Numerical Performance Investigation of Modified NPR Bumper System Crashworthiness

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Abstract

This study presents a numerical investigation for crashworthiness and effectiveness of modified automobile bumper system incorporating Negative Poisson's Ratio (NPR) structure. Frontal, rear and side collisions are the most common crash scenario. In the event of a frontal crash, vehicle damage improvement and passengers' safety in an automobile was analyzed using finite element model developed in ABAQUS 2017. Negative Poisson Ratio (NPR) of honeycomb structure was integrated with a conventional bumper system and its performance was assessed under varying impact velocities and NPR thicknesses. FEA model validation against experimental results demonstrated good agreement. Findings indicate that the modified NPR bumper system significantly enhances crashworthiness and effectiveness compared to the conventional bumper system in several parameters. Parametric analysis revealed optimal improvements in crashworthiness indicators particularly for NPR thicknesses up to 1.1 mm, while excessive thickness reduced crashworthiness due to mass effects. Energy absorption (EA) of the NPR bumper system improved by approximately 3-16%, depending on the NPR thickness. Due to increased weight the system showed lower SEA which can be mitigated by reducing the thickness of the main bumper. The results highlight the potential of NPR structures to improve vehicle passenger's safety and mitigate structural damage.

Keywords
NPR, FEA, Crashworthiness, Bumper System, Numerical Analysis

1. Introduction
Advanced transportation demands in modern life is increasing on a daily basis which led to continuously increasing numbers of vehicles. Vehicular crash accidents have also increased and inevitably become an alarming worldwide safety issue. Vehicle's structures should be able to protect occupants through converting most of the kinetic energy during a crash situation into other forms of energy in a predictable and controllable fashion. The capability of a structure to manage and absorb the force of a serious crash and to reduce death and injury risk of the occupants is known as crashworthiness. Vehicle manufacturers continually compete to enhance performance and safety. As a result, crashworthiness has become a key research focus aimed at developing vehicles that protect occupants and reduce fatalities during collisions (Abdullah et al., 2020). Bumper structure is a crucial energy-absorbing component that enhances vehicle safety during frontal and rear collisions. New materials and structures particularly those with Negative Poisson's Ratio (NPR) are being adopted to improve crashworthiness. NPR structures are lightweight, offer superior energy absorption and reduce both vehicle weight and production costs in automotive and aerospace applications (Sun et al., 2019).

1.1 Objectives
In this research, the frontal crash situation was considered. The dynamic impact test on the cross beam or bumper was investigated using FEA software and validated with the experimental results that are available in the literature. The

NPR structure was introduced at the front of the beam to investigate the crashworthiness of the modified bumper system. Then the effectiveness of the modified NPR bumper system was analyzed for various thickness of NPR strips.

2. Literature Review

Structures with Negative Poisson's Ratios (NPR) are widely used in engineering for efficient energy absorption and weight reduction. Research has shown that NPR structures significantly enhance performance, leading to their growing adoption across various industries and applications.

In literature, different types of crush box structures were reviewed and summarized on basis of several research articles (Abdullah et al., 2020). High strength steel in cross beam, frontal rail and side beam of a car to test the crashworthiness of the system both experimentally and numerically and compared them according to the parameters of crashworthiness as well as parametric analysis was done changing of thickness, yield strength and impact velocity to develop effective and cost-efficient model (Sun et al., 2019). Bumper system was designed attaching NPR structure in the frontal part of the existing bumper system and safety analysis was done for collision with pedestrian's lower leg (C. Y. Wang et al., 2018). Bumper system of automobile is modified using built in origami patterns to improve the energy absorption of the bumper system for vehicle safety and parametric investigation at low and high impact velocities was performed (Yuan et al., 2019). Numerical investigation on composite bumper system in high-speed frontal crash situations as well as parametric analysis was performed varying the type of material, thickness and layup of the composite (Zeng et al., 2016). Frontal bumper beam of automobile was modified using carbon fiber composite material to analyze the displacement, stress analysis and optimize the design of the frontal bumper system (Godara & Nagar, 2019). Hybrid glass/carbon composite bumper beam was designed and manufactured via design optimization process as well as impact analysis was performed to investigate the performance improvement (Kim et al., 2015). Design of bumper system was optimized considering multiple impact loading conditions using experimental and numerical investigation for improved intrusion and energy absorption under different low speed impacting conditions (Sun et al., 2021). Crashworthiness and design optimization of the crash box was analyzed integrating the crash box with an outer thin-walled tube and inner Negative Poisson's Ratio (NPR) cellular core under axial load at different geometric parameters using impact simulation (T. Wang et al., 2020). Investigation of the crashworthiness of novel cylindrical Negative Poisson's Ratio (NPR) structure under axial impact loading (Gao et al., 2020). Performance investigation of traditional crash box and Negative Poisson's Ratio (NPR) structure filled core crash box and parametric analysis for the design optimization (Zhou et al., 2016). Negative Poisson's Ratio (NPR) effect of novel honeycomb structures was investigated performing elastic analysis based on the standard beam theory as well as compressive tests on the structure made with aluminum alloy were performed with different geometrical parameters to verify the theoretical analysis (Zhang et al., 2013). Deformation and failure modes of honeycomb structures were studied comparatively by in-plane uniaxial compression loading behavior of regular honeycomb, re-entrant auxetic honeycomb, locally reinforced auxetic-strut structure and a hybrid structure of combining regular honeycomb and auxetic-strut structure on 3D printed samples (Ingrole et al., 2017). Honeycomb NPR structures were designed and tested the energy absorption property of the NPR structures and how this property can be improved (Correa et al., 2015). Two-dimensional and three-dimensional auxetic geometries using Computer Aided Design tools comparatively studied using Finite Element Analysis (FEA) software and the behavior of the different auxetic geometries and elaborate a systematic comparison, considering relevant properties of these geometries (Álvarez Elipe & Díaz Lantada, 2012).

