Crashworthiness of thin walled structures: results of numerical analyses

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Abstract

When a crash of railway vehicles occurs, energy absorption takes place both in the structural components and in specific energy absorbing components. A thin walled structure with rectangular cross section shapes was studied in order to develop a data base system relating to the formation of plastic hinges on components for railway structures which have optimized cross section shapes.

A study was made of the collapse mechanism, the variations of the load-carrying capacity and the energy absorption on shell thickness, initial imperfection and strain rate, both in the case of quasi-static buckling and of dynamic impact.

The thin walled rectangular cross section was studied in order to use it as a structural and/or an absorbing energy component.

1 Introduction

Computer capabilities and dynamic software have made enormous progress in the period from the development of the first railway vehicles with crash-worthy features to the present day.

Numerical simulation offers the possibility to reduce expensive and complicated dynamic testing to optimise the structure design. Nowadays crash simulations are made on a regular basis for most new designs of main line trains.

The size and type of the finite elements had to be adapted for railway applications in dynamic software and the laws governing the behaviour of
materials had to be used in order to obtain very accurate simulations of complex structure, as railway vehicle structures and their sub-assembly. The most important aspect is the necessary improvement of the simulation to assess the behaviour of the separate elements with an acceptable degree of accuracy (Nex [1], Drazetic [2] and Dannawi [3]).

For new and safer structural arrangements with the capacity to absorb higher levels of energy in a controlled manner, a thin walled rectangular cross section shape was investigated, by means of numerical analyses and a simplified analytical model, in order to use it as a structural and/or an absorbing energy component (Belloni [4]).

The design requirements for component optimisation have been established according to the main lines of the crashworthiness criteria for railway vehicles:

- to satisfy the UIC Standards for the compression test of the vehicles under exceptional loads;
- to obtain an optimal force-displacement curve that results in acceptable decelerations in the passenger areas;
- to ensure survival space for the driver;
- to ensure no deformation in passenger areas at the collision speed of the selected collision scenario.

In order to satisfy these criteria the component must:

1. survive to a fixed maximum static load without permanent deformations;
2. collapse in a controlled manner under impact load;
3. maximize the absorbed energy on the collapse length.

Aspects of buckling, post-buckling and impact behaviour were interpreted by means of finite element analyses carried out with state-of-the-art codes such as Abaqus Standard and Abaqus Explicit and with a simplified analytical model and some preliminary crushing tests.

Finally the increase of the ratio of dynamic to static crumpling load with impact speed was investigated, stating that this ratio is a reflection of changes in the buckling mode due to inertia and a consequence of strain rate effect in the material.

2 Thin walled rectangular cross section

The thin walled cross sections, built from mild steel, were designed to remain in the elastic range under static load equal to 1000 kN, to collapse at load level under 1500 kN–2000 kN and to maximize the absorbing energy on
the collapse length. The proposed collapse mechanism is based on thickness reductions to initiate the crash.

Figure 1 shows that the thickness reductions, three on the upper side and three on the lower side, are localised in the middle and at the ends of the column. The reduced thickness shells remain in the elastic range when the load is lower than 1000 kN while, for higher loads, they begin to yield until the local instability of an upper and a lower reduced thickness shell occurs. Then the lateral shells approach one another involving large deflections; the cross section yields completely and the localised plastic hinge is formed. The sequence of plastic hinges formation and, of course, the global collapse mechanism develop differently depending on initial imperfection (\(z_0\) in figure 1) and impact velocity (\(v\)). When the imperfection is high the first plastic hinge occurs in the middle cross section, then two similar plastic hinges start at the end sections and global collapse evolves like the collapse of two rigid bars with a perfectly plastic link at midspan and at the ends. In this case all the plastic hinges show an asymmetric mixed mode with three individual lobes deforming outwards and one inwards (figures 2 and 4). On the other hand, when the imperfection is small the local instability of the reduced thickness induces a symmetric mode, two lobes inwards and two lobes outwards and the global collapse mechanism leaves the beam axis unchanged (figures 3 and 5). The transition between these two collapse mechanisms occurs for more high imperfections depending on the impact velocities.

3 Buckling analyses

Three thickness combinations and four different values for the initial imperfection of the rectangular cross section were examined under quasi-static load by means of FEM analyses and a simplified beam model. The FEM model was constructed using 4 node quadrilateral shell elements to represent the sheet metal. The shell elements account for finite membrane strain, which is required for accurate simulation of the crushing process. The elasto-plastic material properties were obtained from tensile-testing. Two rigid surfaces, one of which was given a fixed displacement, were used to

<table>
<thead>
<tr>
<th>Column type</th>
<th>Shell thickness [mm]</th>
<th>Reduced thickness [mm]</th>
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</thead>
<tbody>
<tr>
<td>P86</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>P96</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>P97</td>
<td>9</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 1: Examinted thickness combinations.
Computational Methods and Experimental Measures

Figure 2: Plastic hinges show asymmetric mixed mode, numerical results.

