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A LIBRARY FOR CONCEPTUAL DESIGN OF VEHICLE BODY CRASHWORTHINESS USING EQUIVALENT MECHANISMS

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ABSTRACT

An equivalent mechanism (EM) is a computationally inexpensive concept model capable of simulating crash modes with a straightforward link to FE models. A library approach is presented to enable the use of EM in the vehicle conceptual design process for crashworthiness, based on a prototype implementation into LMS Imagine.Lab AMESim, an integrated platform for multi-domain system simulation from the concept phase onwards. The library allows easy assembly of structures and setup of test cases, performing fast simulations with geometric visualization of crash modes. The elements developed for the library are divided in beam, joint and boundary condition components. Beam and joint components are characterized through FE simulations of collapsing thin-walled structures. Boundary condition components allow clamping beams and simulate contact condition with rigid walls. Once characterized, the components are re-usable in different assemblies. The simulation of a C-shaped structure impacting against a rigid wall is presented as application case for validation of the model through comparison with the correspondent detailed FE simulation. The conceptual model replicates accurately the deformation mode of the full FE model, and the simulation runs 480 times faster. The deceleration hihistory and final displacement of the wall are estimated by running both the detailed and the concept simulation and compared to each other. A maximum difference of 15% for the displacement and of 0.4% for the deceleration peak, which are acceptable values for the conceptual phase of automotive body design.

INTRODUCTION

Although all the efforts put on incrementing road safety, both for passengers and for pedestrians, the number of car accidents or crashes is continuously increasing as the number of registered vehicles increases. Fortunately, beside the increasing number of accidents, the number of deaths and serious injuries is being kept almost constant, thanks to the continuous efforts on incrementing vehicle safety during a crash. The vehicle structure is crucial for guaranteeing passengers safety. It must absorb the kinetic energy of the vehicle in a controlled manner (keeping crash deceleration pulse below the threshold of human resistance), and limit the deformation of the cabin for ensuring a minimal survival space for passengers.

The term *crashworthiness* refers to a measure of the capacity of the vehicle structure and each of its components for protecting the passengers lives in case of crash. The analysis of the crashworthiness of a vehicle is a highly complex task and requires the development of specific tools for understanding and improving the crash behaviour of the structure. In the last decades, the number of tools available for helping engineers make the correct design choices toward crashworthiness have been increasing, thanks mainly to the development of non-linear finite element (FE) techniques and to the evolution of computers. Running computerized simulations of vehicle crashes using FE is a very useful tool, allowing repeatability of the crash test and decreasing costs by reducing the number of test prototypes. Unfortunately, these simulations are still too expensive in terms of time, both for the time required for modelling the structure and for the high computation times when running the simulation (increased by the fine granularity of the meshes and the different sources of non-linearity of the elements). For this reason, FE simulation is not the most appropriate tool for the first stages of the design, when a lot of design variants are to be tested and validated.

The availability of tools for generating design variants in less time is crucial in the first phases of the development. Given the high number of simulations to run, it is also clear the need for models that can be simulated in short time, even if some accuracy is lost. The main goal in this phase is not to reproduce reality in a precise way, but rather to establish a domain of admissible solutions that could be explored later with more accurate simulations techniques.

From the many choices of concept models developed for this purpose, *equivalent mechanisms* (EM) models present the advantage of being physically-based and thus they enable a direct application of the simulation results, giving enough detail for visualization of the deformation history of independent elements of the vehicle structure (such as beams or joints). The core idea of the method is that the main components of the vehicle structure, which are typically simulated with shell finite elements, can be approximated with a correct parameterization of rigid bodies and non-linear springs. To obtain the parameterization of the non-linear springs, some FE simulations must be run first to predict the behaviour of the component. The simulations may include cases of axial crashing, bending and torsion. A database of equivalent mechanisms approximating different components can be built, by obtaining the characteristic curves for each type of component.

The aim of this paper is to present the implementation of the equivalent mechanism concept modelling technique within LMS Imagine.Lab AMESim environment for conceptual design of vehicle body crashworthiness. The library contains a set of already characterized components, such as beams or joints, that can be easily reused on many different assemblies. Modelling and testing a new design variant with the implemented library requires only placing the components with the mouse (thanks to the intuitive GUI of AMESim) and running the simulation of the concept model, which is achieved in a few minutes or hours depending on the complexity of the model, compared with the many hours or even days required for the correspondent FE simulation.

