

# Design Optimization of Progressively Crushing Rails

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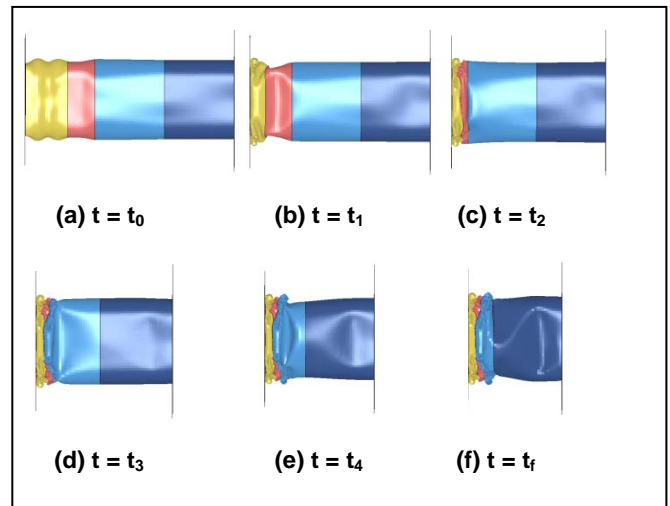
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## 1. Introduction

Lower rails are one of the key energy absorbers during frontal and rear crash of automotive structures. These components not only absorb a significant amount of kinetic energy, but also control the maximum forces that are transmitted to the remaining structure. When designing crush rails, a common goal is to identify the geometry, gage thickness and material of the rail so as to maximize its energy absorption while satisfying constraints on mass, the minimum amount of energy to be absorbed, and the allowable axial force. Using such a statement within an automated design optimization study can lead to lightweight designs that absorb large amounts of energy. However, these designs may not necessarily absorb energy in a progressive manner, in which crush initiates near the tip of the rail and then progresses rearward in a controlled fashion, as shown in Figure 1.

A lower rail design with a robust, repeatable crush mode is a key ingredient to achieving robust crashworthy behavior of the entire vehicle during frontal and rear crash events, both in terms of crash modality and total energy absorbed. In addition, during a minor crash only a small portion of the rail may experience crush. If this crushed region is limited to the tip of the rail, then repair costs can be minimized.

Here, we demonstrate a new strategy for achieving progressively crushing designs during an automated design optimization study. Independent crush zones are defined along the length of the rail. The main goal of the optimization is then to encourage maximum energy absorption in a given crush zone to occur prior to any energy absorption in rearward crush zones. In other words, crush should initiate in the tip and progress from zone to adjacent zone toward the rear of the rail. Compared to traditional optimization statements that focus only on total energy, the current approach can produce designs with similar total energy absorption but with a dominant progressive mode.

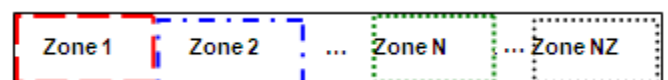


**Figure 1.** Crushing sequence of progressively crushing lower rail.

## 2. Progressive Energy Absorption Strategy

Traditional crush optimization strategies produce designs that absorb a lot of energy, but not necessarily progressive crush. The new strategy presented here attempts to find optimal designs that not only absorb a lot of energy, but also exhibit progressive crush behavior. The strategy utilizes a measure of the amount and timing of energy absorbed in different regions of the rail to promote progressive crush.

Figure 2 displays a rail profile in which different crush zones have been defined. In an ideal progressive crush scenario, zone  $N-1$  will crush almost entirely before zone  $N$  begins crushing (for  $N > 1$ ).



**Figure 2.** Specified crush zones in a rail. The tip of the rail corresponds to Zone 1, and the rear of the rail corresponds to Zone NZ.

We define a measure called progressive energy absorbed (PEA) as:

$$PEA = \sum_{N=1}^{NZ-1} PEA_N - EA_{NZ} \quad (1)$$

where  $PEA_N$  is the progressive energy absorbed in Zone  $N$ ,  $NZ$  is the total number of zones defined in the rail, and  $EA_{NZ}$  is the total energy absorbed by the last zone in the rail. We also define:

$$PEA_N = EA_N(U_N) - EA_N(U_{N-1}) \quad (2)$$

where  $EA_N(U_N)$  is the total energy absorbed so far by Zone  $N$  when the impactor has displaced an amount  $U = U_N$ ,  $EA_N(U_{N-1})$  is the total energy absorbed so far by Zone  $N$  when the impactor has displaced an amount  $U = U_{N-1}$ .  $U$  is the distance the impactor has traveled (or in practical terms how far a reference point has moved) after impact (see Figure 3).