Figure 3: Plastic hinge show symmetric mode, numerical results.

Figure 4: Crush test (P5) of a column type P86 with \( z_0 = 0.013 \) L, scale model 1:4.

Figure 5: Symmetric mode in the crush test (P2) of a column type P86 with \( z_0 = 0 \), scale model 1:4.

represent the impactor and the load surface respectively.

The quasi-static collapse was studied by means of a two step analysis. The first step was the elastic buckling analysis, based on eigenvalue extraction. It was carried out on the perfect structure without inelastic effects and with contact conditions fixed in the base state. In this step the collapse modes were established and the accurate discretization of these modes was verified. Then an imperfection was introduced in the geometry by scaling the buckling modes to a fraction of a shell thickness and adding it to the perfect geometry.

The second step was a post-buckling non linear analysis including geometrical and material nonlinearity.

Figures 6 and 7 show respectively the load-displacement diagram with different thickness combinations and initial imperfections. It can be observed that small thickness adjustments allow a significant variation of limit load (about 20%). Moreover, the high sensitivity of the structure to initial imperfections results in a large variation (about 60%) of the limit load when
The initial imperfection varies between 0 to 0.02 L, being L the length of the column.

The buckling and post buckling analyses show that the structure largely remains in the elastic range when the load rises up to 1000 kN for each examined thickness combination. After which a relatively fast transition from the elastic state to a perfectly plastic state occurs. But, when the buckling occurs, in any case, plastic deformations are concentrated in the plastic hinges.

This makes it possible to use a simple model, like imperfect Shanley’s column, for the buckling of the thin-walled column with local reduced thickness. The model doesn’t take into account the folds formation, but enables numerical rapid estimate of the buckling load, of the load deflection diagram and of the absorbed energy. Figure 8, related to the model of the structure
(scale 1:4, thickness shell combination P86, $z_0 = 0$), shows the comparison between the load-displacement diagram obtained by means of the simplified model, the diagram obtained by means of FEM analysis and the diagram obtained by means of experimental tests (P1 and P2). Table 2 reports the absorbed energy for scale model both with zero imperfection and with imperfection equal 0.013 L, related to a crush distance of 14 mm. It can be observed that the numerical results (absorbed energy, collapse load, load-displacement diagram) agree well with experimental results.

4 Impact analyses

Dynamic explicit FEM analyses were carried out, with the same real scale model described in the previus paragraph, in order to compare the overall behaviour of the structure subjected to a dynamic and quasi-static crumpling load.

Analyses have been carried out assuming the impactor rigid surface at rest, while the column and the load surface move with constant velocity. The impact velocity ranged between 0 to 16.8 m/s and the crash length was 200 mm.

The inertia effect and the strain rate effect on changes of buckling modes were investigated.

Strain rate sensitivity was incorporate into material model using Cowper-Symonds costitutive equation with strain rate parameter obtained by literature data (Davies [5] and Manjoine [6]).

A key feature of the simulations is that the column folds upon itself during dynamic event, which is modeled with the shell self contact capability. The effect of changing shell thickness is accounted as point the surfaces come into contact and afterwards the surfaces slide along one other.

Four different values of initial imperfection were considered for column type P86, but only the results related to the case with zero imperfection will be presented. Figure 9 shows the buckling modes for different impact velocities. Low velocities give a similar quasi-static buckling modes, higher velocities give a deformation concentration localized in one of the reduced thickness cross section. The position of deformation concentration moves from the load surface towards the impactor one when the velocity rises.

During the plastic hinge formation the strain rate is in the range between $10^1$ to $3 \times 10^2$ s$^{-1}$ and its value is maximum in the inner of the fold. Figure 10 shows the stress wave on lateral shell of the column (shell without thickness redution) in the case of impact velocities equal to 16.8 m/s. Point 0 L is near the impactor surface, point L is near the load surface. It can be observed that the maximum value is in the cross section where the first plastic hinge formation occurs.

Table 3 reports the absorbed energy on 200 mm of crash length. The absorbed energy is higher the higher the speed of impact and reaches 0.3 MJ when impact velocity is 16.8 m/s (60 km/h).
Concerning the maximum impact load it has been observed that its values is higher than the quasi-static buckling load. The dynamic maximum load can raise up to twice the quasi-static buckling load depending on the impact velocity and on the acceleration distribution along the column axis. Verification of the results have been provided by comparing the values of significant variables (such as velocity distribution along the column axis, absorbed energy) with the corresponding values produced by an equivalent model solved by means of an implicit dynamic procedure.

5 Conclusion

Comparison between the overall behaviour of the structure, subjected to a dynamic and quasi-static crumpling load, enables us to observe the high influence of the material strain rate, which is important for steel even when
the loadings are close to the quasi-static one. Moreover, a satisfactory agreement between numerical quasi-static results (absorbed energy, collapse load and load-displacement diagram) with experimental quasi-static results has been obtained with a shell FEM model. Impact numerical results will be compared with dynamic experimental data in the next development of this work.

References


