparison between numerical and experimental solution in terms of frontal displacement vs time is presented. Notice in Figure 24 a good agreement between both curves despite of the several uncertainty due to a lack of information of the crash test carried out.

Figure 23: Crash Test made by TRC. (Dias de Meira Junior, 2010)

In the case of beam model, the impact velocity is 13.89 m/s. In the case of the TRC model can be approximated speed assuming that between 5 ms and 35 ms, the displacement was 0.397 m a time of 30 ms, which produces a speed of 13.25 m/s.

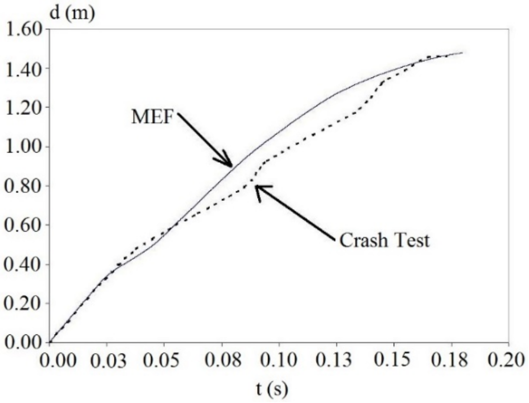


Figure 24: Displacement vs Time – Comparison Crash Test Numerical Model.

Furthermore, in the present case the comparison between the experimental and numerical results shows that the beam model used allows to represent with high level of reliability events of this nature.

6.2 Crash Test Quantitative Assessment Using a Model Proposed by Riera (1980)

Riera (1980) presents a simplified methodology that lets to determine the reaction force *Fx(t)* due to the unidimensional missile that impacts against a rigid blank. In this method the structure was discretized in lumped masses and non-linear springs series connected. The parameters that define the characteristic of this elements were obtained by mean of the energetic method. The force variation *Fx(t)* during all the impact process is obtained using the Equation 3.

$$F_x(t) = P_C[x(t)] + \mu_x(t)V^2(t) \tag{3}$$

where $\mu_x(t)$ represents the mass of the missile per length unit; $x(t)$ represents the distance measure since the frontal part of the missile; V(t) represents the missile velocity that reach the rigid blank and finally $P_C[x(t)]$ that represents the structural collapse force that the part of the missile that is colliding produces over the rigid blank. In the Figure 25 is represent a scheme typical of Riera model.

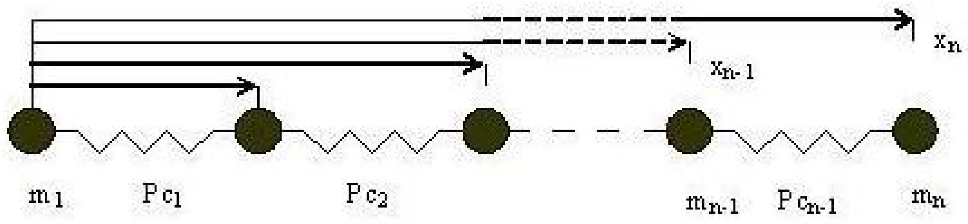


Figure 25: Scheme typical of Riera Method. (Riera, 1980)

The strength of collapse P_C is the force required to compress until the collapse of the structure studied, which can be determined experimentally or numerically. This collapse force can be determined for structures as the cave of an intercity bus body, the fuselage of an airplane or a simple profile. This collapse force is a result of the interaction among collapse forms, as the plastic and different kinds of buckling (local, distortional or global).

The Riera model (Riera 1980) was originally used to consider the computation of the impulse evolution produced by an aircraft impacting over a reinforced concrete nuclear reservoir wall, in this context the influence on the total force function F(t) of the yielding force PC(t) produced for target crushing is marginal (less than 20 % of the total impact force). But when using the same approach in the simulation of bus crash where the missile velocity range is low, the influence of the collapse force in the determination of the total impact force is very important, for this reason we propose a more elaborated way to consider Pc(t) in the case of the bus crash scenarios. The approach proposed combines analytical expressions used combining the Design of cold-formed steel structures NBR 14762. (2010), and the Direct Strength Method (Schafer and Peköz (1998) and Hancock et al. (1994)). These expressions consider the interaction between different kinds of buckling with the plastic yielding.

