Crashworthiness design of a train based on European Standard EN15227

Description of the numerical/experimental methodology applied to the new Metro Light Automatic (MLA) platform project

Modern trains must not only fulfil traditional static load and fatigue requirements, but also passive safety necessities. These crashworthiness requirements must all be considered in the design of the structural part of the coach.

Sophisticated crashworthiness analyses today are a regular step in the engineering process of developing a new train. A vehicle crash is a dynamic phenomenon featuring a complex interaction between structural and inertial behavior. It is generally recognized that in a typical collision, the end structure first experiences the impact and then undergoes large deformation in the impact region. The passengers only later experience the effect of the impact. The first phenomenon is normally referred to as the primary collision and the second, related to the passengers, is normally referred to as the secondary collision.

Due to the geometrical complexities of rail vehicle structures and to the complicated material behavior involved in large deformation, finite element computer programs with elastoplastic dynamic analysis capabilities have to be used (LS-Dyna). This article describes the methodology that was adopted in the analysis and design of the structural crashworthiness of rail vehicles: the project led to the development of new products with new technologies using innovative approaches and materials.

Fig. 1 - Front cab layout

The main goal of the project was to make the vehicle compliant with the current European Standard (EN15227) for Crashworthiness by means of a redesign of the structural strength. This was made even more complex by the presence of the aesthetic and mechanical interface restraints linked to the "Platform" concept. In particular for this project, the sacrificial elements designed for placement in the impact region are innovative because they have been made from a special composite material that combines the qualities of lightness, efficiency and low cost.

The aim of this article is to describe the crashworthiness design process for the new Metro Light Automatic (MLA) platform project that was carried out by Hitachi Rail Italy, according to the EN15227 standard. This process was carried out following the steps described by the standard.

The new MLA platform belongs to category C-II as defined by the EN15227 standard, which requires that the crash behavior of the train be verified during the following scenario: a symmetrical collision at a relative speed of 25 km/h between two identical trains with 40 mm of vertical offset.

The elements of the new MLA platform that are specifically involved in absorbing this energy are the front absorbers placed in front of the cab structure (Figure 1). These critical elements are made of a special composite material developed to respect the fire and smoke regulations too.

Hitachi Rail Italy's validation process

The whole crashworthiness design process of the vehicle has been summarized in Figure 2. The process consists of numerical calculation phases and special

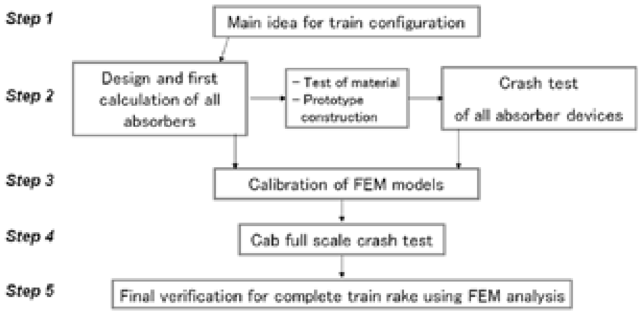

Fig. 2 - Crashworthiness design process

tests dedicated to each step that are useful to validate the Finite Element Method (FEM) models developed.

Step 1

In this phase of the project, all the possible configurations of the absorber elements were investigated. At the end of this stage, the final configuration (in terms of load, stroke and energy dissipated) of the absorber elements is defined. During this step, each part of the vehicle is represented by means of spring elements and lumped masses. This representation (a 1D FEM model) is used to allow an effective and immediate evaluation of both the behavior of the train during a crash and of the soundness of the solutions. The LS-DYNA software made it possible to obtain good results using the *ELEMENT_DISCRETE associated with material card S-06 (*MAT_SPRING_GENERAL_NON_LINEAR).

Step 2

After freezing the main characteristics of the absorber devices in terms of load, stroke and energy dissipated, Step 2 and Step 3 respectively aimed to virtually design and experimentally validate the absorber.

Many design unknowns, such as the composite material's mechanical behavior, ply-up and overall dimensions are directly involved in the design phase and hence the virtual simulation becomes an asset to speed up the design process.