Based on the above literature review, it can be said that the research on NPR-based bumper should be advanced further. Therefore, this work integrates NPR with traditional bumper and investigates its crashworthiness through numerical analysis.

3. Methods

Crashworthiness is defined as the ability of materials to absorb impact energy by means of controlled failure mechanisms and modes. It is the capability of an automotive structure to safeguard its occupants or structure in the event of an impact. This refers commonly to the ability of a structure to absorb the impact's kinetic energy through a controlled and anticipated deformation, converting it into inelastic strain energy, heat, and fracture energy.

There are several crashworthiness indicators that are commonly used in the analysis of any structural crash situation. Among various indicators for structural crashworthiness evaluation, the total energy absorption is commonly used which is given by (Sun et al., 2019)

$$E_a = \int_0^d F(x)dx,$$

where $F(x)$ is the instantaneous crash force corresponding to the crash distance x. E_a can be calculated based on the area under the force-displacement curve obtained from the crushing test (Sun et al., 2019).

The specific energy absorption (SEA) is given by

$$SEA = \frac{E_a}{M},$$

where M is the total mass of the structure, and denotes the total energy absorbed in the course of crushing deformation. Crush force efficiency (CFE) is employed to measure the uniformity of progressive deformation; and a higher value indicates higher energy absorption efficiency (Sun et al., 2019), which is defined as,

$$CFE = 100 \times \frac{F_{avg}}{F_{max}} \%$$

where, F_{max} is the maximum value of $F(x)$ during the entire crushing process. F_{avg} represents the mean crash force, and can be calculated by dividing the total energy absorption by a given crash displacement d (Sun et al., 2019) as,

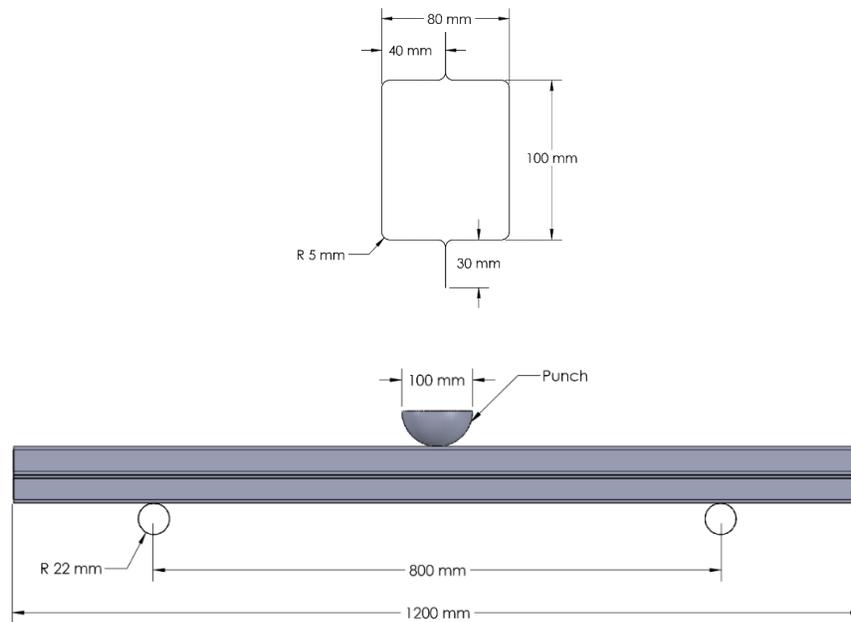$$F_{avg} = \frac{E_a}{d}$$

3.1 Geometric Model

Figure 1. Dimensions of the geometric model (Sun et al., 2019)

