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# Optimization of Anti-Climb Energy-Absorbing Structures in Urban Trains Using RBF Neural Network Modeling and the Multi-Objective Genetic Algorithm

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## Abstract

Enhancing passenger safety during train collisions requires the design of railway vehicles with efficient energy absorption capacity. Energy-absorbing structures installed at the ends of cars play a vital role in managing impact energy. This study presents a multi-objective optimization framework for an anti-climber energy-absorbing structure consisting of a conical tube and an anti-climber plate under eccentric loading (40 mm offset) according to EN 15227. Using Hammersley sampling, 100 finite element models were developed in Abaqus/Explicit with varying design variables: tube thickness (4-10 mm), base radius (50-110 mm), and cone angle (0-15°). To address high computational costs, a high-accuracy Radial Basis Function (RBF) surrogate model ($R^2 > 0.97$) was constructed. Multi-objective optimization using NSGA-II generated a Pareto frontier of 21 non-dominated solutions, explicitly quantifying the trade-off between maximizing Specific Energy Absorption (SEA) and minimizing Maximum Crushing Force (Fmax). The minimum distance method selected a balanced optimal design ($t=8.8$ mm, $R=93.7$ mm, $\theta=10.9°$) with SEA=3.17 kJ/kg and Fmax=1179.71 kN. FE validation confirmed prediction errors below 2%, demonstrating the framework's reliability for crashworthiness design in railway vehicles.

**Keywords:** Energy Absorbing Structure; Anti-Climber; Radial Basis Function Network; NSGA-II; Multi-objective Optimization.

## 1. Introduction

Despite significant advancements in railway passive safety, vehicle overriding remains a catastrophic outcome in train collisions [1]. Energy-absorbing (EA) structures installed at the front of leading vehicles play a vital role in managing impact energy and preventing override. The EN 15227 standard mandates that these structures maintain effectiveness under eccentric impacts, typically considering a 40 mm vertical offset [2].

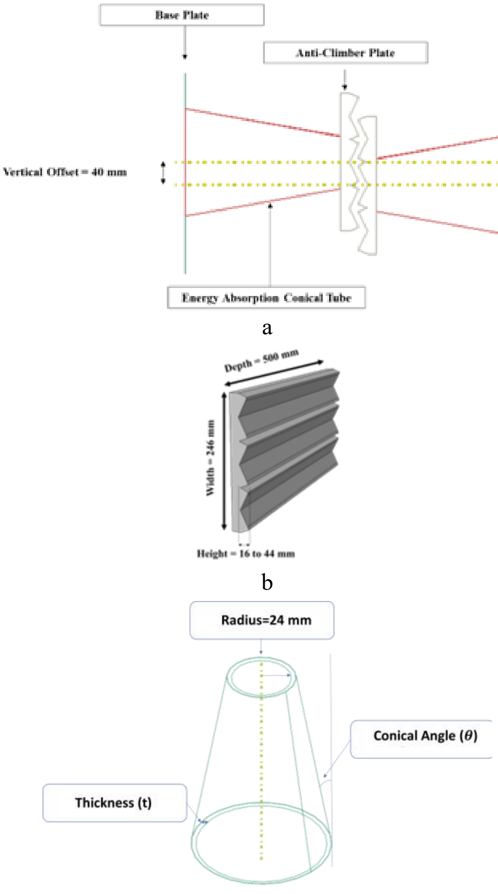
Conical tubes have demonstrated superior energy absorption characteristics under both axial and oblique loading due to their stable, progressive collapse mode and high weight efficiency [3-4]. While previous studies have investigated anti-climber devices [5-6] and conical absorbers [7-8] separately, the optimal design of an integrated system combining both components under standardized eccentric loading—explicitly considering the inherent trade-off between energy absorption efficiency (SEA) and structural load (Fmax)—has not been systematically addressed.

The novelty and contribution of this work lie in developing a comprehensive, computationally efficient framework that: (1) integrates Hammersley space-filling sampling with high-fidelity FE analysis, (2) employs highly accurate RBF-based surrogate modeling to replace expensive simulations, and (3) applies NSGA-II multi-objective optimization to identify the complete Pareto-optimal frontier for this critical safety component. The framework is rigorously validated through direct FE simulation of optimal designs.

