

EXPERIMENTAL RESEARCH OF CHARACTERISTICS OF RIGID POLYURETHANE FOAM FOR KINETIC COLLISION ABSORPTION SYSTEMS - OGDEN MATERIAL MODEL

Jovan TANASKOVIC¹ [0000-0002-2936-5535]Francis FRANKLIN² [0000-0003-2847-5000]William NIGHTINGALE³

Abstract – Rigid polyurethane (PU) foam was investigated as a filling material for a tube collision energy-absorbing component intended for railway vehicle crashworthiness applications. Quasi-static uniaxial compression tests were performed on cubic specimens extracted from a cylindrical PU foam block with a nominal density of 175 kg/m³ in order to characterize its compressive behavior and obtain material parameters for finite element analysis (FEA). The experimental stress-strain curves exhibited the characteristic nonlinear response of cellular material. An Ogden foam constitutive model was subsequently calibrated in Ansys using experimental compression data and implemented in numerical simulations of energy absorber designs. The numerical study evaluated the force-displacement behavior and energy absorption capability of each configuration under quasi-static axial compression applied through a conical bushing. For a compression stroke of 60 mm, the fully foam-filled tube demonstrated a 16% increase in absorbed energy compared with the empty tube, while the configuration incorporating the concentric steel core achieved an improvement of 9.5%. The findings confirm that the incorporation of rigid PU foam enhances the quasi-static energy absorption performance of tubular railway crash absorbers.

Keywords – Collision Energy Absorber, Rigid PU foam, Ogden foam model, Experimental investigation, Numerical simulation.

1. INTRODUCTION

Increasing train operating speeds require more efficient crash-energy management systems to improve passenger safety and protect vehicle structures during collisions [1]. Owing to its low density, low cost, and high energy absorption capability under compressive loading, rigid polyurethane (PU) foam has attracted considerable attention as a potential filler material for energy absorbers [2]. Its cellular structure enables efficient dissipation of impact energy through compression, making it suitable for railway crashworthiness applications. In modern railway vehicles, crash energy is primarily dissipated through deformable structural components such as crush tubes and anti-climbing devices. The concept investigated in this study consists of a steel tube filled with rigid PU foam that is compressed by passing through a conical bushing, Figure 1.

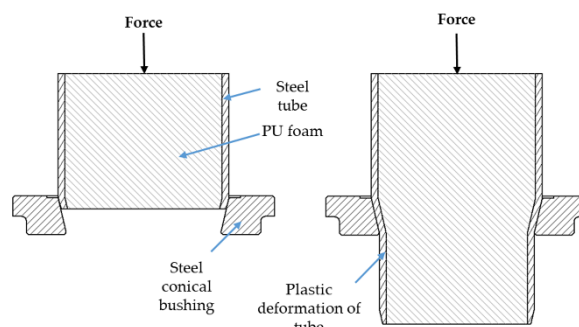


Fig.1. Collision absorber diagram (a) at start of force application (b) post force application.

During deformation, both the steel tube and the foam core contribute to energy dissipation through plastic deformation, foam compression, and friction, providing an effective mechanism for impact energy absorption. Accurate numerical modelling of foam-filled energy absorbers requires an appropriate constitutive model capable of reproducing the compressible nonlinear behavior of rigid PU foam.

¹ University of Belgrade Faculty of Mechanical Engineering, Department of Rail Vehicles, Kraljice Marije 16, 11120 Belgrade, Serbia, e-mail: jtanaskovic@mas.bg.ac.rs

² School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK; francis.franklin@newcastle.ac.uk

³ School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK; willnightingale98@gmail.com

Previous studies have shown that rigid PU foam exhibits characteristics between elastomeric materials and cellular foams, making conventional incompressible hyperelastic models unsuitable [3]. Among available material models, the Ogden foam formulation has been identified as suitable for reproducing PU foam behavior in Ansys simulations [4], although accurate calibration requires reliable experimental data.