For geometric modeling of the conventional and modified NPR bumper system ABAQUS 2017 was used. The shapes and dimensions of the double-hat specimen were determined by referring to real vehicle structures (Sun et al., 2019). As illustrated in Figure 1, the height, width, and wall thickness of the hat structure are $40, 100,$ and $1.6\ mm$ respectively. The width of the flanges is $30\ mm$. The corner radius at the edges of hat structures is $5\ mm$. Under the lateral impact, the total length of the hat structure is $1200\ mm$. The double hat structures were placed on the two cylindrical supporters with $44\ mm$ in diameter and $800\ mm$ in span. The specimen was impacted at the mid-span by a cylindrical rigid punch at $5, 10\ and\ 15\ ms^{-1}$ impact velocities. The diameter of the punch is $100\ mm$ and the inertia mass is $18.3\ kg$.

The conventional bumper system was modified with Negative Poisson Ratio (NPR) structure and was designed using honeycomb unit cells.
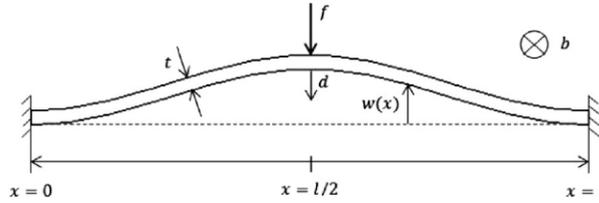
Figure 2. Height of the curvature of honeycomb unit cell curved beam (Correa et al., 2015)

The cell dimensions were adopted from (Correa et al., 2015) shown in Figure 2 for curved beam and in Figures 3 for full cell. The height of the curvature was defined by the equation (Correa et al., 2015)

$$w(x) = \frac{h}{2}\left[1 - \cos\left(2\pi\frac{x}{l}\right)\right].$$

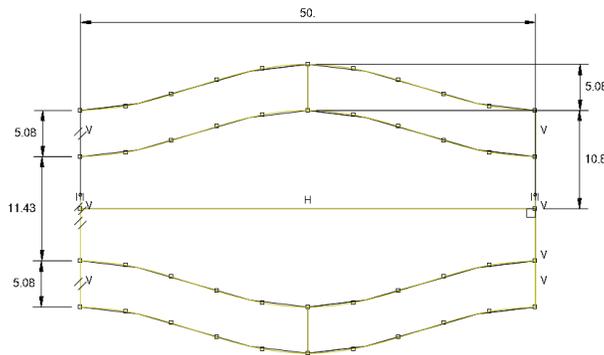Figure 3. Height of the curvature of honeycomb unit cell (Correa et al., 2015)

The unit cells were designed as deformable type shell instances. Honeycomb unit cells were linearly patterned maintaining zero gap between the unit cells as shown in Figure 4. A front plate of 1.6 mm thickness was attached to the NPR structure. The thickness of the NPR structure was varied for the parametric analysis to determine the effective crashworthiness parameters.
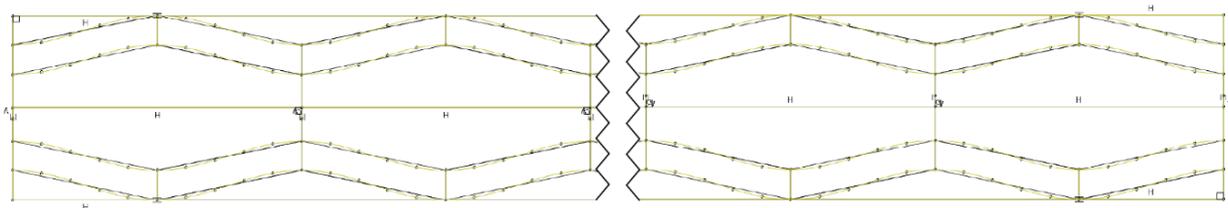

Figure 4. NPR Structure for modifying bumper system

3.2 Material Properties
The material considered for hat structure and the NPR structure in this analysis is DP590 whose properties are as follows.

Table 1. Mechanical Properties of DP590 (Sun et al., 2019)

Material	Density ρ (g/cm^3)	Young's Modulus E (GPa)	Poisson's Ratio v	Yield Strength (MPa)
DP 590	7.90	210	0.3	418

True stress and true strain data from quasi-static, 1, 100, 300, and 800/s strain rates were considered and were adopted from (Sun et al., 2019).