The rest of the paper is organized as follows. Section 2 presents related work on vehicle body modelling for crashworthiness analysis. The new Concept Car Body Crash library implemented within AMESim is described in Section 3. Section 4 illustrates a case of study analysed to verify the accuracy of the implemented model. Conclusions are given in Section 5.

RELATED WORK

There exist different approaches for crashworthiness analysis, some of them oriented to the first stages of the design (concept models) and other for a more advanced phase when all the geometric details must be defined (detailed models).

Regarding detailed models, *topology optimization* [2] is a technique which can be used to optimize the topology of beam components. In this way, a mass reduction can be achieved while keeping the same energy absorption in the case of impact with a mass with a specific direction and velocity. In [3] the authors presented the *mode match adjustment method* for a front impact, consisting in modifying the design variables of the structure for obtaining the desired deformation history. An expert engineer can estimate the proper deformation history and introduce the necessary modifications to structure to achieve it. In this way, an acceptable solution can be obtained running only a few FE simulations. *Surrogate models* are general-purpose meta-models used in a lot of engineering applications [4]. A meta-model is actually a model of models. In applications implying models with an elevated computational cost, a meta-model can represent a convenient approximation of the model. The problem of these models is the high level of abstraction and the lack of physical sense. Once the model is built, its performance (such as the deformation energy) varies depending on the input variables (such as the dimensions of the structure), but it gives no insight on which element of the structure is more or less deformed.

Regarding concept models, some authors propose to use *simplified FE models* [5]. These models are characterized by the simplification of the formulation of the elements and by a simplification of the mesh, allowing a reduction of computational cost. The problem of these models is that, if a very coarse mesh is used, the results can be too inaccurate, while using a too big time step may cause the loss of information about the transient phase of the solution and thus the deformation history could be completely different. The simplified formulation of the elements may also be the cause of the deformations without associated energy (hourglassing). Finding a compromise between simulation time and accuracy is then needed and very often the simulation time must be very big to keep a reasonable level of accuracy.
Kamal [6] introduced *lumped-parameter models* for simulating the response of a vehicle under frontal impact. This model approximates the vehicle with a 1D mass-spring system. Due to the high simplification of the representation, this model requires engineers with a lot of experience in the field of structures, for parameterizing the springs and masses and for translating the output into design data. Indeed, with Kamal model it was very difficult not only to setup the mass-spring system but also to understand how to modify the structure once the results from the simulation are obtained; the output data was very far from geometric parameters of the structure.

To overcome all these problems, new simplification methods were developed with the aim to obtain the behaviour of the vehicle starting from the behaviour of the components of the structure (i.e. shells and beams). The approximation of these elements is the core of the most recent techniques for physically-based concept modelling of vehicle structures for crashworthiness. New lumped-parameters models were developed focusing not only on the global response of the structure, but rather on the behaviour of each component. The global response can then be obtained by correctly assembling the components that form the structure. Karim et al. [7] proposed the *equivalent mechanism method*. An equivalent mechanism consists of a network of rigid bodies connected through prismatic and revolute joints (characterized by springs with non-linear stiffness) that approximate the behaviour of a beam component. These springs are set up for replicating the force-displacement relationship characteristic of the beam. To obtain the parameterization of the non-linear springs, some FE simulations must be run first. The *non-linear beam model* [8] is based on a first order analysis using beam elements with non-linear characteristics. The procedure for characterizing the non-linearity of the beam consists in running detailed FE simulations for obtaining force-displacement and torque-rotation relationships. Compared to the spring element, the beam element has 6 DOFs and thus allows to describe the behaviour of the component under different load conditions.

IMPLEMENTATION OF A LIBRARY FOR EQUIVALENT MECHANISM

In this work, a library has been developed in the environment LMS Imagine.Lab AMESim, as a tool for modelling and simulation of vehicle structures for crashworthiness using the equivalent mechanism (EM) concept model. The EM model consists in the substitution of parts of the structure with masses and prismatic and revolute joints with non-linear behaviour. The new library is composed by ten components for assembling any type of structure and simulating its crash behaviour. Those components are super-components formed by elements already implemented in the libraries Planar Mechanical and Signal Control of AMESim. They can be divided in three groups: Beams, Joints and Boundary Conditions.
Beam components are used to approximate the behaviour of a real beam structure. Joints are components allowing to link two or more Beam components, so that the whole structure is built in a modular fashion. The Boundary Conditions allow to clamp a Beam component or to define the contact (impact) with a rigid wall.