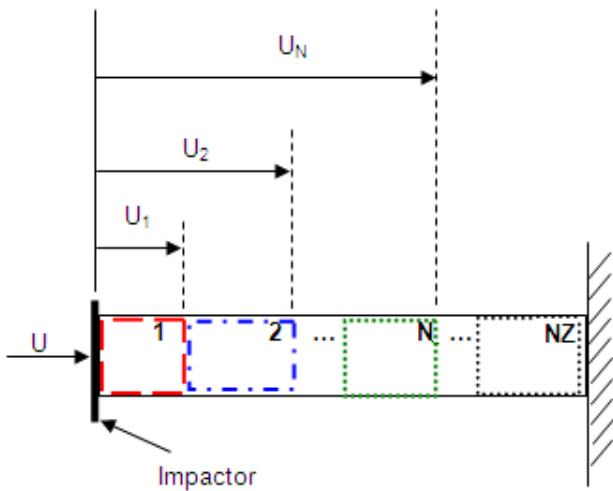


Figure 3. Definition of impactor displacements, as used in the calculation of PEA.

We assume here that Zone  $NZ$  should not crush at all, so the role of the final term in Equation (1) is to penalize PEA for energy absorption that occurs in Zone  $NZ$ . In system level crash models, often there is a zone such as  $NZ$  that must maintain its integrity during the crash. Further, in component level models such as considered here, it is common to constrain the rear of the rail at a location beyond which crush is expected or desired. So crush in Zone  $NZ$  is undesirable in both scenarios.

The optimization problem statement of a progressive crush optimization can now be stated as:

**Maximize:** PEA  
**Subject to:** Constraints on mass, force, etc.

### 3. Axial Rail Crush Analysis and Design Model

The following crush scenario and corresponding model were used to assess the proposed strategy for progressive crush optimization. A tube (rail) of length 500 mm was fixed at its right (rear) end. A flat rigid impactor with 500 kg mass traveling initially at 50 kph was used to crush the tube for 25 ms, as shown in Figure 4.

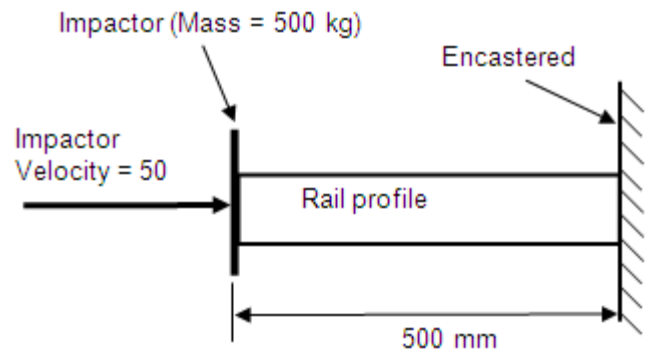


Figure 4. Analysis model used in the current study.

At each iteration during the optimization study, the shape of the rail was varied according to the following scheme. The cross-sectional shapes at several stations along the length of the profile (see Figure 5) were designed independently, thereby allowing the shape of the profile to vary along the length.

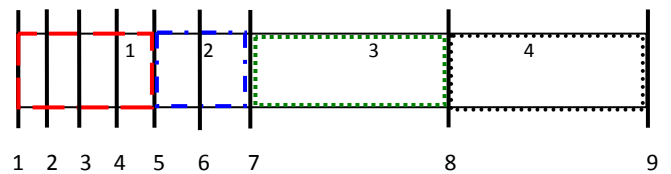
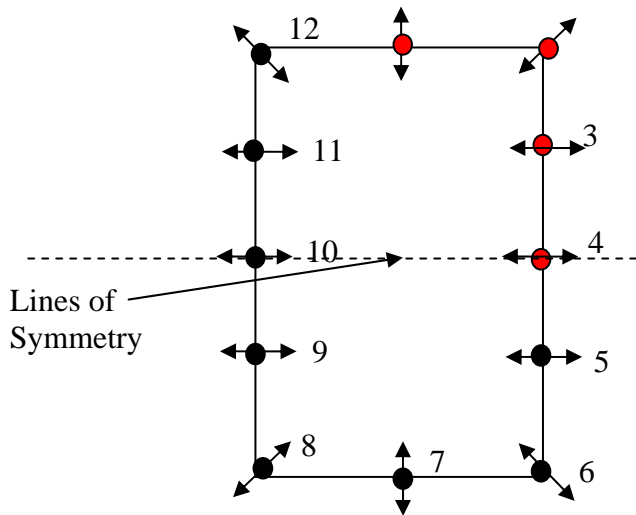


Figure 5. Crush zones and cross-sectional design stations used in the rail analysis and design model.

Nine independent stations were used along the length of the rail. Each cross-sectional shape was governed by 12 control points (only 4 of which were independent due to symmetry). Control points that could move in the horizontal direction (in Figure 6) were allowed to vary within 30% of the baseline coordinate.



