Computational Modeling of the TPU Shock Absorber using Ls-Dyna

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1 Abstract

In this study, various analysis and test activities are presented, which were carried out for the development of shock-mitigating floor mats. These impact-absorbing floor mats are produced from hyperelastic materials and are designed to absorb high-amplitude, short-duration shock loads in defense or civil applications. Throughout the study, the ***MAT027** model is examined for its suitability in modeling hyperelastic materials in both static and dynamic analyses, conducted using the non-linear finite element code LS-DYNA®. The ***MAT027** model accurately describes the behavior of hyperelastic materials and is often preferred for this type of material. To correctly apply this model, specific parameters pertaining to the hyperelastic material must be determined. This study primarily focuses on the determination of these material parameters through tests conducted on samples made of Thermoplastic Polyurethane (TPU) material. In the initial phase of the study, a literature review concerning TPU material was conducted, and material parameters were obtained using the test data presented in this study. The material parameters were then optimized using LS-Opt® to achieve the best material behavior. Following the determination of material parameters, dynamic simulations were performed using LS-DYNA®, and the simulation results were subsequently compared with experimental data. With the material parameters in hand, the second phase of the study involved the design of cellular structures with various geometric shapes. The force-displacement graphs of these newly designed shapes were analyzed through dynamic analyses.

Keywords: Thermoplastic Polyurethane, Hyperelastic materials, Cellular solids, Shock absorber

2 Introduction

In recent years, the utilization of TPU (Thermoplastic Polyurethane) as a material in shock-absorbing structures has gained significant popularity in both defense and civil applications, primarily owing to its lightweight properties and hyperelastic behavior. Within the defense industry, TPU-based floor mats are frequently employed in military vehicles to mitigate the risk of personnel injuries in the event of a mine explosion. Jiang et al. carried out experimental and numerical analysis studies to examine the behavior of floor mats [1]. In this study, a finite element model of the equivalent geometry was created, and material parameters were obtained using the test data presented in this study.

The material used for the floor mat is thermoplastic polyurethane, a material known for its hyperelastic behavior [2]. To model this material's behavior, the ***MAT027** model was employed, allowing for the simulation of material behavior with just two parameters. These material parameters for ***MAT027** were determined using LS-Opt®.

In the analysis, a 9 kg rigid block was dropped onto the test sample at a velocity of 4.13 m/s, replicating the same boundary conditions as those in the reference article's experimental work. Subsequently, in the next stage of the study, a single cell from the original product was examined. A rigid mass of 1.07 kg was dropped onto this single cell at a speed of 5 m/s. The analysis was conducted, and the force-time graph was obtained. Following this, the analyses were repeated for the newly designed cell structure under the same boundary conditions. Force-time graphs were generated and compared between the original product and the newly designed cell structure.

3 Material Parameter Identification

In the study by Jiang et al., they conducted impact and drop tests to examine the behavior of the equivalent product. In this study, comparisons were made between the newly designed product and the equivalent product, with reference to the drop test. In the reference study, the mechanism shown in Figure 1 was designed for the drop test. In this study, a sample was fixed onto a rigid surface, and impact loads were applied to the top surface of the sample using a steel hemisphere-shaped impact tool connected to a steel frame. An accelerometer was mounted on top of the impact apparatus, and a load cell was placed beneath the sample to obtain the necessary output values. The total mass of the frame and impact equipment was 9 kg, and the radius of the hemisphere was 80 mm. In the reference study, the impact equipment was dropped from three heights (0.22, 0.47, and 0.87 m), and the results were examined. Following the examinations, a finite element model of the same test setup was created and drop analysis from the specified three heights was conducted on the equivalent product. For the analysis of the equivalent product, three different homogenized foam material cards were defined and compared with the test results. Figure 1 illustrates the comparison of the test and analysis results with a force-displacement curve. Maximum compression was observed at 0.87 m during the tests. Therefore, tests and analyses were not conducted at heights exceeding this value. In the analyses, maximum stresses were observed in the scenario representing a drop from 0.87m, which represents one of the three drop heights.