Beam Component

The Beam component allows to simulate the behaviour of a beam structure after an impact. Figure 1 shows a simplified model of the Beam component in AMESim sketch mode.

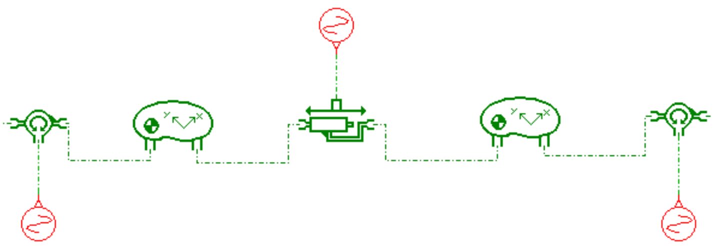

Figure 1: Schematic representation of a Beam component. A prismatic joint is in the middle coupling the two masses. At the other extremity of each mass a pivot joint is connected. The blocks in red contain the reaction curves of the joints.

The two bodies with two ports have null dimensions and their mass is half the mass of the beam. The prismatic joint coupling the two masses is responsible for applying the reaction force to the axial displacement of the masses. The other ports of the bodies are linked with pivot (revolute) joints. These joints simulate the formation of plastic folds and exert a reaction torque in consequence to relative rotation of interconnected Beam components.
The reactions that the joints apply to the movement of the masses depend on the rotations and on the axial displacements. They are calculated by interpolation of the force/displacement or torque/rotation curves included in the model as a table and obtained from detailed FE simulations involving the beam structure under axial and flexional loads separately.
The reaction curves are composed of three sections, as depicted in Figure 2: a constant stiffness section (for the linear behaviour of the component), a table-based section for the non-linear behaviour after the collapse for negative displacements or rotations and a table-based section for the non-linear behaviour after the collapse for positive displacements or rotations.

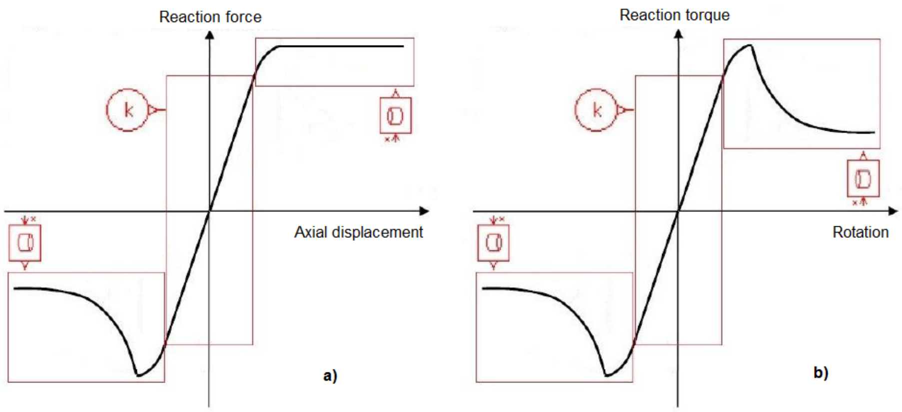

Figure 2: Constitutive sections of the reaction curves characterizing the joints of the Beam component. a) Reaction force / Axial displacement curve and b) Reaction torque / Rotation curve.

As already mentioned, the curves of force/torque reaction as a function of axial/rotation displacement is the guide for the prismatic/pivot joint of the Beam component, and they are obtained from detailed FE simulations of collapsing beam structures. As an example, the results of a FE simulation for the characterization of a pivot joint of the Beam component are shown in Figure 3.