The present study investigates rigid PU foam as a filler material for a tube railway vehicle collision absorber consisting of a foam-filled steel tube compressed through a conical bushing. Experimental compression tests were performed on foam specimens extracted from different regions of a cylindrical sample, and the obtained data were used to calibrate an Ogden foam model in Ansys. The validated model was then applied to compare the performance of three absorber configurations: an empty tube, a fully foam-filled tube, and a foam-filled tube reinforced with a concentric steel core. Such a model enables preliminary assessment of absorber performance under quasi-static loading conditions before further crashworthiness evaluation.

1.1. Hyperelastic models and Ogden foam model

Hyperelastic models are widely used in finite element analysis to describe the nonlinear elastic behaviour and large deformations of materials such as rubbers and elastomeric foams, whose response cannot be accurately represented by conventional elastic parameters.

The Ogden foam model, also known as the hyperfoam model, uses a modified Ogden [5] form of strain energy potential function for compressible foams. The function is given by [6]:

$$W = \sum_{n=1}^N \frac{\mu_n}{\alpha_n} \left(J_{cl}^{\alpha_n/3} (\bar{\lambda}_1^{\alpha_n} + \bar{\lambda}_2^{\alpha_n} + \bar{\lambda}_3^{\alpha_n}) - 3 \right) + \sum_{n=1}^N \frac{\mu_n}{\alpha_n \beta_n} (J_{cl}^{-\alpha_n \beta_n} - 1)$$

where: μ_n , α_n are material constants, β_n is the compressibility parameter, $J_{cl} = J$ is the determinant of the elastic deformation gradient, $\bar{\lambda}_i$, the principal stretch ratios due to tensile/compressive strain and N is the order of fitting. The parameter β_n governs the compressibility of the material and is related to Poisson's ratio ν_n :

$$\beta_n = \frac{\nu_n}{1 - 2\nu_n}$$

Poisson's ratio can be determined experimentally by measuring the lateral strain during the compression test.

2. EXPERIMENTAL RESERACH

2.1. Material

PU foam is created by reacting a liquid isocyanate

with two or more isocyanate groups per molecule with liquid polyol, an organic compound containing multiple hydroxyl groups per molecule in the presence of a catalyst [7]. In this research, the PU foam was produced in circular tubes of diameter 85 mm and length 200 mm, with a density of 175 kg/m³. A 100 mm length of the foam cylinder was initially cut into twenty cubic 20 mm samples, Figure 2.

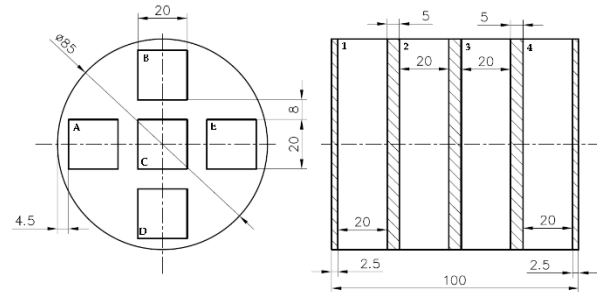


Fig. 2. (a) Cutting pattern from cylindrical sample. (b) Cubic samples cut from one 100 mm column.

This configuration was chosen to test whether cubic samples taken from the centre (C) exhibit different material properties to samples taken from other locations in the cylinder (A,B,D,E).

2.2. Testing

Uniaxial compression tests were performed on cubic samples using a Shimadzu tensile test frame with a 10 kN load cell, Figure 3. Tests were conducted at room temperature with a constant crosshead speed of 25 mm/min. until the predefined stroke was reached. Samples labeled as type 1 were compressed to 2 mm, type 2 to 4 mm, type 3 to 8 mm, and type 4 to 12 mm, corresponding to approximately 60% strain. A preload of about 1 N was applied before each test, and force, stress, strain, and stroke data were recorded at 0.01 s intervals.