3.3 Finite Element Modeling

For numerical performance investigation of the crashworthiness of conventional and modified NPR bumper systems, a numerical model was developed in ABAQUS 2017. The hat structure was modeled using deformable-type shell elements and the punch and cylindrical supports were discrete rigid-type shells. The thickness of the hat structure was assigned in the section module. The static friction coefficient, kinetic friction coefficient, and decay coefficient were respectively 0.3, 0.2, and 0.5 (Sun et al., 2019). General contact (Explicit) – All* with self was defined between all the instances and friction formulation was defined as the Static Kinetic Exponential Decay method. Rigid body constraint was defined for the punch and support rollers. Two flanges of the hat structures were attached together by tie constraint. Dynamic - Explicit solver was used for crash analysis. Both support rollers were fixed at their positions. Punch displacement was restricted in all directions except the direction of velocity and the magnitude was defined under the predefined field. The NPR Structure was also modeled using deformable-type shell elements along with the front and bottom plate. The bottom plate is attached to the hat structure using a tie constraint. A representative figure of the bumper with NPR structure is shown in Figure 5.
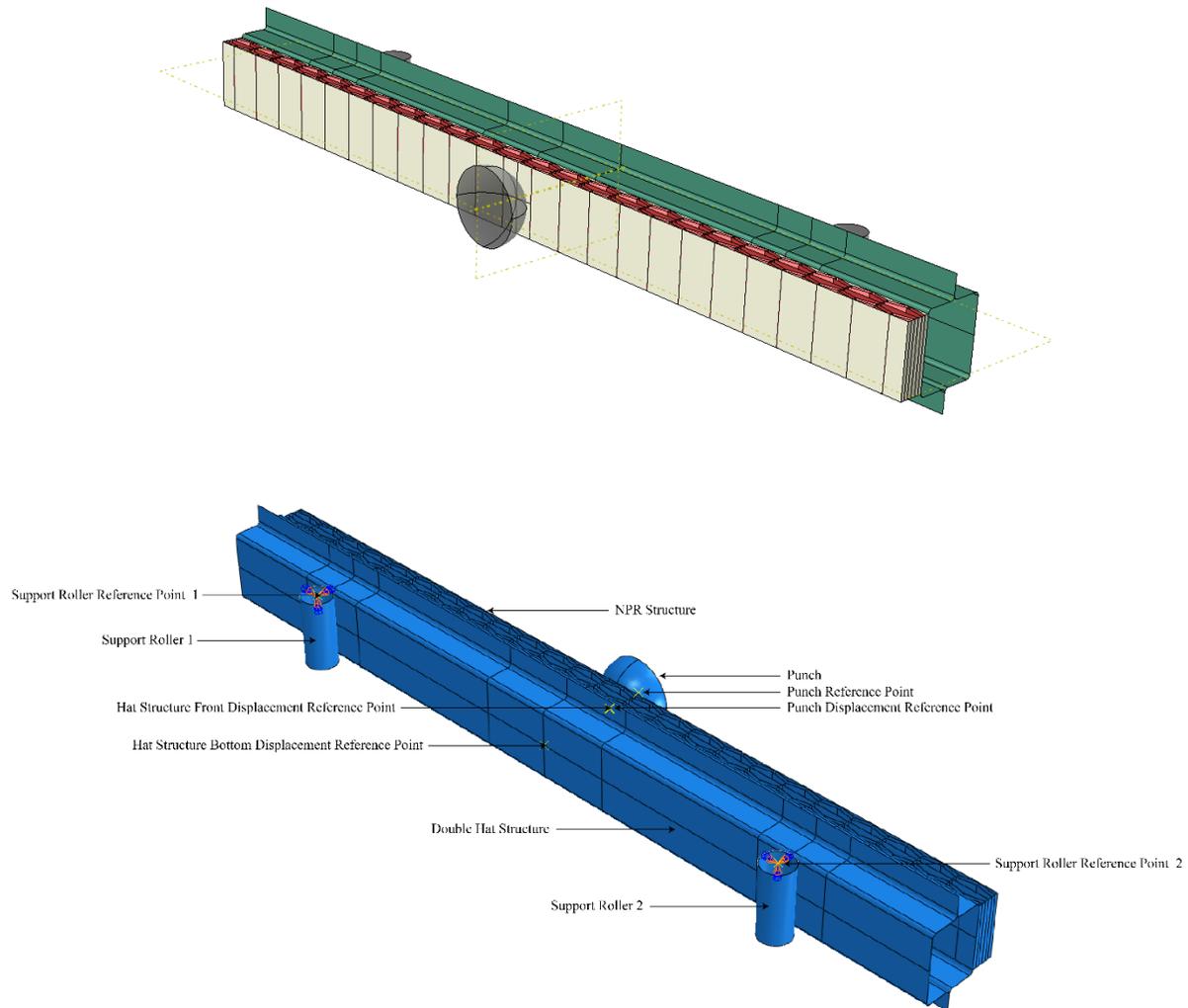
Figure 5. Numerical modeling of bumper system boundary conditions and loading