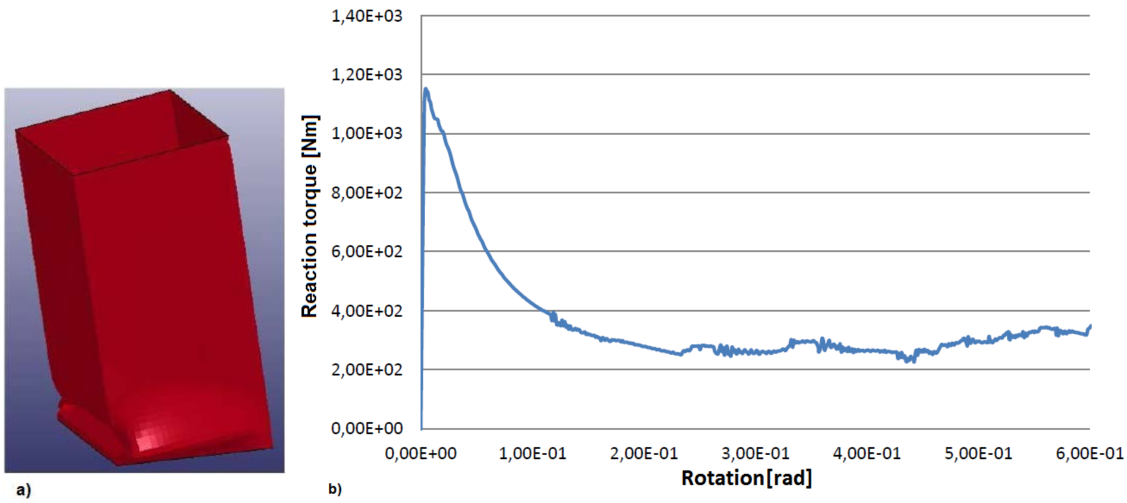

Figure 3: a) Deformation of the beam due to bending momentum and b) curve of reaction torque with respect to rotation.

The obtained curve corresponds to the expected behaviour; it shows a first linear section until a resistance peak after which the collapse of the beam starts.

Joint Component

Joint components allow to interconnect Beam components and to consider the contact of the structure with a rigid wall. They are used to model the critical parts of the structure with a behaviour that cannot be properly described using only Beam components, such as the intersection points of various beams with different angles. Various types of Joint components have been implemented. Figure 4 shows the schematic representation of one of the Joint components, which is a T-joint allowing coupling of three Beam components.

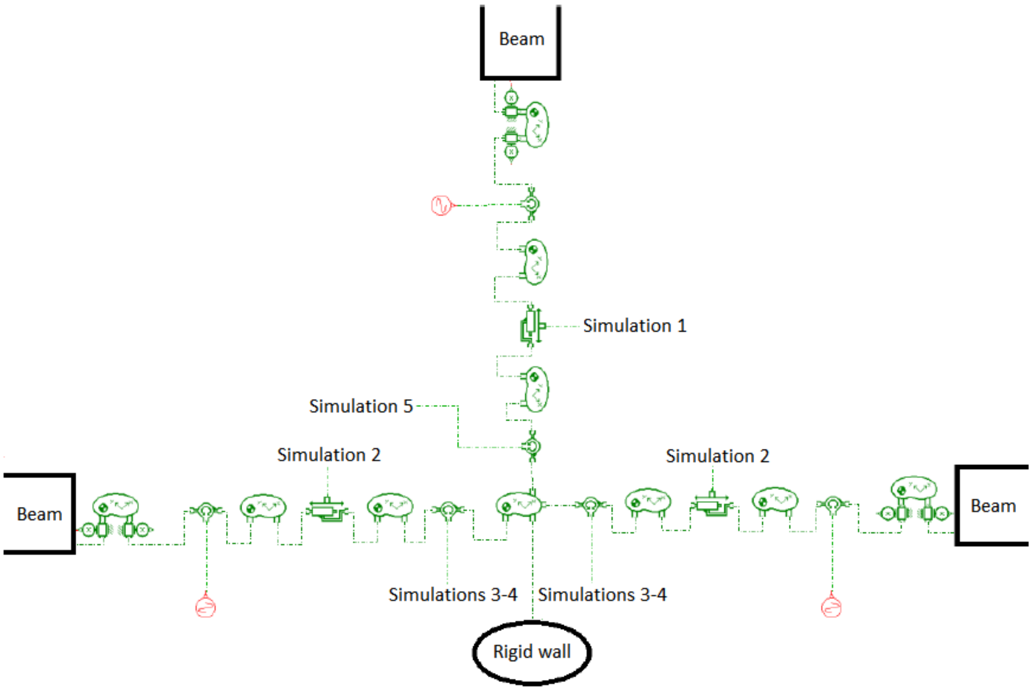

Figure 4: Schematic representation of a T-Joint component. The characteristic curves are assigned from different simulation cases at different points of the model.