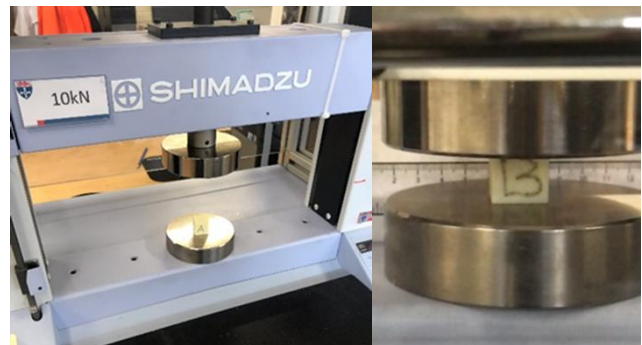


Fig. 3. Mechanical testing using Shimadzu 10 kN load cell.

3. EXPERIMENTAL RESULTS

Figure 4 shows the compression curves obtained from testing, with each graph containing four curves

labeled A to E. The curves show similar trends, except for sample C. All specimens exhibit linear elastic behavior up to approximately 8% strain, but the lines do not pass through the origin, likely due to the low preload. Therefore, arbitrary offsets will be applied when determining the Ogden foam model constants. For the 12 mm stroke tests, excluding sample C, the maximum difference between samples is 0.7 MPa at approximately 10% strain. Curve D shows the largest scatter, with the 12 mm specimen differing by 0.71 MPa, compared with 0.10, 0.19, and 0.09 MPa for cases A, B, and E, respectively.

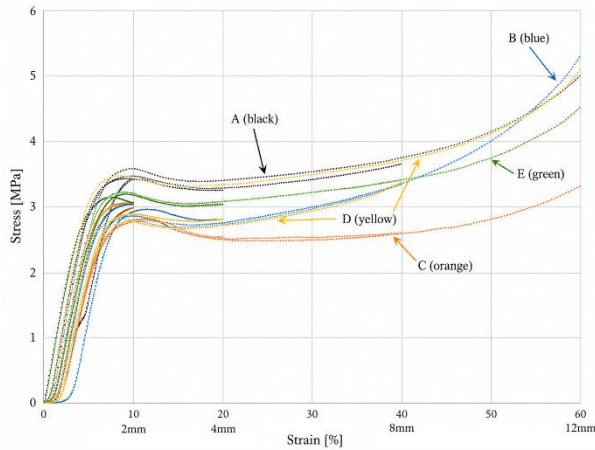


Fig. 4. Compressive stress-strain curves for all cubic samples.

Stress-strain curves up to 60% strain show the typical hyperelastic response, with linear, plateau, and densification regions. A representative curve was extrapolated from cubic sample B, Figure 5. The three regions represent distinct deformation mechanisms: linear elastic cell-wall bending, plateau-stage cell collapse, and densification through cell-wall compression, with the response influenced by the foam's anisotropy.

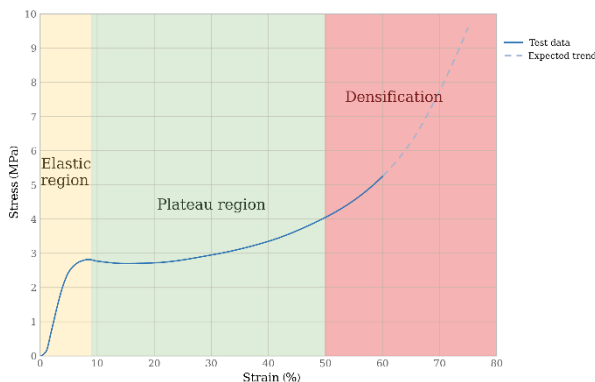


Fig. 5. Stress-strain curves of cubic sample B.