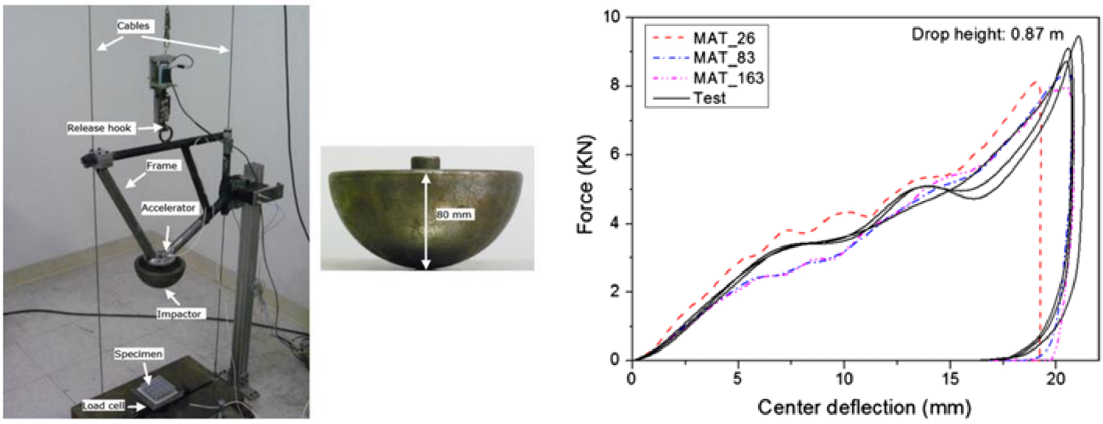

Fig.1: Comparison of The Numerical Analysis and Experimental Studies Performed for The Reference Publication Drop Test Chart and The Equivalent Product

In this study, a similar analysis model to the drop test and analysis in the reference article was created. In the drop simulation, **`*AUTOMATIC_SINGLE_SURFACE`** contact definition has been employed for defining contacts between parts. The structural parts such as the floor plate and the rigid impactor have been modeled using solid elements with element sizes of approximately 2 - 5 mm. To capture critical geometric details for floor mat, the element size has been regionally decreased to values of 0.5 - 1 mm. "Elform -1" element formulation has been used for "Lagrange" hexahedral solid elements, and "ELFORM -16" has been used for shell elements. The created analysis model is shown Figure 2.

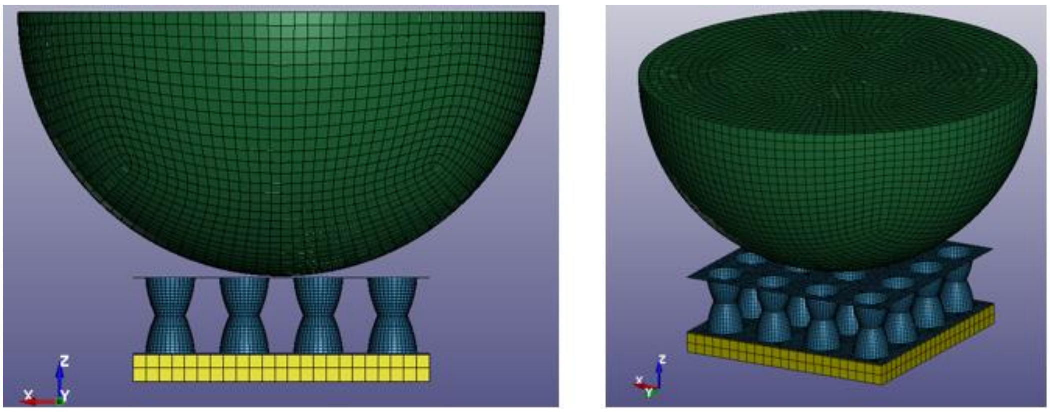

Fig.2: Finite Element Models of The Equivalent Product and Other Parts to Simulate the Drop Test

In the analyses, the floor plate has been fixed from the bottom surface for all degrees of freedom. A rigid impactor, consisting of a 9 kg weight and an 80 mm radius hemisphere, was launched at a speed of 4.13 m/s onto the sample. This designed analysis scenario was created based on the tests and analyses conducted in the reference article.

In the analysis model, steel material definitions have been made for both the floor plate and rigid impactor components. For these definitions, **`*MAT001-ELASTIC`** has been used for the floor plate component, while **`*MAT020-RIGID`** material cards have been used for the rigid impactor component. **`*MAT027 Mooney-Rivlin (*MAT_MONEY-RIVLIN RUBBER)`** material model was used for shock absorbing mats in the analysis. The **`*MAT027`** material model in LS-DYNA® can be simulated with the help of two parameters with methods suitable for hyperelastic behavior. In the first stage of the study, optimization analyses were performed in LS-Opt® software to find the Mooney-Rivlin coefficients. After the optimizations for this scenario, the material parameters presented in Figure 3 were found.