This Joint component is composed of three Beam components coupled to a body with four ports: three of them allow to connect the Beam components while the fourth is available for a potential contact with a rigid wall. This component is composed of prismatic and pivot joints to be characterized. To obtain this characterization, FE simulations are conducted on the joint structure depicted in Figure 5.

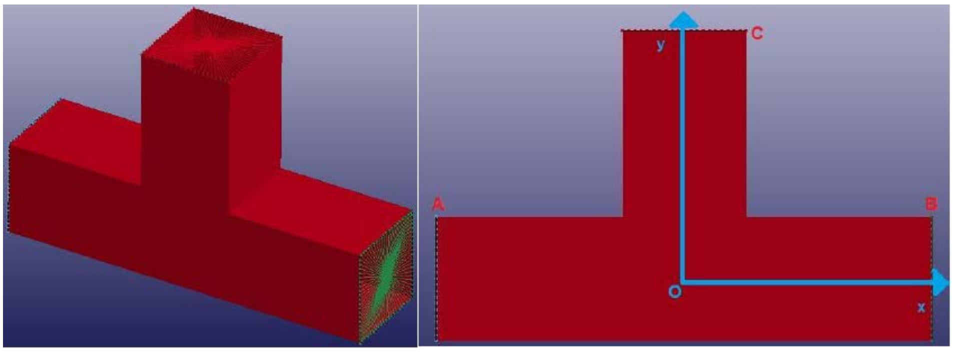

Figure 5: FE model of the three beam joint.

Five simulations are run for this example, two with axial load and three with bending load:

- **Simulation 1**: axial load on the vertical arm (-Y direction).
- **Simulation 2**: axial load on the horizontal arm (-X direction).
- **Simulation 3**: bending load on the horizontal arm in upward direction (Y).
- **Simulation 4**: bending load on the horizontal arm in downward direction (-Y); the configuration is the same of the previous case, but since the structure is not symmetric with respect to X axis, the torque must be evaluated in both directions.
- **Simulation 5**: bending load on the vertical arm.

As an example, Figure 6 shows the joint deformation and the reaction torque curve obtained from Simulation 4.

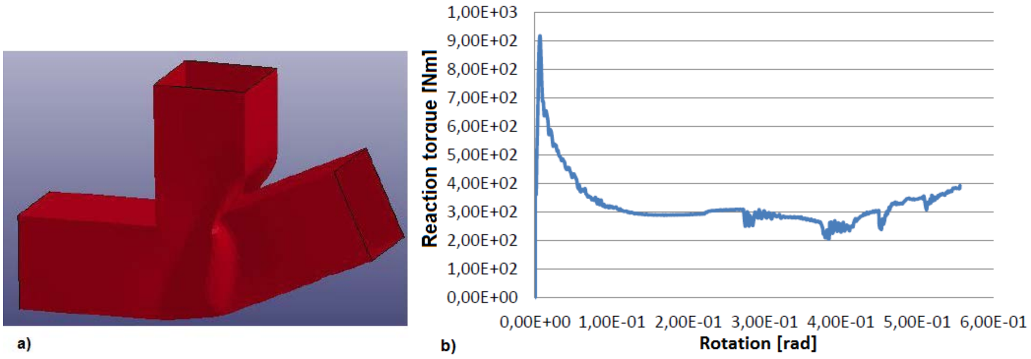

Figure 6: Simulation case of a rigid wall of 750 Kg impacting at one end of the T-joint with initial speed of 1 m/s. The other two ends are clamped to observe the generation of a plastic fold close to the point of intersection of the three beams. a) Final deformation. b) Corresponding reaction torque/rotation curve.