4. NUMERICAL SIMULATIONS

FEA was performed in ANSYS Mechanical 2019 R3 using a third-order Ogden foam model to replicate the compression tests and assess the absorber's energy

absorption [6]. Although hyperelastic models assume reversible, nearly incompressible deformation, the tested foam samples showed clear irreversible deformation after compression, Figure 6. The irreversible collapse of the foam complicates accurate hyperelastic modelling, but a model can be calibrated to reproduce the force response within the strain range relevant to the single-use collision absorber.



Fig. 6. Cubic samples B1 and B4 post-testing.

The measured engineering stress and strain were converted to true values for FEA, Figure 7.

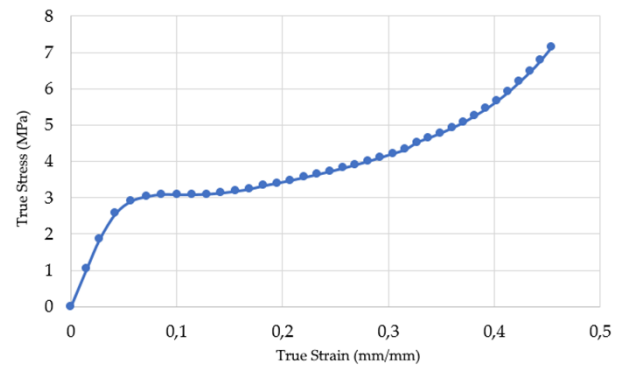


Fig. 7. True Stress vs Strain curve.

The compressibility parameters β_n were derived from experimental data, and the material constants were refined iteratively:

$$\begin{aligned} \mu_1 &= 4.4 \times 10^6 & \alpha_1 &= 20 & \beta_1 &= 0.452 \\ \mu_2 &= 4.4 \times 10^6 & \alpha_2 &= -10 & \beta_2 &= 0.542 \\ \mu_3 &= 9.9 \times 10^6 & \alpha_3 &= 0.45 & \beta_3 &= 1.082 \end{aligned}$$

One-eighth of the cube was modelled with three frictionless supports and displacement loading, using 22 elements along the loading direction and 18 perpendicular, with 31977 nodes, Figure 8. The reaction force was recorded throughout the stroke.

These tests showed that the first-order foam model is sufficient for strains up to 11%, while higher-order modelling is unnecessary. Figure 9 shows the curve fit of the 1st order model to be accurate up to a stroke of 2 mm on a 20 mm cubic sample, equivalent to 10% strain.

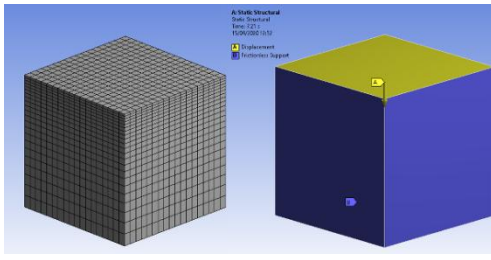


Fig. 8. Boundary conditions and mesh for eighth cubic sample.

The constants used in the material model for the foam in the collision absorber are:

$$\mu_1 = 14 \times 10^6 \quad \alpha_1 = 10 \quad \beta_1 = 0.5$$

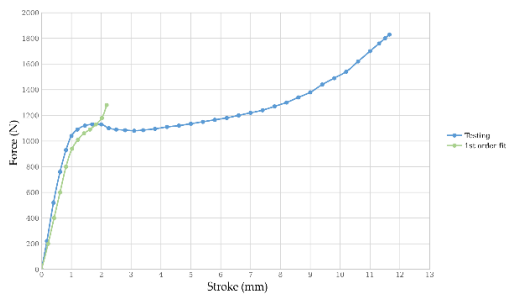


Fig. 9. 1st order model fit for strains up to 11% in cubic sample.

Using the validated PU foam model, three absorber configurations were analysed. A quarter-symmetry model with frictional tube–bushing contact ($\mu = 0.15$) was used, with mesh refinement optimized for convergence, Figure 10.

