Coach passive safety enhancement in rollover accidents by multi-point optimization methodologies

G. Belingardi, G. Chiandussi, I. Gaviglio & A. Giorda
Department of Mechanical Engineering, Turin Technical University, Italy

Abstract

Coach rollover is a less frequent accident characterized by a high risk of injuries for the passengers. The vehicle should absorb the impact energy by plastic deformation of the structural components it is made of. At the same time the survival space for passengers has to be preserved by avoiding the intrusion of structural components as prescribed in ECE 66 regulation.

The purpose of the present study is to improve the coach design in order to guarantee the safety of belted passengers while fulfilling the requirements of the regulation.

With this aim a multi-point optimization methodology has been applied on a mixed multibody and FEM model that simulates a coach module during a rollover accident. EuroSID-1 dummies have been introduced in the module for the evaluation of the passenger injury risk.

1 Introduction

In the European Community approximately 20,000 buses and coaches are involved in accidents with personal injuries. Every year more than 30,000 persons are injured in these accidents and over 150 occupants suffer fatal injuries. Even if rollover is a less frequent accident, it is one of the most dangerous from the passenger safety point of view.

The international organisms of regulation, in collaboration with universities and research centres, are developing an intense and continuous labour to establish new safety requirements for coaches homologation. An important objective was reached with the emanation of regulation ECE 66 in 1986 [1].
Regulation ECE 66 prescribes that during and after the rollover test (fig.1) no part of the vehicle structure has to intrude into a previously defined residual space and no part inside the residual space has to project outside the deformed structure. The residual space is represented by a portion of the volume within the passenger compartment as shown in figure 2.

Regulation ECE 66 does not consider the presence of passengers during the rollover test. Otherwise it is important to consider the presence of human dummies because their added mass influences the structural behaviour during rollover [2]. Moreover, the presence of human dummies allows to estimate the biomechanical injury indexes and to compare them with the maximum allowed values for surviving [3].

The aim of this study is to improve coach structural strength to ensure passenger safety by contemporary fulfilling regulation prescriptions. A multi-point optimization methodology has been applied on a mixed multibody-FEM model simulating a coach module in rollover accident. An anthropomorphic dummy EuroSID-1 for side impact tests has been introduced in the module in order to evaluate injury indexes.

A new parameter called RIP (Rollover Injury Parameter) defined as the weighted linear combination of some injury parameters (HIC, TTI, VC, SPF) calculated on the dummy has been introduced as objective function to be minimized. Six mechanical and geometric properties of the lateral pillars of the coach have been used as design variables. The preservation of the survival space and the limit value (as stated by the standards) of each biomechanical parameter contained in the RIP have been used as constraints.

The research activity described in the paper has been carried out taking advantage of the preliminary results obtained in the 5th EU Framework RTD Project “ECBOS” (Enhanced Coach and Bus Occupant Safety).
2 The model

A portion of a coach between two consecutive pillars, called module, has been used as a reference in the construction of the numerical model (fig.3). Experimental data obtained by the Cranfield Impact Center within the ECBOS project allowed to validate the results of the numerical model [4], [6].

In order to prepare the model with the multibody methodology the module structure has been divided in rigid bodies connected through joints with a behavior defined by a moment/angle characteristic [5].

The simulation of the rollover has been executed following the set-up defined in ECE 66 regulations.

A dummy has been positioned on the most dangerous seat, using three points seat belt systems, to evaluate injury indexes. The presence of other passengers has been considered by introducing three equivalent masses, one at each of the other seats (fig 4).

A EuroSID-1 dummy [5] developed to evaluate occupant protection during lateral impacts has been used. At the moment of this study there is not a dummy developed for the case of rollover. Thus the use of the EuroSID dummy, specifically developed for side impact test, has been preferred to the use of Hybrid III dummy, specifically developed for frontal impact test [6].

With virtual dummies it is possible to evaluate some injury parameters that measure the injury level reached in a particular human body region. Injury parameters considered in present work are [7]:

- The Head Injury Criterion (HIC) in order to estimate the head damage risk during collision:
where \( R(t) \) is the resultant head acceleration in g's measured at the head's center of gravity, \( t_1 \) and \( t_2 \) are the initial and final times of the interval within which the HIC integral is calculated. The \( t_2-t_1 \) interval is of 36 ms at maximum.

- The Thoracic Trauma Index (TTI) in order to estimate the risk of serious injury to the thorax:
  \[
  TTI = 0.5(R_{IBg} + T_{12g}) < 85 \text{g}
  \]
  where \( R_{IBg} \) and \( T_{12g} \) are respectively the maximum values of lateral acceleration at the level of the 4\(^{th}\) and the 8\(^{th}\) rib and of the T12 spinal vertebra.