3.4 Mesh Dependency Analysis and Validation

The instances are meshed with 4-node Quad Linear Explicit elements which are referred to as S4R elements in the ABAQUS manual (*Four-Node Shell Element (S4 and S4R)*, n.d.). The finite element model was analyzed at different mesh sizes such as 1x1 mm, 2x2 mm, 3x3 mm, and 4x4 mm for mesh dependency analysis. But there were no significant changes in the results with the change in mesh size as shown in Figure 6.
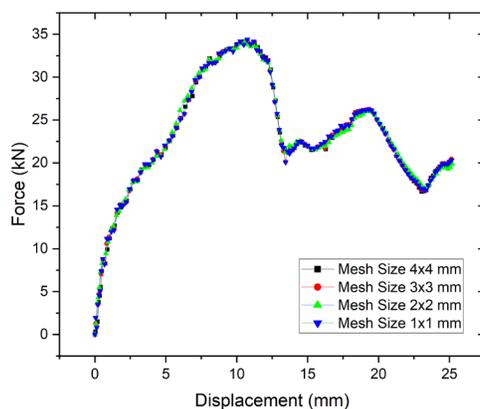
Figure 6. Mesh dependency results of the finite element model

Results obtained from finite element (FE) analysis were compared with the experimental analysis results of reference (Sun et al., 2019) at 15 m/s impact velocity for validation. The trend of the force-displacement curve achieved in the present analysis is in good agreement with the experimental results as shown in Figure 7.
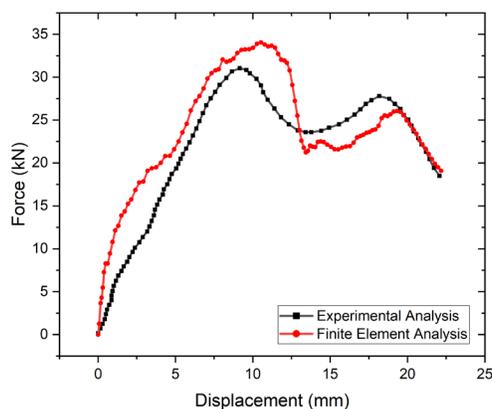

Figure 7. Validation of FEA results with experimental results.

5. Results and Discussion

The reaction force at the support rollers is plotted as a function of punch displacement for three impact velocities and various NPR thicknesses and is given in Figure 8. The conventional bumper beam shows a lower peak reaction force compared to the NPR bumper beam of all thicknesses at all three velocities. The peak force reduced with the decreasing NPR structure thickness. For any impact velocity and for a given displacement up to the peak reaction force, the NPR bumper beam shows a higher force compared to the conventional bumper beam. This indicates a higher energy absorption capacity of the NPR bumper beam. It can also be seen from Figure 8 that the punch displacement is reduced with the integration of NPR in the bumper beam. The lower displacement provides better safety for automobile components.
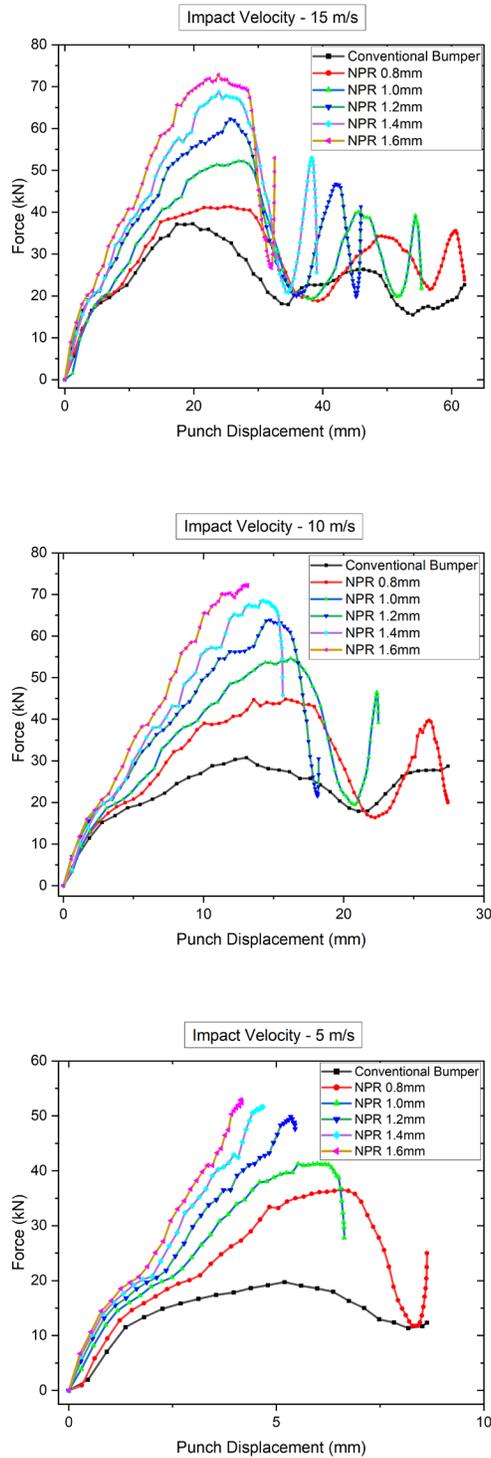
Figure 8. The reaction force as a function of punch displacement for impact velocities (a) 15 m/s, (b) 10 m/s, and (c) 5 m/s.