Specifically, the main goal of Step 2 was to numerically build up an energy absorber model that was able to reproduce the experimental results in terms of the impact force versus the crushing distance, as defined in Step 1. Hence, the mechanical behavior of the composite material and the cohesiveness between the layers had to be characterized. To do so, an experimental testing campaign was conducted to obtain the necessary data to generate the material cards in LS-DYNA. The *MAT_58 (*MAT_LAMINATED_COMPOSITE_FABRIC) card was used for the composite material, while *MAT_138 (*MAT_COHESIVE_MIXED_MODE) was used for the cohesive behavior.

A summary of the experimental tests used for numerically calibrating the material behavior are described hereunder:

- Composite material (*MAT_58) - The mechanical properties of the composite material were investigated at different fiber orientations by means of both tensile and compression tests (0,45,90°).
- Cohesive material (*MAT_138) - The mechanical properties of the bonding between plies was characterized by means of two tests: a Double Cantilever Beam (DCB) and an End Notched Flexure (ENF).

Composite material

Tensile and compression coupons were modeled according to the experimental tested samples.

Cohesive material

Once the base material was characterized in terms of its elastic and failure properties, the next step was to characterize the bonding between the composite plies. Most of LS-DYNA material models implement the fracture mechanics "Cohesive Zone Modeling" (CZM) approach, therefore, the user has to identify several parameters concerning fracture mode I (opening) and mode II (shear).

For these simulations, the simplest and most commonly-used material model in cohesive zone modeling, the *MAT_138 (linear elastic with linear softening), was used. On the other hand, the bonding between the plies was explicitly modeled using solid cohesive elements (ELFORM= 20).

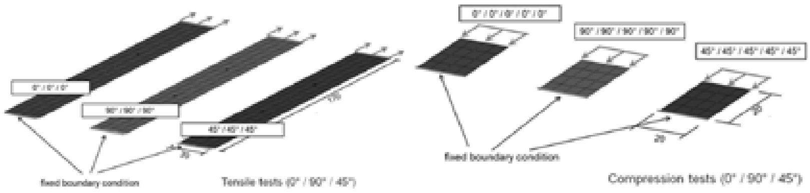

Fig. 3 - Simulated tensile and compression tests coupons with LS-DYNA.

The Mode I parameters were calibrated using a DCB test. The composite layout consists of a stack of several layers that are longitudinally oriented at 0° with an initial aperture (crack). The aim of the DCB test is to apply mode I tension at the layer's interface. Force versus displacement is recorded. As a further step, a regularization method was applied to reduce the spurious mesh dependence in the model. The Mode II parameters were calibrated using an ENF test. As for the previous case, the composite layout consisted of a stack of several layers longitudinally oriented at 0° with an initial crack opening.

Once the mechanical properties of the composite and bonding layers were defined, the numerical calculations of the FEM energy absorber could be executed. Here, the main challenge was to define an initial

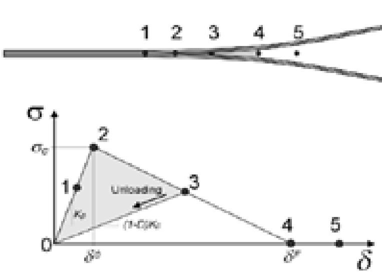

Fig. 4 - Example: Mode I (opening) showing the linear elastic with linear softening of the cohesive material.

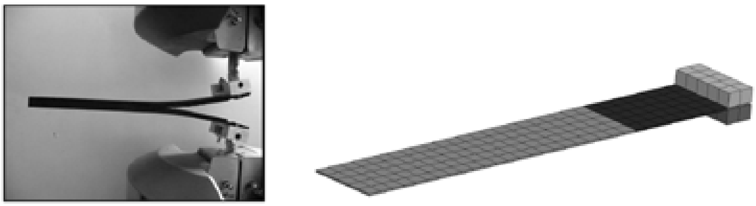

Fig. 5 – DCB Mode I (opening) experimental test and overview of numerical modeling.

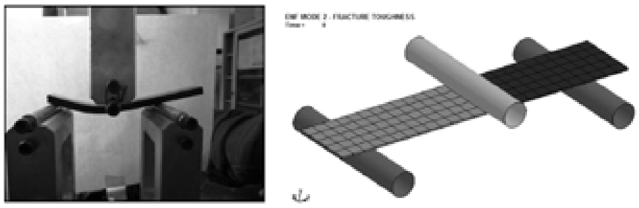

Fig. 6 - ENF Mode II (opening) experimental testing and respective FE model.

ply-up design and the overall dimensions of the absorber while keeping in mind the project requirements in terms of force profile and energy absorption (Step 1).