## 2. Methodology

### 2.1 Finite Element Modeling and Parametric Study

A 3D symmetric FE model was developed in Abaqus/Explicit (Figure 1). The assembly comprises fixed and moving parts, each containing a conical crush tube and anti-climber plate. A 40 mm vertical offset simulates eccentric collision per EN 15227. The anti-climber plate and supports were modeled as discrete rigid bodies, while the AISI 1010 steel conical tube was meshed with 19,600 S4R shell elements (4 mm optimal size after mesh convergence analysis). Surface-to-surface contact ($\mu=0.3$) was defined. A smooth-step amplitude curve applied quasi-static crushing velocity (1000 mm/s), ensuring kinetic energy remained negligible (<5%) compared to internal energy.



a

b

c

**Figure 1. FE model: (a) complete assembly with 40 mm offset, (b) anti-climber plate, (c) conical tube.**

### 2.2 Design of Experiments and Performance Metrics

Three key geometric variables were selected: wall thickness (t: 4-10 mm), base radius (R: 50-110 mm), and cone angle (θ: 0-15°). The Hammersley Sequence Sampling (HSS) method generated 100 uniformly distributed design points—superior to random sampling for space-filling properties. Quasi-static crushing simulations were performed for all 100 designs.

Two crashworthiness indicators were extracted:

- Specific Energy Absorption (SEA): $SEA = \frac{\int P\, d\delta}{m}$ (kJ/kg) — to be maximized.
- Maximum Crushing Force (Fmax): Peak axial force (kN) — to be minimized.

### 2.3 RBF Surrogate Modeling

Due to high computational costs for FE simulations, direct optimization was infeasible. Radial Basis Function (RBF) networks were constructed separately for SEA and Fmax using MATLAB's fitrgp function with a squared exponential kernel:

$$\hat{f}(X) = \sum_{i=1}^{n} w_i\ \phi(\| X - X_i \|) + b^T X + c \tag{1}$$

Where $X = [t, R, \theta]^T$. The dataset was randomly split (80% training, 20% testing) with a fixed seed (rng(42)) for reproducibility. Model accuracy was evaluated using the Coefficient of Determination ($R^2$) and Relative Average Absolute Error (RAAE). Both models achieved excellent accuracy: $R^2 = 0.98$ (SEA) and $R^2 = 0.97$ (Fmax), with RAAE values of 0.017 and 0.018 respectively.

### 2.3 Multi-Objective Optimization

The optimization problem was formulated as:

$$\begin{cases} Minimize\ F(x) = [-\text{SEA}, \text{F}_{\text{max}}(x)]^{\text{T}} \\ Subject\ to\ x = [\text{t}, \text{R}, \theta]^T \\ 4 \le t \le 10 \\ 50 \le R \le 110 \\ 0 \le \theta \le 15 \end{cases} \tag{2}$$

The Non-dominated Sorting Genetic Algorithm II (NSGA-II) was employed with: population size = 60, generations = 100, crossover probability = 0.8, mutation rate = 0.08, yielding 6,000 function evaluations.

## 3. Results and Discussion

### 3.1 Pareto Optimal Frontier

NSGA-II successfully generated a well-distributed Pareto frontier comprising 21 non-dominated solutions. The quality metrics confirmed good performance: Hypervolume = 0.72 and Spacing metric = 0.012, indicating both convergence and uniform distribution.

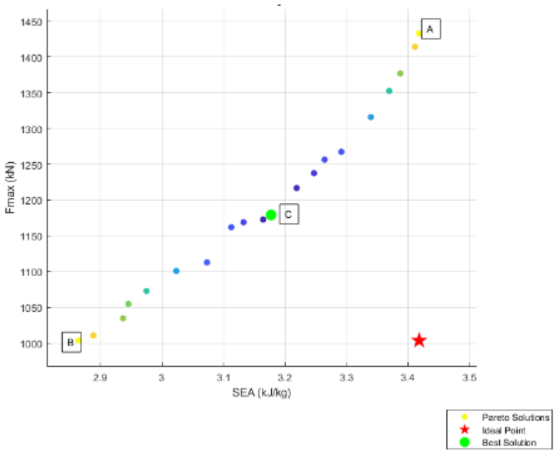


**Figure 2. Pareto frontier showing the trade-off between SEA and Fmax.**

Figure 2 clearly illustrates the inherent conflict: increasing SEA inevitably raises Fmax. Three characteristic designs were extracted:

- **Design A:** Maximum SEA (3.41 kJ/kg) — prioritizes energy absorption.
- **Design B:** Minimum Fmax (1003.39 kN) — prioritizes structural load mitigation.
- **Design C:** Balanced compromise selected via the **Minimum Distance Method** (Euclidean distance to the ideal point in normalized objective space).