Total energy absorption (EA) is obtained after modifying the bumper beam with NPR Structure and plotted as a function of NPR thickness for three impact velocities. EA is found significantly greater in modified NPR bumper beams than the conventional one in all scenarios except for 10 m/s and 5 m/s impact velocities with 1.6 mm NPR

thickness. This is a significant improvement in the crashworthiness parameter, indicating that NPR integrated bumper improves energy absorption performance. It is also observed that Energy Absorption (EA) is decreasing with the increasing thickness of the NPR structure. NPR structure of lower thicknesses has performed relatively better than the NPR structure of higher thicknesses in terms of energy absorption. Modified NPR bumper beam appears to absorb a large amount of kinetic energy during a crash situation which can provide enhanced safety for occupants and vehicle structure from severe damage (Figure 9).
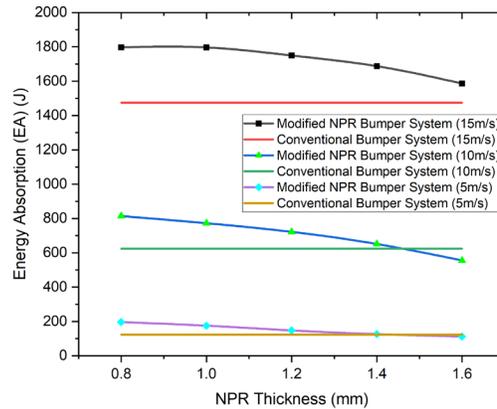

Figure 9. Total energy absorption as a function of NPR thickness.

CFE is inversely related to the size of the peak on a force-displacement curve and a larger peak reduces the CFE, offering the least amount of protection, while a smaller peak increases the CFE to its maximum, offering the most amount of protection (*Crush Force Efficiency &Specific Energy Absorption | Multiscale Systems*, n.d.). The crush force efficiency (CFE) of the bumper beams is given as a function of NPR thickness in Figure 11. The CFE is found to be significantly lower than the conventional bumper beams for NPR thicknesses greater than 0.8 mm for all impact velocities. It is observed that the CFE of the NPR bumper beam is greater than the conventional bumper beam for an NPR thickness of 0.8 mm at an impact velocity of 15 m/s. The CFE appears to be increasing with increasing impact velocity for all NPR thicknesses. It indicates that the NPR bumper beam is effective at higher impact velocities. The CFE dropped significantly in the modified NPR bumper beam due to their larger peak forces and small average crashing forces as shown in Figure 8. It decreases with the increasing thickness of the NPR structure. A small CFE can cause instability and less amount of protection for vehicle structure and occupants which can be improved using airbags, and other safety features (Figure 10).
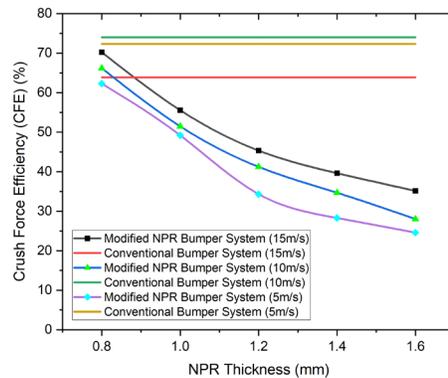

Figure 10. Crash force efficiency as a function of NPR thickness for three impact velocities.