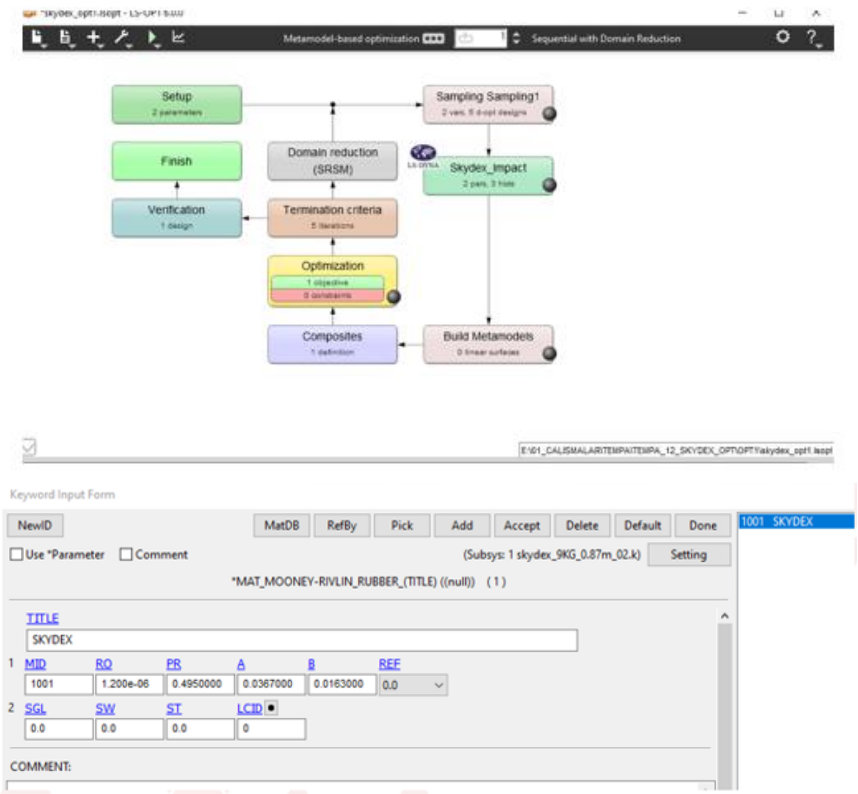

Fig.3: Finding Flow Chart and Material Parameters Used in Ls-Opt Software

After obtaining the parameters, the **`*MAT027`** material card was defined for the equivalent floor mat, and the drop analysis scenario was solved again. Comparisons were made with the results of the drop test conducted in the reference article. Force-displacement curves were used for comparing the analysis and test results. When examining the curves, it was observed that the part defined with the **`*MAT027`** material card created using LS-Opt® software exhibited behavior like the test results. Force-displacement curves for the test and analysis results are provided in Figure 4.

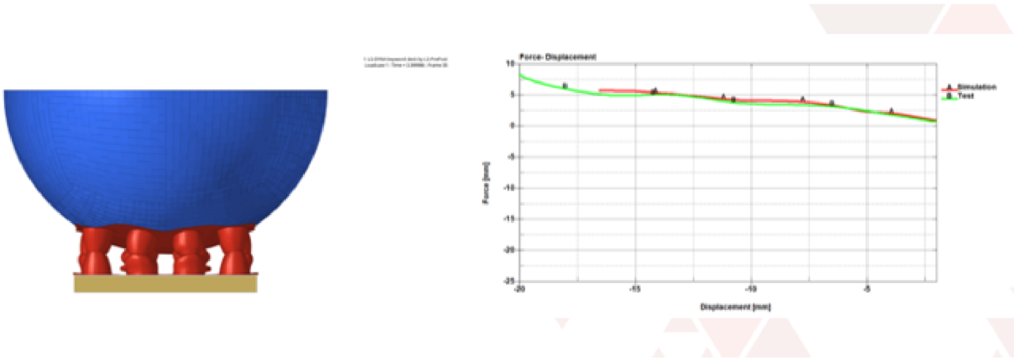

Fig.4: Force-Displacement Curves of Test and Analysis Results

4 Analyses of the Reference Model and Newly Design Model

In the second stage of the study, a single cell was considered for the equivalent product, a rigid mass of 1.07 kg was dropped onto a single cell with a speed of 5 m/s, and the analysis was performed and the force graph on the ground was obtained over time. The design of the single-cell reference model and the force-time graph obtained because of the analysis are presented in Figure 5.