The equations proposed to determine P_C in this case are presented in Equations 4 to 9.

$$P_P = \sigma_1 A \tag{4}$$

$$\lambda_0 = \sqrt{P_P / P_{FG}} \tag{5}$$

$$P_{PFG} = \rho P_P \tag{6}$$

$$P_{CL} \left(\frac{P_{FL}}{P_{PFG}} \right)^{0.4} \left[1 - 0.15 \left(\frac{P_{FL}}{P_{PFG}} \right)^{0.4} \right] P_{PFG} \tag{7}$$

$$P_{CD} = \left(\frac{P_{FD}}{P_P} \right)^{0.6} \left[1 - 0.25 \left(\frac{P_{FD}}{P_P} \right)^{0.6} \right] P_P \tag{8}$$

$$P_C = Min\left(P_{PFG}, P_{CL}, P_{CD} \right) \tag{9}$$

where P_P is the force of the plastic collapse; σ_1 is the material yielding stress; A is the profile transversal area; λ_0 is the reduced slenderness index computed for uniaxial elements submitted to compression; P_{FG} is the global elastic buckling load; P_{PFG} is the force that results from the interaction between elastic buckling load and the plastic collapse load; ρ is the reduction factor associated with the global buckling (NBR 14762, 2010); P_{FL} and P_{FD} represent the buckling forces due to elastic buckling local and distortional respectively; P_{CL} and P_{CD} are the collapse forces, the first due to the interaction between the global and local buckling modes and the second because of the collapse force the takes into account the distortional buckling and plastification, and finally P_C is the collapse force of the analyzed element, this load will be the minimum among the three loads computed (P_{PFG}, P_{CL} and P_{CD}). If we use the strength direct method using some numerical method it is necessary compute the elastic buckling loads P_{FL} and P_{FD}. More details about the methodology to compute the Pc value see Meira Junior (2010).

A quantitative assessment of the bus structure applying the Methodology proposed by Riera (1980) is presented. In this way it is possible the determination of the reaction force due to the bus impact when it collides against a rigid obstacle. This methodology was originally applied to determine the force that a subballistic soft missile produces when it impacts against a rigid wall by Tech and Iturrioz (2005), using the same approach that was applied in the study of bus structures.

The Figure 26 presents the masses distribution used, the structure discretization employed, and the crushing forces computed using the expressions (4-9) used in each part of the bus structure. In this case to represent a bus structure with the Riera Method, was used a set of 26 lumped masses.

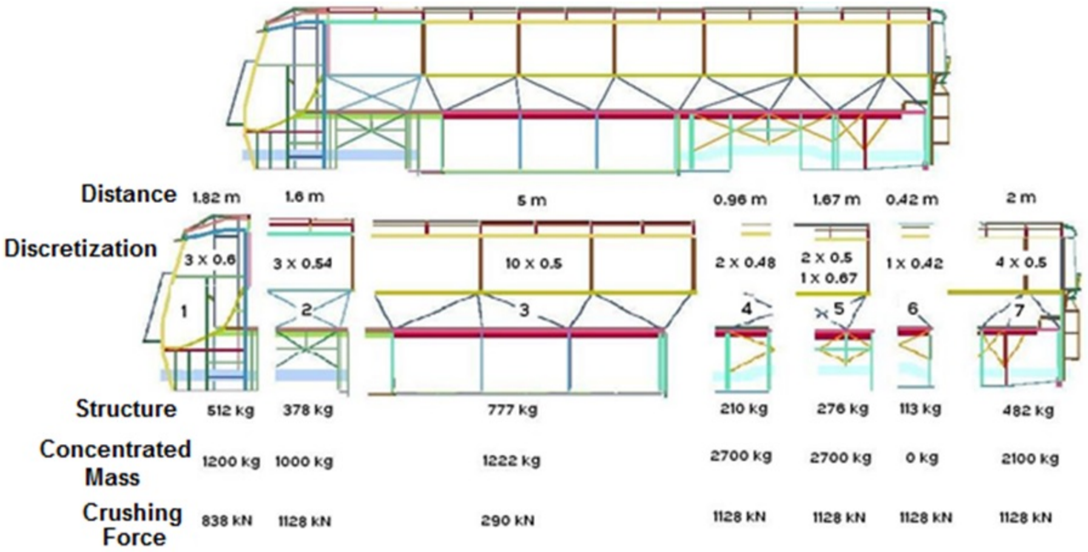


Figure 26: Mechanical properties distribution in the Bus.