**Figure 6.** Section profiles were controlled by 4 independent control points (1 through 4). The other control points were positioned by satisfying vertical and horizontal line of symmetry. The cross-section perimeter was scaled to ensure that it was within 2% of the baseline perimeter.

Control points that could move in the vertical direction were allowed to vary within 60% of the baseline coordinate. For manufacturability, the total perimeter of all cross-sections was constrained to vary only within 2% of the baseline perimeter. This was controlled by scaling of the shape produced for a given cross-section until the perimeter satisfied the perimeter constraint. Symmetry about vertical and horizontal planes was maintained in each cross-section.

With nine cross sections and five degrees of freedom per cross-section, there were 45 shape design variables for this problem. In addition, the gage thickness was allowed to vary, so there was a total of 46 design variables.

#### 4. Progressive Crush Optimization Study

Two optimization studies were performed – one with a conventional strategy which maximized total energy absorbed, and one with a new strategy which maximized progressive energy absorbed. The results of both studies are presented here to assess the ability of each to produce designs that absorb energy progressively.

For each of the two studies, four optimization runs were performed. In each of these four runs, a different set of starting conditions was used to account for the effects of stochasticity and starting conditions on the search. The same four starting conditions were used for the two studies. In each run, 2,000 crash evaluations were performed using the LS-DYNA explicit finite element code. The hybrid and adaptive algorithm SHERPA within the

HEEDS optimization software was used for the optimization runs. At 2,000 evaluations, the optimization runs were not fully converged, but they had made significant progress toward identifying high performing designs, and their rate of improvement had begun to decrease significantly. Since in most industrial applications of optimization it is not feasible to achieve complete convergence due to time constraints, it was deemed more valuable here to compare the results of four nearly converged designs than one fully converged design.

The following conventional crush optimization problem definition was used:

- Maximize:**  $EA$
- Subject to:**  $F_2 \leq 150 \text{ kN}$
- By Varying:** *Control Points*  
*Rail Thickness*

where

$EA$  is the total energy absorbed by the rail during crush,

$F_2$  is the maximum reaction force after initial crush initiation,

*Control Points* are the independent control points varied in Figure 6, and

*Rail Thickness* is the rail gage thickness, which varies between 1 mm and 3mm.

The progressive crush optimization problem statement used was:

- Maximize:**  $PEA$
- Subject to:**  $F_2 \leq 150 \text{ kN}$
- By Varying:** *Control Points*  
*Rail Thickness*

where

$PEA$  is the progressive energy absorbed, as defined in Equations (1,2),

$F_2$  is the maximum reaction force after initial crush initiation,

*Control Points* are the independent control points varied in Figure 5, and

*Rail Thickness* is the rail gage thickness, which varies between 1 mm and 3mm.

Based on the results in Table 1, the following conclusions can be reached. Three out of four runs using the conventional crush design optimization statement yielded optimized solutions that did not exhibit progressive crush behavior, while one of the designs (design D) exhibited very good progressive crush. All of the optimized designs resulting from the progressive crush optimization statement performed very well in terms of progressive crush

On average, the progressive crush strategy yielded designs with over 70% more PEA and 3.6% less total energy than did the conventional crush strategy. Perhaps more importantly, the standard deviation of EA and PEA

for designs based on the progressive crush strategy was significantly lower than that for designs based on the conventional strategy. This indicates that the progressive crush strategy was much more robust in terms of producing designs that behaved as intended.

**Conclusions**

A new strategy was presented for using HEEDS to optimize energy absorbing rails wherein a progressive crush mode is desired. It was demonstrated that this approach yields designs that consistently exhibit progressive crush behavior without sacrificing significantly the total energy absorbed.

**Table 1.** Comparison of progressive crush and conventional crush optimized results.

Optimal Design	Progressive Crush Strategy		Conventional Crush Strategy		Improvement of Progressive Crush Over Conventional	
	EA (kJ)	PEA (kJ)	EA (kJ)	PEA (kJ)	EA	PEA
A	29.21	17.73	26.19	10.28	11.53 %	72.97 %
B	28.12	16.25	28.92	5.96	-2.76 %	172.65 %
C	26.79	15.79	29.60	5.66	-9.5 %	178.98 %
D	26.33	15.25	29.87	16.29	-11.85 %	-6.38 %
<b>Average</b>	<b>27.61</b>	<b>16.25</b>	<b>28.64</b>	<b>9.55</b>	<b>-3.60%</b>	<b>70.39 %</b>
<b>St Dev</b>	<b>1.31</b>	<b>1.06</b>	<b>1.68</b>	<b>4.96</b>	<b>NA</b>	<b>NA</b>