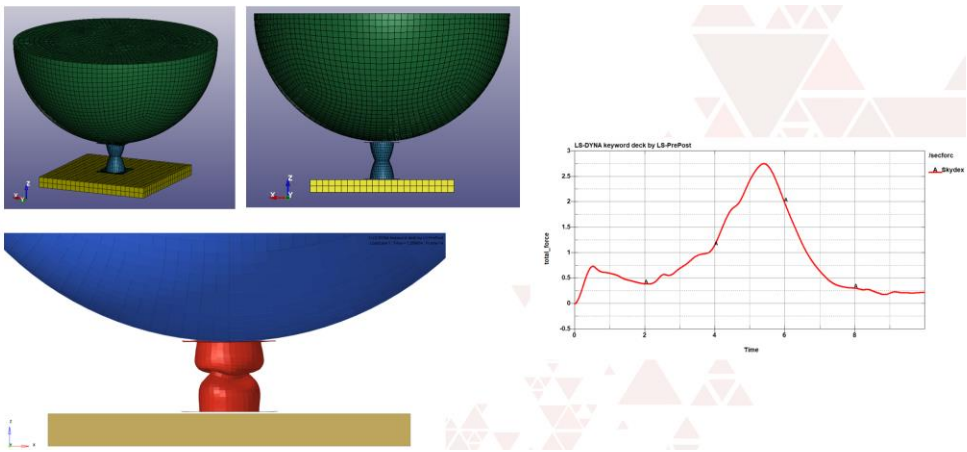

Fig.5: The Single Cell Reference Model and Force-Time Graph

In the continuation of the study, the cell structure in the newly designed geometries were analysed under the same boundary conditions, and the force-time graph was compared with a single cell of the equivalent material.

In this study, drop analyses were conducted for three newly designed cell structures. It is believed that variations in the thickness of the cells have a significant impact on energy absorption. Therefore, the drop analysis scenario was solved for three different thicknesses of the newly designed cells. Figure 6 illustrates the newly designed cell models.

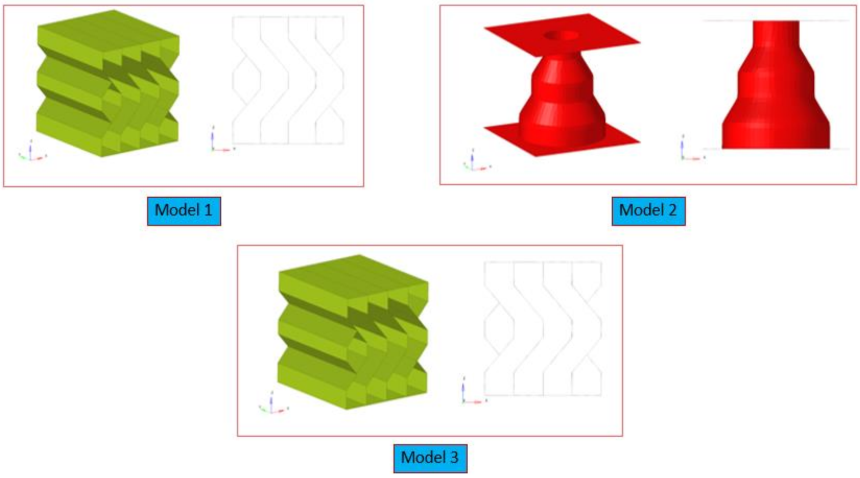

Fig.6: Newly Designed Models

Analyses were performed for the newly designed Model 1 with thicknesses of 0.75, 1, and 1.5 mm, and the results are presented in Figure 7, Figure 8, and Figure 9, respectively. When the results are examined, as expected, the design with the lowest thickness calculated the highest force. In the model with a thickness of 1.5 mm, similar maximum loads to the equivalent product were observed. Additionally, in this model, there was a slight improvement in energy absorption time compared to the equivalent product.