The obtained curves are clearly different from the curves obtained with the simulation of independent beams. The main differences are in the curves of reaction force as a function of axial displacement. Those characteristic curves are applied to the prismatic and pivot joints composing the Joint component, as illustrated in Figure 4. In the same figure, the blocks in red contain the reaction curve obtained from the FE simulation of the independent beam structure, as explained in the previous section.
The same procedure is followed for the characterization of all the other Joint components. This characterization is needed to obtain accurate enough results, since the behaviour of these critical parts of the structure has a big influence on the global response of the structure itself. In these parts the large plastic deformations are located and the resistance to collapse is lower than that of a single beam because of geometric discontinuities.

Boundary Condition Components

Boundary Condition components allow to constrain the degrees of freedom of a Beam component (Clamp component) or to model the contact with a rigid wall (Rigid Wall component). A schematic representation of those two possibilities offered by the Boundary component is given in Figure 7.
For the Clamp component a simple element from the Planar Mechanical library of AMESim is used, providing zero displacement and velocity to the connected beam.
The parameters used for modelling contact are: the elastic modulus of both bodies, the damping of the contact and the different types of friction. This component requires the definition in the plane of the contour of both objects in contact, which is done through text files, reporting pairs of coordinates (x,y) and curvature radius of the contour vertices.
To allow the connection of the same wall to the different types of Joint components, it is needed to add different types of contact elements and the component must have the proper number of ports. A rigid body with a dynamic number of ports has been used, allowing to establish the number of ports at the moment of placing the component in the design of the structure.

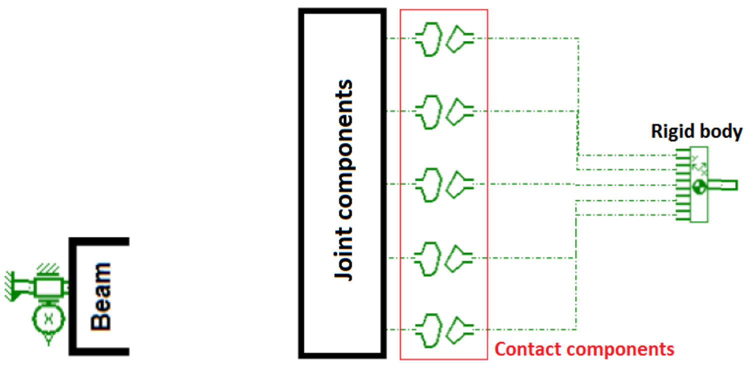

Figure 7: Schematic representation of Boundary Condition components. Left: Clamp component. Right: Rigid Wall component.

APPLICATION CASE

To assess the accuracy of the implemented model, an application case has been analysed. It consists of a simple "C" structure composed by thin-walled beams with square section impacted by by a rigid wall. The deceleration history of the rigid wall after the collision and its displacement in the direction of the impact are considered. The obtained results are compared to the correspondent detailed FE simulations. The rigid wall has a total mass of 500 kg and an initial speed of 1 m/s, moving in the direction of the blue arrow in Figure 8.

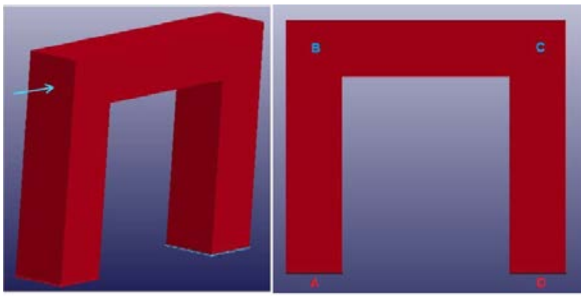

Figure 8: FE model of the C-shape structure.

The section of the beams is square, with 50mm of width and 1mm of thickness. All the beams have a length of 200 mm. *A* and *D* ends are clamped. The material is elastic and perfectly plastic with an elastic modulus of 207 GPa, a yield point of 240 MPa, a Poisson coefficient of 0.3 and a density of 7800 kg/m^3. The modelling of the structure with the implemented library was very fast, requiring only to place a few components in the sketch. Figure 9 shows the structure in AMESim Sketch and Visualization modes.