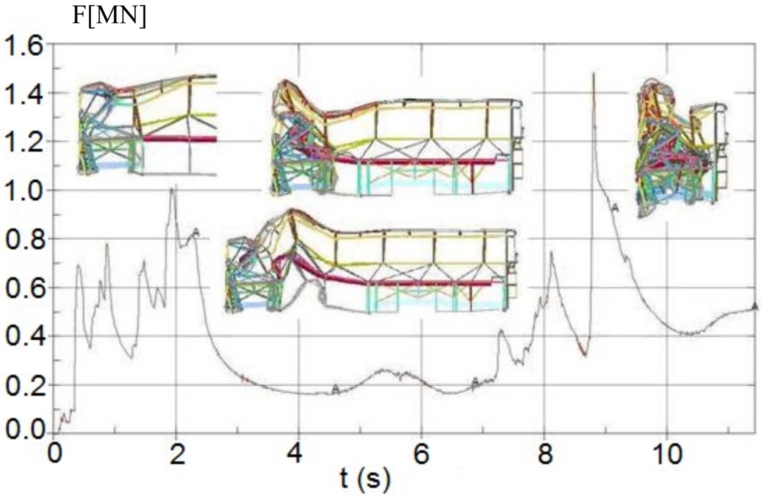


Figure 27: Collapse force and the correspondent numerical spatial configuration, when we applied over the model a static prescribed frontal displacement.

Notice in Figure 28 that the failure in the bus structure front region happened due to the buckling in the C profile of the bus truck. After the collapse of this profile, it happened the abrupt collapse of the remainder structural elements. It is also possible to observe that the bus central region failure happened in the longitudinal member of the biggest transversal section (box profile of 60 x 100 x 2 mm) and its collapse happened also by buckling. When the failure of this element happened, the bus structure presented a characteristic configuration, see Figure 28 (b).

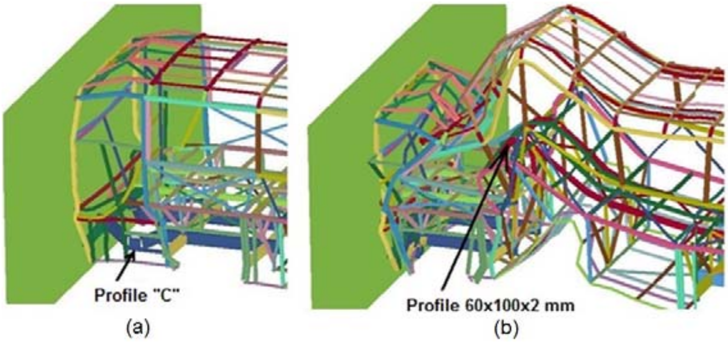


Figure 28: Failure Modes.

The structure behavior in the frontal region is governed by two C profile of (80 x 200 x 6 mm) and in the bus central region the structural behavior is controlled by the rectangular profile (60 x 100 x 2 mm). Considering that in the bus frontal region labeled by (1), in the Figure 26, the crushing strength is mainly due to "C" 80 x 200 x 6 mm, the total crushing force was Fc=838 kN. In the following part of the bus indicated in the Figure 26 by the label (2), the crushing strength is Fc=1.128 kN, considering the presence of two profile "C" 80 x 200 x 6 mm and two rectangular tubes of 60 x 100 x 2 mm. In the region indicated by the label (3) in the Figure 26 the crushing force is Fc=290 kN, considering the collaboration of two rectangular profile 60 x 100 x 2 mm. Notice that the longitudinal members of the chassis were removed in this bus region. In the back part of the bus indicated with labels (4, 5, 6 e 7) was computed a Fc=1.128 kN justified for the strength of (two profiles "C" 80 x 200 x 6 mm and two rectangular profile 60 x 100 x 2 mm).

In the Figure 27 the variation of the bus reaction force obtained when the beam model is compressed at low velocity against a rigid wall is presented. In this case the total force does not present the influence in the reaction force of the inertial effects. Notice that if you compare the crushing forces presented in the different bus region (see Fig.26) with the static reaction obtained with the beam model presented in Fig. 27 the results are coherent.

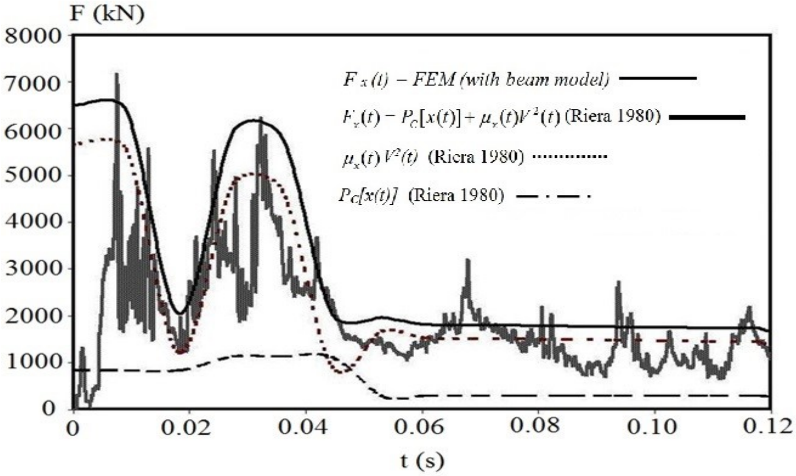


Figure 29: Bus structure that impacted against a rigid wall: Comparison between a beam model used in the other simulations and the Riera Approach. The impact velocity was 66.67 m/s.