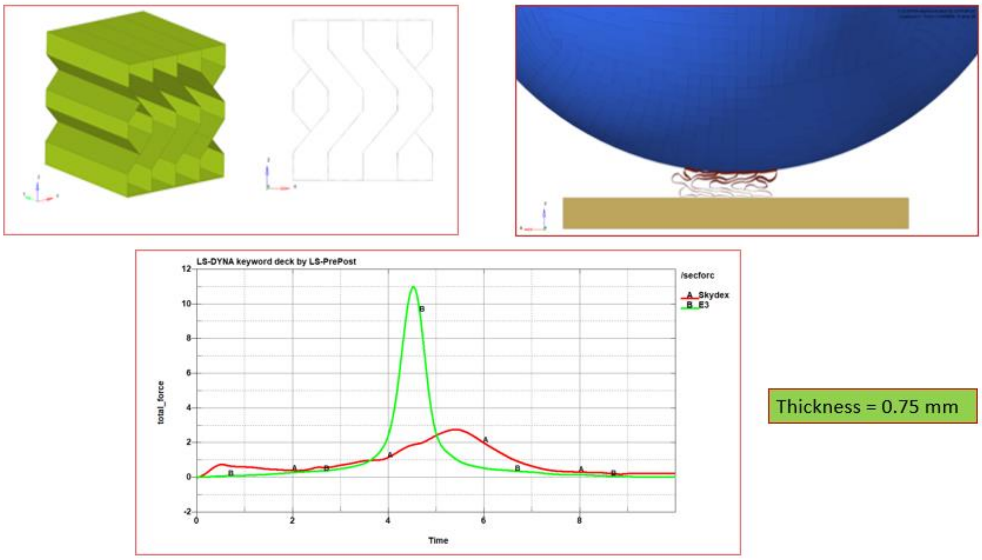

Fig.7: Newly Designed Model 1 (Thickness= 0.75 mm) and Force-Time Graph

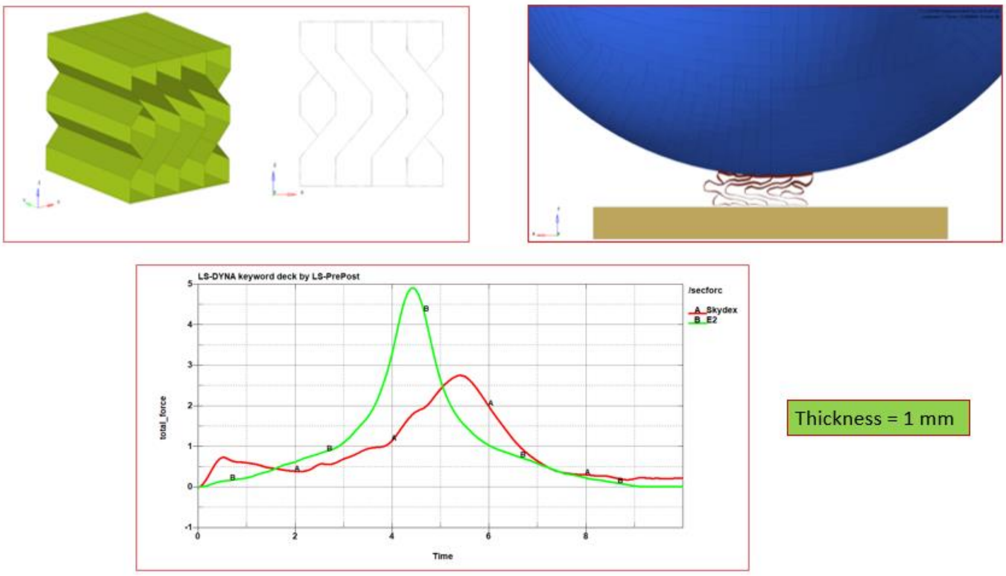

Fig.8: Newly Designed Model 1 (Thickness= 1 mm) and Force-Time Graph

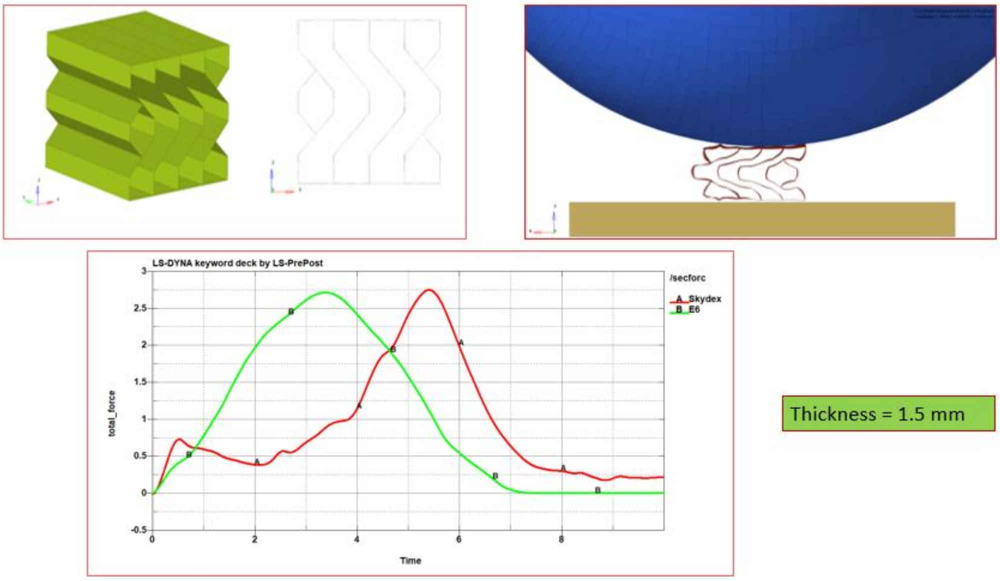

Fig.9: Newly Designed Model 1 (Thickness= 1.5 mm) and Force-Time Graph

Analyses were performed for the newly designed Model 2 with thicknesses of 1, 1.5, and 2 mm, and the results are presented in Figure 10, Figure 11, and Figure 12, respectively. When the results of the three thicknesses and the equivalent product are examined, it is observed that the product with a thickness of 1.5 mm provided the best results both in reducing the maximum load generated and extending the energy absorption time.