- The Viscous Criterion (VC) in order to estimate the risk of serious damages to the soft parts of the thorax due to deformation rate:
  \[
  VC = \max \left( \frac{dD(t)}{dt} \cdot \frac{D(t)}{SZ} \right) < 1 \text{m/s}
  \]
  where \( D(t) \) is the thoracic width, \( SZ \) is a reference width.

- The Pubic Symphisis Force (PSF) in order to estimate the risk of serious damages of the basin bones:
  \[
  PSF < 6000 \text{N}
  \]
  where PSF is the maximum force acting on the pubic symphisis.

The maximum value prescribed for each parameter by regulation has been considered as a constraint in the optimization problem.

## 3 The optimization problem

The optimization problem has been set up on the minimization of the parameter RIP. Parameter RIP (Rollover Injury Parameter) as been defined by the authors as the weighted linear combination of some injury parameters:

\[
RIP = 0.3 \cdot \frac{HIC}{1000} + 0.25 \cdot \frac{TTI}{85} + 0.25 \cdot \frac{VC}{1} + 0.2 \cdot \frac{SP}{6000}
\]

Weights have been assigned proportional to the different importance of the injury in the various human body zones.

The same four injury parameters have been used as constraint by imposing a maximum allowable value corresponding to serious injury or death for the passenger.

The use of this objective function might be not necessary because a solution that satisfies all constraints would be a result sufficient to consider the module sure. The objective function has been however set up to find a solution as far as possible from constraint limits and therefore with the highest safety margin.
Another constraint has been set up considering the minimum distance of the centers of the lateral pillar elements from the plane representing the survival space violation. Since negative distances indicate intrusion in the survival space, this value has to be greater than zero.

Pillars have been studied with particular attention: in fact the greatest part of the kinetic energy involved in the accident is transformed in plastic deformation energy by these structural elements.

Optimization variables have been defined in order to control both the geometric and the mechanical properties of the lateral pillars. Five optimization variables have been used to control the geometry of the pillar thin-walled box beam cross section in three different areas, near the pillar extremities, in the middle of the pillar and in the intermediate areas. They have been associated to the followings entities:

- X1: depth of the first characteristic section
- X2: depth of the second characteristic section
- X3: depth of the third characteristic section
- X4: width, considered equal for the three sections
- X5: thickness, considered equal for the three sections

A sixth design variable has been used to control the material yield stress, considered equal for all the three sections.

In this way a parametric geometry of the pillar, represented in figure 5, has been prepared through a multibody model with joints of various momentum/angle mechanical characteristics.

![Figure 5: Parametric representation of pillar.](image)

4 The optimization code

The optimization problem has been solved with the code OPTISTAT. This code has been developed at the Department of Mechanics of the Technical University of Turin and is based on multi-point optimization methodologies. The overall
optimization process is structured as a sequence of local optimization problems defined on a restricted portion of the space of admissible variables. The objective function and the constraint equations are approximated with polynomial models explicit in the variables of optimization (Response Surface Methodology) obtained by means of regression analysis. The values of the responses for the evaluation of the response surfaces are obtained by the execution of a set of analysis as prescribed by the predefined numerical experiment sets (Design Of Experiment). At every iteration response surfaces are evaluated using response from previous iterations and/or with the execution of new analyses or new experimental sets ([8], [9], [10], [11]).

The optimization code allows to use responses coming from different analysis codes and to solve problems of multidisciplinary optimization. The disadvantage of the high number of analyses needed to evaluate response surfaces has been reduced by using a system working simultaneously on more computational units.

5 The computational system

The optimization variables are linked to the geometric and mechanical characteristics of the lateral pillars of the coach module. The evaluation of the responses for objective function and constraint calculation for every design variable configuration requires two structural analyses. A first structural analysis is required in order to obtain the momentum/angle mechanical characteristic of the pillar joints depending on the geometrical design variables controlling their dimensions. A FEM analysis that simulates the bending plastic collapse of thin walled element is used in this case. A second analysis is required where the rollover of the model is simulated taking into account the joint characteristics previously calculated. The independence of the points of the experimental plan allow to solve simultaneously different analyses on several computational units. The complete system is divided in three main modules: the optimization code, the analysis code and a manager/interface.
The manager/interface module:

- transforms the optimization variables in models for the bending plastic collapse analyses;
- analyzes the results of the bending plastic collapse analysis and extracts the necessary curves for rollover analysis;
- extracts from rollover analysis the necessary responses for the optimization process;
- manages all the operation of file transfer, program execution and synchronization on different calculation units.

In particular this optimization has been executed using the multibody/FEM analysis code MADYMO for rollover simulation and CRASHCAD for the evaluation of the bending collapse.