The reaction force obtained in the case in which the bus impact against a rigid obstacle with a velocity 66.67 m/s (240 km/h) with the two methodologies is presented in Figure 29. The methodologies used were: a beam model used in the other simulations, and the simple model proposed by Riera (1980). Also in this case it is possible to verify the coherence between the results obtained with the two approaches.

7 CONCLUSIONS

In the present work was presented a numerical model built by beam elements that represents an intercity bus structure, and its performance in different ways was assessed.

At follow we point out the main insight obtained in the development of the present work:

- Linked with the qualitative simulation presented in the section 4, was possible to present coherent results in terms, not only of final configuration but also of the global parameters as the displacement in the frontal part of the vehicle, the deceleration measure in the same bus region, and in terms of the energy balance. This global measures could be used as parameters to be minimized in an optimization algorithm, some advances in this direction were presented in Dias de Meira Junior, 2010.
- In connection with the two accident scenarios that happened in the Brazilian roads presented in section 5, notice that despite the simplicity of the numerical model used (elastoplastic beam elements implemented in a commercial package Ls-Dyna), and the lack of details about the accident conditions, information that is necessary to carry out a good calibration of the numerical model, and the ignorance of the specific structural characteristic of the vehicles, involucrated in the accident, the obtained results with the models analyzed show coherence when compared with the real cases.

For this reason, it is possible to conclude that the numerical method proposed is capable of representing the bus in different scenarios of accident with the aim to search for improvement in its performance.

- The authors know that more sophisticated models could be built using finite element method using shell models, considering geometry and material non linearities, (in section 1 we present some reference of this approach), but, the utilization of the methodology proposed in the present work (model built by elastoplastic beam) could be very useful if the simulation was linked in a optimization process, in this case many simulations of similar conditions must be necessary and to reduce the computational cost could be crucial to turn the process viable.
- In connection with the bus crash test made for the TRC (2010), presented in the subsection 6.1, this test was also simulated by the beam model with the more complete information extracted of a crash test video available in a public internet site. Also in this case the numerical results will be shown coherent with the experimental one, in terms of the final configuration and global parameters evolution.
- In the subsection 6.2 to simulate the same Crash test was used a very simple model proposed by Riera (1980) to determine the force of impact produced by a missile against a rigid target. Notice that the methodology employed to compute the missile collapse force was proposed by the authors to compute the yield force produced by the bus structure. In this methodology a

combination of analytical expressions extracted of cold steel profile and a numerical method (The Direct Strength Method) are done. The performance comparison of the bus model here proposed (the non linear beam model) and the simple model proposed by Riera (1980) let us understand better how the bus structure works in an impact scenario, and perceive with other point of view, where and how to propose improvement in the bus structure to minimize the damage in crash situations.

In relation to the mechanism of collapse that could be simulated with the beam model, the beam element used captured a material and geometric non linearity. For this reason it was possible to simulate the collapse taking into account the interaction between the plastic and global buckling effects, the results have shown that the global behavior of the collapse was captured with this simple model.

- In relation to more general questions it is possible to point out that using the beam model here proposed it was possible to conclude that the bus structures are deficient in its capacity to absorb the impact preserving the occupants integrity. Although for impact velocities of 13.89 m/s (50 km/h) the bus driver remains totally exposed. This situation, up the authors, is due to the inefficient legislation, that proposes the assessment of the frontal impact strength of the bus structure. Prove of this affirmation is that it is inadmissible to use the pendulum test, described in brief manner in the Section 2 of the present work, as index to assess the safety of the bus structure against frontal and semifrontal impact situations. The energy developed in this test is approximately 34 times lower that the energy involved in a bus frontal impact when the bus velocity is 13,89 m/s (50 km/h).

As the last commentary, we emphasize the convenience to use the beam model because it furnished a response with a low computational effort. Another advantage that we would like to point out is that this kind of models facilitate the synthesis of the problem analysis. Therefore, we have less parameters to take into account and the complexities in the behavior could be introduced with a short expression that combines experimental and analytical knowledge. A more sophisticated method to analyze the local behavior of the structure where beam element jointed with non linear connection adjusted with specific curves are proposed by Dias de Meira Junior, 2010. As examples of other works that also follow this work philosophy could be mentioned Amorin et al 2014.

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