Conventional bumper beam absorbs collision energy during a crash situation. In a modified NPR bumper beam, the NPR structure absorbs the energy up to a certain level during crash situations and protects the conventional bumper and other structural components of the vehicle. So, a lower punch displacement and impact time for a constant impact velocity would provide better safety for the occupants and the car's internal components. After modification of the conventional bumper beam with NPR structure, a significant improvement is observed in punch displacement and impact time in all impact scenarios. Maximum punch displacement and impact time are given as a function of NPR thickness for three impact velocities in Figure 12(a) and (b) respectively. The punch displacement and impact time decrease with increasing the NPR thickness and they are found to be significantly lower in the modified NPR bumper beam due to the energy absorption capability of the NPR structure. This is not always desired that the punch displacement and impact time should be lower because the peak impact force would increase significantly which will result in lower crash force efficiency as discussed earlier. Therefore, a compromised decision should be made between the maximum punch displacement and time, and the crash force efficiency. However, in this work, the NPR structure with 0.8 mm thickness would provide benefits in terms of CFE, maximum punch displacement, and impact time because in this design the CFE is higher while the maximum punch displacement and impact time are lower than the conventional bumper beam (Figure 11).
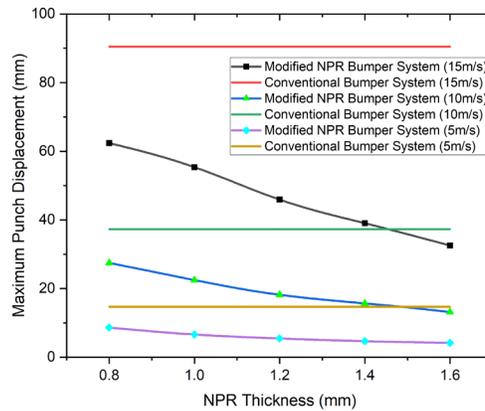
(a)
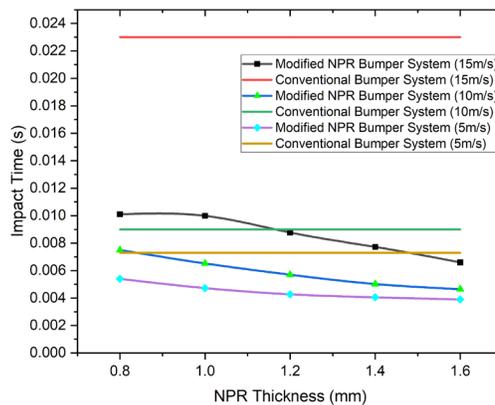
(b)

Figure 11. (a) Maximum punch displacement and (b) impact time as a function of NPR thickness.

Specific energy absorption (SEA) indicates whether a structure is lightweight or not. In Figure 13, the SEA is given as a function of NPR thickness for three impact velocities. It appears that the SEA for the NPR bumper beam is significantly lower than the conventional bumper for all scenarios. As the NPR structure adds a large amount of mass which reduces the SEA despite a significant increase in energy absorption. However, The SEA may be improved by utilizing a lightweight and highly elastic material for NPR structures as well as modification of the hat structure which would be a topic for future research to get the benefit of integrating NPR structure in the automobile bumper beam (Figure 12)
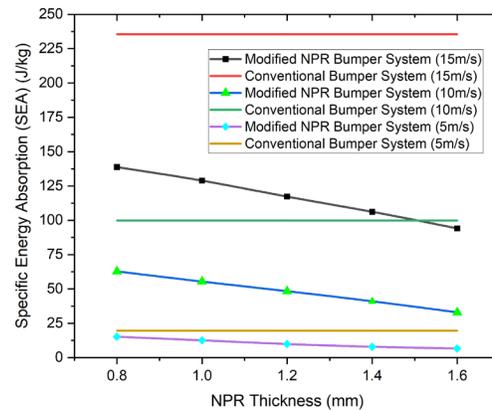

Figure 12. Specific energy absorption as a function of NPR thickness.

6. Conclusion

Incorporating a Negative Poisson's Ratio (NPR) structure with a conventional bumper system significantly improves crashworthiness and effectiveness in frontal impact scenarios. Improvement in crashworthiness parameters were obtained in all NPR thickness for all three impact velocities 5 m/s, 10 m/s and 15 m/s. Modified NPR bumper system exhibits enhanced energy absorption, lower punch displacement and shorter impact duration compared with conventional automobile bumper system. Parametric results indicate that optimal performance is achieved for NPR thicknesses up to 1.1 mm, while further increases in thickness reduce efficiency due to additional mass. An improvement of approximately 3-16% in energy absorption (EA) was observed for the NPR bumper system, depending on the NPR thickness. However, the SEA was found to be lower for NPR bumper system due to increased weight which may be further improved by reducing the thickness of the main bumper. These findings confirm the potential of NPR structures to strengthen vehicle crash safety by mitigating structural deformation and improving passengers' protection. The application of lightweight and high-strength NPR structures can significantly improve specific energy absorption and further advance crash performance.