The pre-processing operations (the creation of the FEM model, materials, contacts, boundary conditions etc.) were carried out with LS-Prepost_4.3. The solver used was LS-DYNA MPP 9.1.0 64-bit for Linux, the post processor LS-Prepost_4.3.

Step 3

The FEM model of the absorber built-up in the Step 2 was experimentally tested and numerically validated in this design step. As a matter of fact, it took several virtual design iterations to come up with a design option that was ready for the prototyping. Some of the numerical parameters that were studied included the ply-up and the fiber orientation. The test consisted of 1 vs 1 absorber impact. The simulations were performed in accordance with the experimental set up. The absorbers were positioned to create a vertical offset between the longitudinal axis of both components, as required by EN15227. The reliability of the calibrated material data and of the FE model from Step 2 was confirmed by the experimental results.

Step 4

In "Step 4", a full-scale crash test of the cab was conducted. The main purpose of this test on the first car was to validate the numerical model used in Step 3 in a real scenario and hence to correctly reproduce the energy absorbing collapse. The cab full-scale crash test is required to reflect the energy absorption requirements of the crash scenario requested by EN15227.

As in Steps 2 and 3, numerical simulations were used to predict the behavior of the event before the test. The calibrated FEM models of the absorber devices (from Step 3) were used in the numerical simulations of this phase of the project.

Step 5

In Step 5, the whole-train FEM model was developed to simulate the crash scenario as required by EN15227. The requested scenario concerns a collision between two trains, the first one traveling at a speed of 25 km/h and the second one being stationary with no brake system engaged. In such a critical situation, the design of the passive safety system must ensure that the impact energy is properly dissipated without compromising the structural integrity of the cars.

The FEM model of the scenario was comprised of the following components:

- the validated FEM model of the front absorbers and the front cab structure (from Step 3 and Step 4);
- coaches "A" and "C", modelled with 1D, 2D and 3D elements;
- the FEM model of the first three bogies;
- the remaining vehicles of the train unit were represented by means of a lumped mass/spring system representing their overall behavior (as requested by EN15227)

Conclusions

The main challenge of the current study was to design an innovative sacrificial element for energy absorption purposes in the railway industry. This component was made of a special composite material which combines the qualities of lightness, efficiency and low cost. The selected absorber configuration is the result of an extensive virtual study and experimental testing program that was aimed at fulfilling the homologation requirements prescribed by the EN 15227 standard. Simulation was used to speed up the design phase and to better understand the product performance. These key factors helped to reduce the number of prototypes required for testing.

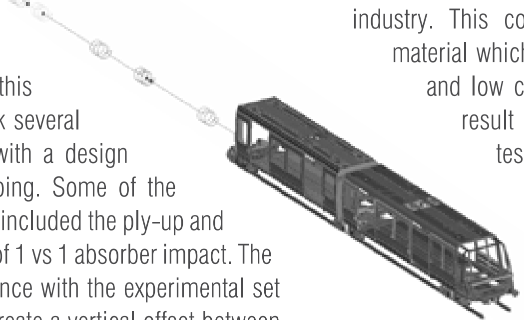

Fig. 10 - Whole train FEM modeland respective FE model.

Moreover, the virtual design process for the crashworthiness of a train as described in the previous pages was developed and has been consolidated into Hitachi Rail Italy. The process, followed step by step, allows the company to achieve design compliance with the EN 15227 standard since it respects and fulfills the following parameters:

- Average acceleration of the train vehicles below 5g.
- Survival space and structural integrity maintained for the occupied areas of the vehicle structure.
- Absence of significant plastic deformations in the passenger area.
- No overriding at the train unit extremities and between the vehicles.

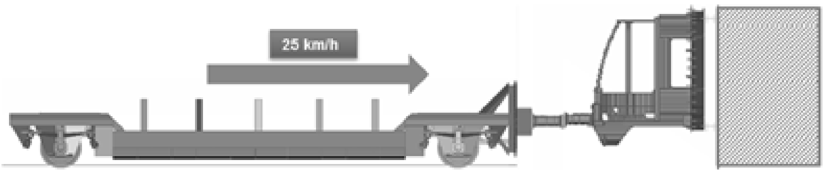

Fig. 7- Cab full scale crash test layout

Angelo Surini, Stefano Raiti,
Hitachi Rail Italy

David Blanco, Dario D'Agostino
EnginSoft