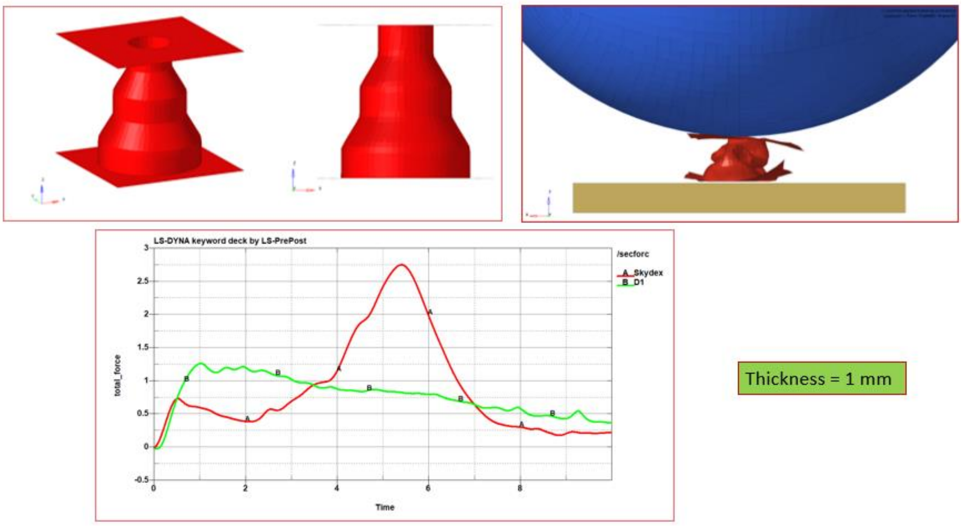

Fig.10: Newly Designed Model 2 (Thickness= 1 mm) and Force-Time Graph

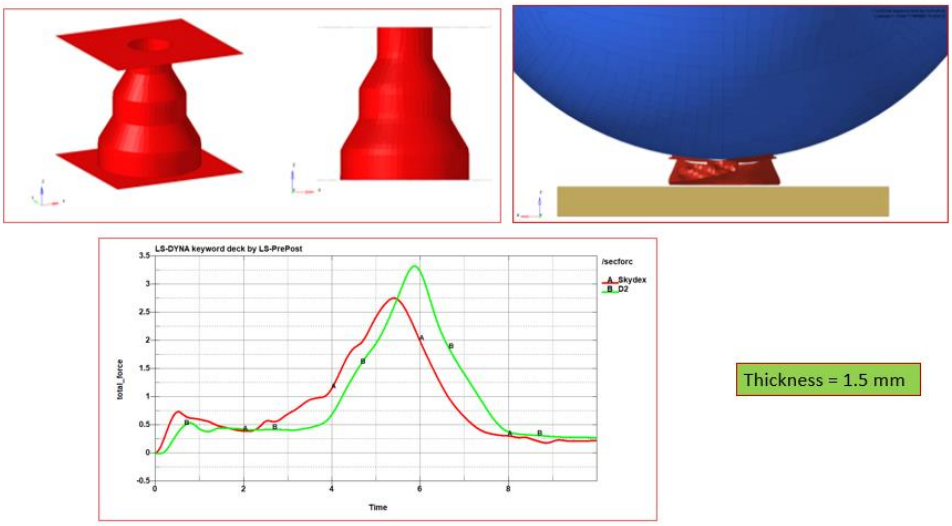

Fig.11: Newly Designed Model 2 (Thickness= 1.5 mm) and Force-Time Graph

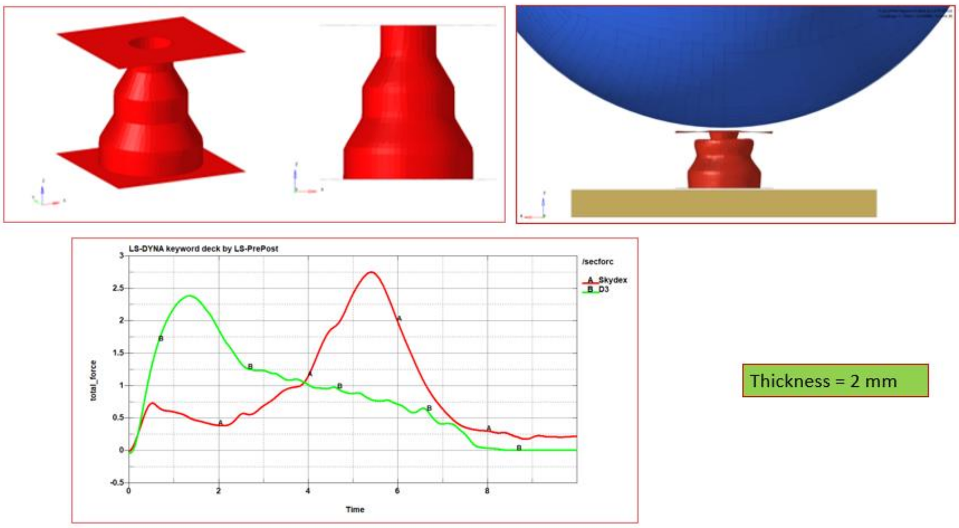

Fig.12: Newly Designed Model 2 (Thickness= 2 mm) and Force-Time Graph

Analyses were performed for the newly designed Model 3 with thicknesses of 1, 1.5, and 2 mm, and the results are presented in Figure 13, Figure 14, and Figure 15, respectively.