References

Abdullah, N. A. Z., Sani, M. S. M., Salwani, M. S., and Husain, N. A., "A review on crashworthiness studies of crash box structure," *Thin-Walled Structures*, vol. 153, 2020, doi: 10.1016/j.tws.2020.106795.

Álvarez Elipe, J. C., and Díaz Lantada, A., "Comparative study of auxetic geometries by means of computer-aided design and engineering," *Smart Materials and Structures*, vol. 21, no. 10, 2012, doi: 10.1088/0964-1726/21/10/105004.

Correa, D. M., Seepersad, C. C., and Haberman, M. R., "Mechanical design of negative stiffness honeycomb materials," *Integrating Materials and Manufacturing Innovation*, vol. 4, no. 1, pp. 165–175, 2015, doi: 10.1186/s40192-015-0038-8.

Crush Force Efficiency & Specific Energy Absorption (CFE & SEA), *Multiscale Systems*, n.d. [Online]. Available: multiscalesystems.com

Four-node shell element (S4 and S4R), *CalculiX Documentation*, n.d. [Online]. Available: web.mit.edu

Gao, Q., Zhao, X., Wang, C. Z., Wang, L. M., and Ma, Z. D., "Crashworthiness analysis of a cylindrical auxetic structure under axial impact loading," *Science China Technological Sciences*, vol. 63, no. 1, pp. 140–154, 2020, doi: 10.1007/s11431-018-9467-6.

Godara, S. S., and Nagar, S. N., "Analysis of frontal bumper beam of automobile vehicle by using carbon fiber composite material," *Materials Today: Proceedings*, vol. 26, pp. 2601–2607, 2019, doi: 10.1016/j.matpr.2020.02.550.

Ingrole, A., Hao, A., and Liang, R., "Design and modeling of auxetic and hybrid honeycomb structures for in-plane property enhancement," *Materials & Design*, vol. 117, pp. 72–83, 2017, doi: 10.1016/j.matdes.2016.12.067.

Kim, D. H., Kim, H. G., and Kim, H. S., "Design optimization and manufacture of hybrid glass/carbon fiber reinforced composite bumper beam for automobile vehicle," *Composite Structures*, vol. 131, pp. 742–752, 2015, doi: 10.1016/j.compstruct.2015.06.028.

Sun, G., Deng, M., Zheng, G., and Li, Q., "Design for cost performance of crashworthy structures made of high strength steel," *Thin-Walled Structures*, vol. 138, pp. 458–472, 2019, doi: 10.1016/j.tws.2018.07.014.

Sun, G., Wang, X., Fang, J., Pang, T., and Li, Q., "Parallelized optimization design of bumper systems under multiple low-speed impact loads," *Thin-Walled Structures*, vol. 167, 2021, doi: 10.1016/j.tws.2021.108197.

Wang, C. Y., Wang, W. W., Zhao, W. Z., Wang, Y., and Zhou, G., "Structure design and multi-objective optimization of a novel NPR bumper system," *Composites Part B: Engineering*, vol. 153, pp. 78–96, 2018, doi: 10.1016/j.compositesb.2018.07.024.

Wang, T., Li, Z., Wang, L., and Hulbert, G. M., "Crashworthiness analysis and collaborative optimization design for a novel crash-box with re-entrant auxetic core," *Structural and Multidisciplinary Optimization*, vol. 62, no. 4, pp. 2167–2179, 2020, doi: 10.1007/s00158-020-02568-6.

Yuan, L., Ma, J., and You, Z., "Energy absorption capability of origami automobile bumper system," *Proc. Inst. Mech. Eng. Part C: Journal of Mechanical Engineering Science*, vol. 233, no. 18, pp. 6577–6587, 2019, doi: 10.1177/0954406219862307.

Zeng, F., Xie, H., Liu, Q., Li, F., and Tan, W., "Design and optimization of a new composite bumper beam in high-speed frontal crashes," *Structural and Multidisciplinary Optimization*, vol. 53, no. 1, pp. 115–122, 2016, doi: 10.1007/s00158-015-1312-2.

Zhang, Z. K., Hu, H., and Xu, B. G., "An elastic analysis of a honeycomb structure with negative Poisson's ratio," *Smart Materials and Structures*, vol. 22, no. 8, 2013, doi: 10.1088/0964-1726/22/8/084006.

Zhou, G., Ma, Z. D., Li, G., Cheng, A., Duan, L., and Zhao, W., "Design optimization of a novel NPR crash box based on multi-objective genetic algorithm," *Structural and Multidisciplinary Optimization*, vol. 54, no. 3, pp. 673–684, 2016, doi: 10.1007/s00158-016-1452-z.

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