## 6 Results analysis

The solution of the optimization problem has turned out rather complex due to the contrasting requirements for constraint satisfaction in terms of design variable values. Constraints on the biomechanical parameters lead to the identification of a compliant structure able to absorb as much as possible the impact energy. The intrusion constraint, instead, requires a stiff structure in order to minimize overall deformation of the module and in order to keep the survival space for passenger not intruded.

<table>
<thead>
<tr>
<th>RIP</th>
<th>Int [m] (&gt;0)</th>
<th>HIC (&lt;1000)</th>
<th>TTI [g] (&lt;85)</th>
<th>VC [m/s] (&lt;1)</th>
<th>PSF [N] (&lt;6000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial values</td>
<td>0.695</td>
<td>-6.3e-2</td>
<td>941</td>
<td>62</td>
<td>0.13</td>
</tr>
<tr>
<td>Optimized values</td>
<td>0.496</td>
<td>9e-3</td>
<td>642</td>
<td>53</td>
<td>0.11</td>
</tr>
<tr>
<td>Variation</td>
<td><strong>-29%</strong></td>
<td><strong>-114%</strong></td>
<td><strong>-32%</strong></td>
<td><strong>-15%</strong></td>
<td><strong>-15%</strong></td>
</tr>
</tbody>
</table>

The optimization led to the identification of a solution that represents a valid compromise between the two requirements: the survival space is preserved and the injury parameters keep being under the maximum allowed requirements values. As can be seen on table 1 and on figure 7 the most significative variations between the initial values and the optimized ones have been obtained on the Intrusion, the HIC (-32%) and the PSF (-38%) parameters. This is due to the fact that the initial value of these parameters was the nearest or over the allowed limit.

<table>
<thead>
<tr>
<th>X1 [mm]</th>
<th>X2 [mm]</th>
<th>X3 [mm]</th>
<th>X4 [mm]</th>
<th>X5 [mm]</th>
<th>X6 [Mpa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial values</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>Optimized values</td>
<td>41</td>
<td>67</td>
<td>71</td>
<td>49</td>
<td>3.8</td>
</tr>
<tr>
<td>Limits</td>
<td>20÷80</td>
<td>20÷80</td>
<td>20÷80</td>
<td>20÷80</td>
<td>2÷4</td>
</tr>
</tbody>
</table>
Figure 7: Behaviour of responses during iterations.

Figure 8: Response surfaces.
The interesting results obtained for the biomedical parameters are related to the particular process of pillar deformation that brings to an elevated absorption of energy due to the formation of many plastic hinges. On the impact side pillar it is possible to distinguish a first phase where there is the formation of a plastic hinge at the third joint (point A in figure 9) and a second phase where this hinge bends back (point A’) and there is the formation of a second hinge (point B) in the first joint. In the pillar on the not impacting side there is the formation of a single plastic hinge (fig.9 Point C). As confirmed by the values of the variables in the optimal configuration (table 2) and from the response surface plots (fig.8) the best solution seems to be obtained with the formation of the hinges A and C in the joints associated to the sections having smaller dimensions (X1xX4). Estimating also the values obtained for the thickness (X5) and the material yield stress (X6), a tendency of the optimization process can be found to move towards solutions characterized by sections with a lower maximum collapse load (section of reduced dimensions, lower value of material yield stress compared to the maximum allowed), but able to absorb a great amount of energy during the formation of the plastic hinges (the thickness reaches the maximum allowed value).

Figure 9: Plastic hinges formation during impact.

7 Conclusions

The problem of the design of the lateral pillars between the windows of a coach has been faced in order to find a solution that satisfies ECE66 regulation (coach rollover). The presence of dummies has been considered fundamental from the beginning of this work. A problem with contrasting requirements has been faced: the non violation of the survival space requires a very stiff structure, while the respect of the limits on the biomechanical parameters needs a structure with large energy absorption capability. The formation process of plastic hinges along the pillars is fundamental for an adequate energy absorption.
The use of an optimization program based on the exploration of the response surfaces with fractional factorial plans (DOE) allows to obtain a design solution satisfying each request.

The biomechanical parameters are used alone as constraints and are opportunely combined to calculate the objective function RIP. The HIC and the maximum force on the pubic symphisis resulted the most critical while VC and TTI were in all the cases lower than prescribed.

The feasibility of this type of studies with adequate models and reasonable elaboration times is subordinated to the use of distributed computational resources.

Acknowledgements

This work is part of research activity done within the frame of COFIN 2001. The support of the Italian Ministry of Research is gratefully acknowledged.

References

[1] Regulation ECE 66, Uniform provisions concerning the approval of large passenger vehicles with regard to the strength of their superstructure, Geneve, 1986.