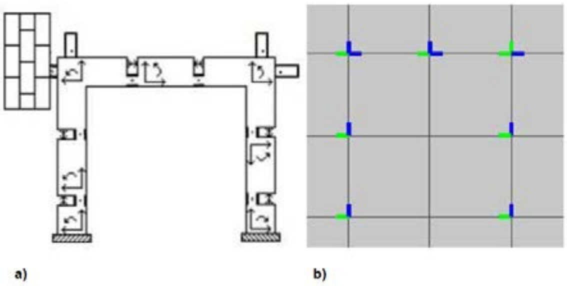

Figure 9: Simple C-shaped structure in AMESim a) Sketch and b) Visualization modes.

In the simulation, the deceleration and the displacement of the rigid wall in the direction of impact are measured and compared with the corresponding results in the detailed FE simulation, as shown in Figure 10.

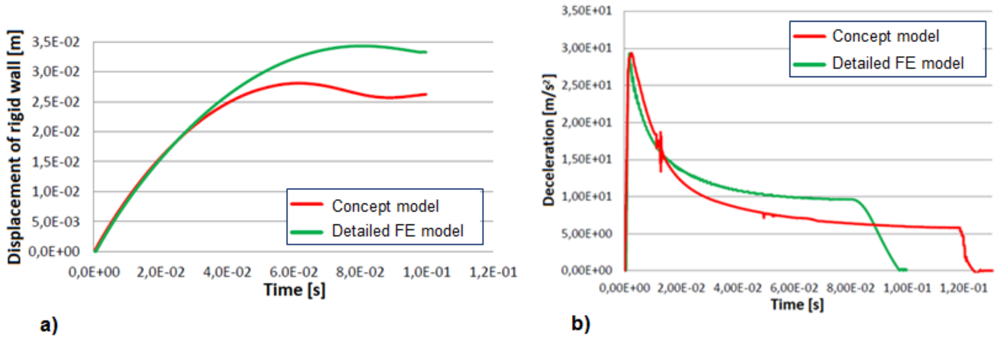

Figure 10: Comparison between the detailed FE model and the approximated model. a) Curve of displacement of the rigid wall with respect to time. b) Curve of deceleration of the rigid wall with respect to time.

The curves of displacement start being almost coincident, and then the maximum difference is close to 15%. The maximum difference in the deceleration curve is about 0.4%, and it is located after the collapse of the structure. These values of differences are acceptable in the first phases of the design, considering the big save in computation time with respect to the detailed simulation: 8 hours for the detailed FE model and 60 seconds for the concept model, with a reduction factor of 480.
Figure 11 shows the deformation of the structure obtained with the detailed FE simulation (left) and with the simplified model (Right).

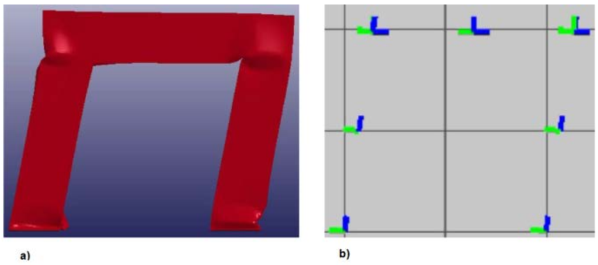

Figure 11: Visual comparison of the deformation on the a) detailed FE simulation and the b) approximated model.

The deformation mode in both models is the same, forming 4 plastic folds, two in the clamped ends and two in points B and C.

CONCLUSION

The presented work consists in the implementation of the equivalent mechanism model within LMS Imagine.Lab AMESim environment, for conceptual design of vehicle body crashworthiness. A new library of 10 components was created, allowing to assemble geometrically complex structures subject to boundary conditions. The modelling phase is extremely simple using the library, requiring only to place and connect the different components in the Sketch layout. The impact of *a* C-Shaped structure against a rigid wall was presented as application case of the library. The results obtained with the application case are accurate enough for conceptual design and with very reduced computation time with respect to the correspondent detailed FE simulation. A possible future work would be to improve further the simplicity of the model for reducing even more the computation time, or working in a more accurate definition of the plastic behaviour of the elements for incrementing the accuracy in the prediction of the deformation of the structure. The library currently allows only the definition of structures with co-planar elements, so an obvious improvement would be to extend it to 3D structures. The presented methodology is generic. The included Beam and Joint components are characterized from steel-made square section beams, but the methodology is applicable to structure with different types of section and other materials. This extension merely requires running a detailed FE simulation and, once characterized, the new components could be re-used in different assemblies.

ACKNOWLEDGMENTS

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