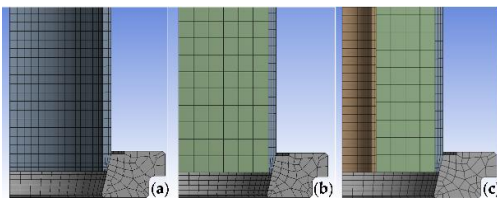


Fig. 10. Collision absorber meshes. (a) Empty tube. (b) Foam filled tube. (c) Concentric filled tube.

Figure 11 shows the force vs stroke for the three different energy absorber models up to a stroke of 60 mm.

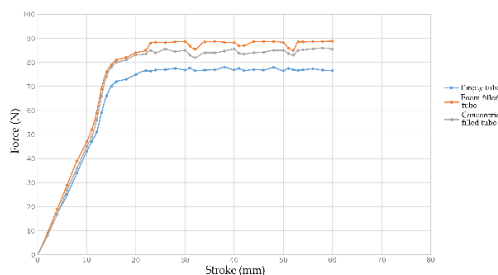


Fig. 11. 1st order model fit for strains up to 11% in cubic sample.

As shown, both foam-filled absorbers exhibited higher quasi-static energy absorption than the empty

tube, by approximately 16% for the fully filled and 9.5% for the concentric configuration.

5. CONCLUSION

This study demonstrated that rigid PU foam can enhance the quasi-static energy absorption of tubular railway collision absorbers. Compression tests confirmed the nonlinear foam response and some cross-sectional property variation, while the Ogden model adequately reproduced the experimental behavior; considering the predicted maximum strain of $\sim 11\%$, a first-order model was adopted for the final simulations. Among the three investigated configurations, the fully foam-filled absorber showed the highest energy absorption (4.61 kJ), representing an increase of $\sim 16\%$ over the empty tube (3.96 kJ), while the concentric-core configuration absorbed 4.38 kJ ($\sim 9.5\%$ increase). Further work should address dynamic foam testing, transverse strain measurement, mesh/contact sensitivity and experimental validation, including the effects of foam density, absorber geometry, tube dimensions and installation constraints.

ACKNOWLEDGEMENT

The results presented here are the outcome of research supported by the Ministry of Science, Technological Development, and Innovation of the Republic of Serbia under Contract 451-03-33/2026-03/200105 dated February 5, 2026.

REFERENCES

- [1] EN 15227:2020+A1:2024. Railway Applications Crashworthiness Requirements for Rail Vehicles; European Committee for Standardization: Brussels, Belgium, 2024.
- [2] Xiao, Y.; Yin, J.; Zhang, X.; An, X.; Xiong, Y.; Sun, Y. Mechanical performance and cushioning energy absorption characteristics of rigid polyurethane foam at low and high strain rates. *Polym. Test.* 2022, 112, 107531.
- [3] Kim, S.; Shin, H.; Rhim, S.; Rhee, K. Y. Calibration of hyperelastic and hyperfoam constitutive models for an indentation event of rigid polyurethane foam. *Compos. Part B: Eng.* 2019, 163, 297–302.
- [4] Petre, M.T.; Erdemir, A.; Cavanagh, P.R. Determination of elastomeric foam parameters for simulations of complex loading. *Comput. Methods Biomech. Biomed. Eng.* 2006, 9(4), 231–242.
- [5] Ogden, R.W. Large deformation isotropic elasticity—On the correlation of theory and experiment for incompressible rubberlike solids. *Proc. R. Soc. Lond. A Math. Phys. Sci.* 1972, 326(1567), 565–584.
- [6] ANSYS Workbench Mechanical, Release 2019 R3 and Release 2025 R2.
- [7] Seymour, R.B.; Kauffman, G.B. Polyurethanes: A class of modern versatile materials. *J. Chem. Educ.* 1992, 69(11), 909–910.