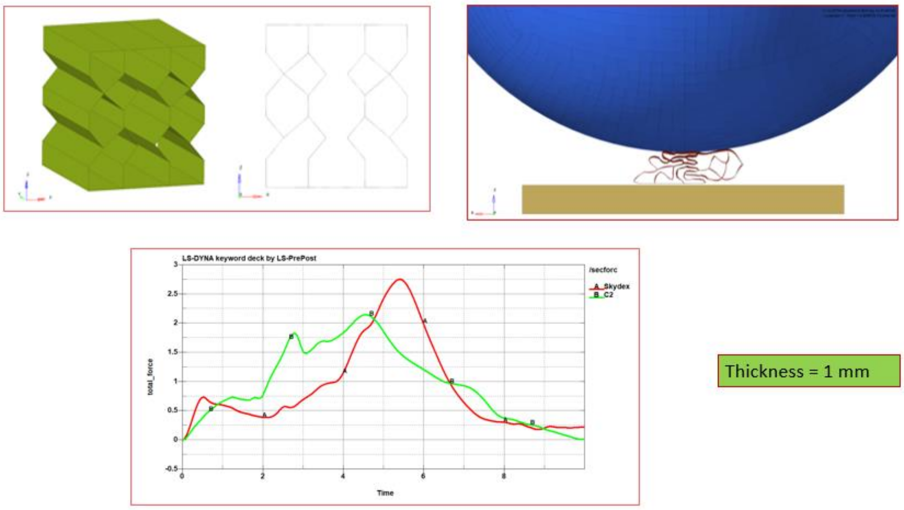

Fig.13: Newly Designed Model 3 (Thickness= 1 mm) and Force-Time Graph

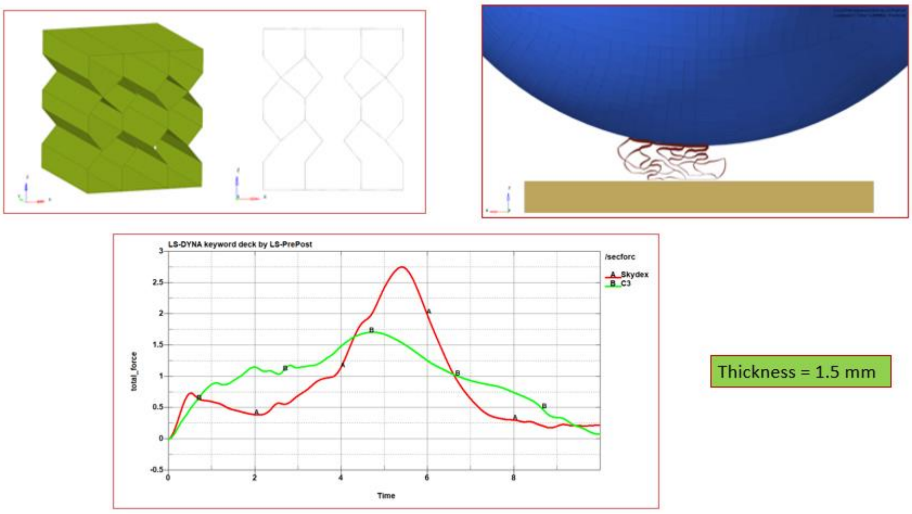

Fig.14: Newly Designed Model 3 (Thickness= 1.5 mm) and Force-Time Graph

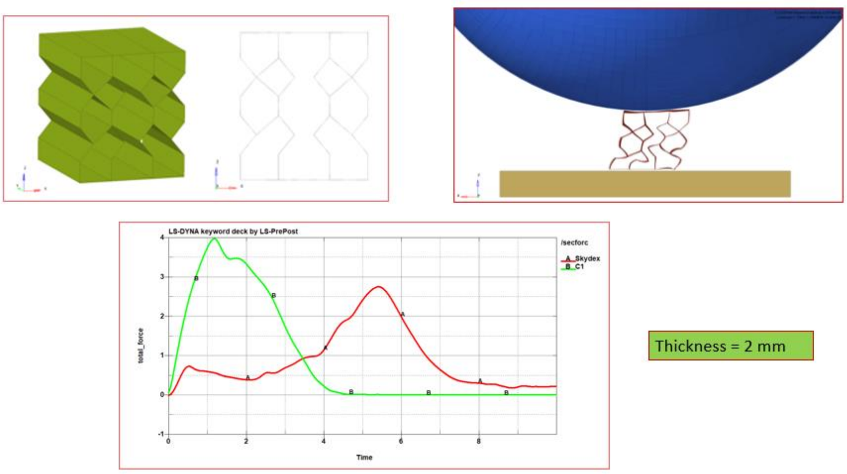

Fig.15: Newly Designed Model 3 (Thickness= 2 mm) and Force-Time Graph

5 Summary and Future Works

The drop analyses of the newly designed structures for shock-absorbing mats were conducted using models created based on the evaluation of test and analysis results from the reference article. The results were compared with the analysis results obtained with the equivalent product. Additionally, for mats made from hyperelastic materials, a **`*MAT027`** material card definition was established. In this definition, optimization studies were conducted with the help of the LS-Opt® program for the two required parameters. It is believed that to control dynamic loads at high speed and amplitude to the desired level, it is necessary to extend the duration of the impact, reducing the amplitude of the load. Therefore, reducing the maximum load on the structure and extending the energy absorption time is critical for a successful shock absorber. When the graphs were examined, it was observed that among the newly designed products, model 2 with a thickness of 1 mm provided the best reduction in the maximum load and increase in energy absorption time. In future studies, the behavior of the newly designed products under simulated test conditions will also be examined and compared with simulation results.

6 Literature

[1] Jiang B., Zhu B., Jin X., Cao L., Yang K. H., “Computaional modeling of the crushing behavior of SKYDEX material using Homogenized Material Laws”, Composite Structures, 106, 2013, 306-316.

[2] Oi H. J., Boyce M. C., “Stress – Strain behavior of thermoplastic polyurethanes”, Mechanics of Materials, 8, 2004, 817-839.