### 3.2 Validation and Optimal Design

Direct FE simulations were performed for the three optimal designs. Table 1 compares RBF predictions with FE validation results.

**Table 1. Validation of optimal designs: RBF vs. FE** simulation

| Parameter | Design A (Max SEA) | Design B (Min Fmax) | Design C (Balanced) |
|---|---|---|---|
| **Design Variables** | | | |
| t (mm) | 8.6 | 9.0 | 8.8 |
| R (mm) | 95.1 | 94.5 | 93.7 |
| θ (°) | 10.1 | 12.8 | 10.9 |
| **RBF-Predicted Responses** | | | |
| SEA (kJ/kg) | 3.41 | 2.86 | 3.17 |
| Fmax (kN) | 1432.95 | 1003.39 | 1179.71 |
| **FE-Simulated Responses** | | | |
| SEA (kJ/kg) | 3.52 | 2.74 | 3.23 |
| Fmax (kN) | 1423.24 | 1012.32 | 1201.24 |
| **Relative Error** | | | |
| SEA (%) | 3.13 | 4.37 | 1.86 |
| Fmax (%) | 0.68 | 0.88 | 1.79 |

For the recommended balanced design (C), relative errors are below 2% for both objectives, confirming the surrogate model's exceptional accuracy. Figure 3 shows the force-displacement curves obtained from FE validation simulations for the three optimal designs. All curves exhibit a characteristic initial peak force followed by a plateau region, indicating stable, progressive crushing. Design A exhibits the highest force plateau and SEA, while Design B shows the lowest initial peak force and SEA. Design C demonstrates a well-balanced response, with a moderated peak force and sustained energy absorption capacity.

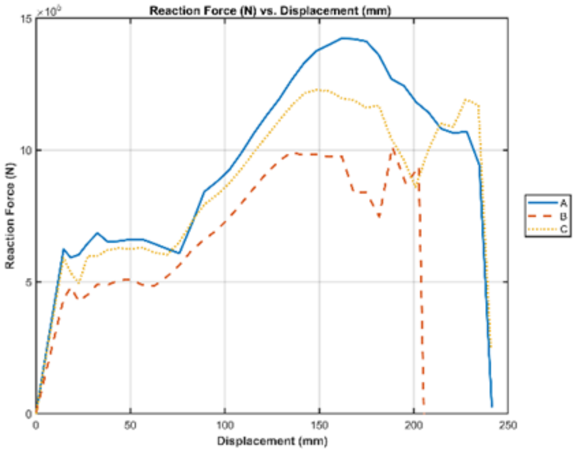


**Figure 3. Force-displacement curves from FE validation for designs A, B, and C.**

The optimal parameters (θ=10.9°, R=93.7 mm, t=8.8 mm) provide clear design guidance. For manufacturing, these can be rounded to θ=11°, R=94 mm, and t=9 mm with negligible performance deviation. The Pareto front offers designers flexibility: Design A for weight-critical, high-energy applications; Design B for infrastructure with strict load limits; and Design C as a robust general-purpose solution.

## 4. Conclusions

This research successfully developed and validated an efficient multi-objective optimization framework for an integrated anti-climber/conical tube energy absorber under eccentric loading. The key conclusions are:

1. **Methodological contribution:**
   The combination of Hammersley sampling, high-fidelity FE analysis, RBF surrogate modeling ($R^2 > 0.97$), and NSGA-II optimization provides a robust, computationally efficient approach for crashworthiness design of complex railway structures.
2. **Optimal solutions identified:**
   The Pareto frontier explicitly quantifies the SEA-Fmax trade-off. The balanced optimal design (t=8.8 mm, R=93.7 mm, θ=10.9°) achieves SEA = 3.17 kJ/kg and Fmax = 1179.71 kN, representing an excellent compromise between energy absorption efficiency and structural load control.
3. **Validation:**
   Direct FE simulation of optimal designs confirmed prediction errors predominantly below 2%, demonstrating the framework's exceptional accuracy and reliability.
4. **Practical value:**
   The methodology provides actionable design guidance for railway engineers to develop next-generation crashworthy structures, enhancing passive safety and mitigating catastrophic override consequences.

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