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A Comprehensive Investigation of Deformation, Equivalent Stress Responses, and Fatigue Characteristics of Diverse Materials in LPG Cylinders Under Impact Loading Through Simulation

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ABSTRACT

This study evaluates the structural performance of materials used in LPG cylinders under impact loads through numerical simulations using ANSYS Explicit Dynamics, focusing on both linear and nonlinear models for structural steel, aluminum alloys, and stainless steel. The primary objective is to examine the deformation, failure characteristics, and fatigue behavior of these materials under an impact velocity of 7.5 m/s. This study shows that nonlinear structural steel outperforms other materials in terms of endurance, displaying the best strength and the least amount of deformation at 0.0392 m. According to fatigue studies, aluminum alloys break down after 3042 cyclic cycles, while structural steel can withstand at least 10,007 cyclic loads. Structural steel exhibits a marginally higher average safety factor of 10.402 than aluminum alloys, while both materials reach a maximum safety factor of 15. These results highlight structural steel's outstanding performance, which makes it the best option for guaranteeing longevity and safety in LPG cylinders, particularly during transit. The study also highlights how crucial nonlinear material models are to effectively capture mechanical responses in the actual world. This research promotes the utilization of nonlinear structural steel in the design of LPG cylinders, hence improving safety and structural comprehension.

Keywords: LPG cylinder, Nonlinear structural steel, ANSYS explicit dynamics, Impact simulations, Fatigue analysis

1. Introduction

For safe use and transport of liquefied petroleum gas (LPG) cylinders, proper design is essential. Poor maintenance, incorrect installation, or the structural breakdown of the cylinders during transportation can be responsible for a number of incidents, including explosions brought on by gas leaks and inappropriate handling [1] [2]. Since LPG is frequently used in homes for cooking, particularly in Bangladesh, the material utilized to make these cylinders is crucial to their durability and safety [1]. Stainless steel and structural steel, which are both heavy and provide major transportation issues, are traditionally used to make LPG cylinders. The cylinders are frequently dropped as a result of this weight, creating internal stresses that may affect their structural soundness [4] [14].

In some recent studies LPG gas cylinder are analyzed as different approach. One study analyzed the physiochemical properties of LPG in Bangladesh, focusing on the propane-butane ratio, sulfur content, and calorific value. It found that the LPG mixtures met safety standards with low sulfur, no free water, and a favorable propane-butane ratio for the tropical climate [19]. Other the study compared the performance of LPG cylinders made from Low Carbon Steel and E-Glass Epoxy composites. Using SolidWorks for modeling and ANSYS for finite element analysis, it assessed deformation and stress under internal pressure to evaluate their structural efficiency [20].

The drawbacks of conventional steel cylinders have been suggested to be solved through the use of innovative materials such as composites and aluminum alloys. Because of their high strength-to-weight ratio and resilience to impact pressures, composite materials in particular have showed promise. [3] [9]. Conventional steel LPG cylinders are gradually being replaced with overwrapped composite pressure vessels because they are lighter and easier to handle. [4] [18]. These materials offer improved resistance to deformation, reduced weight, and longer fatigue life [9] [14].

To better understand the impact response of LPG cylinders, numerical simulations using tools like ANSYS Explicit Dynamics have been employed [10] [16]. This method helps determine the most effective material for LPG cylinders by allowing the investigation of multiple materials under a range of impact instances, including variations in impact angle and velocity [8] [10]. Studies has demonstrated that, in comparison to their linear counterparts, nonlinear structural materials provide superior fatigue life and deformation resistance. [12] [14]. This research aims to provide insights by simulating the impact behavior of different materials, into the most suitable materials for LPG cylinders to enhance their durability and safety [5] [6].

Evaluating the structural behavior of LPG cylinders under impact loads and suggesting design changes that include the application of stronger, lighter materials are the primary objectives of this study. [3] [9] [13]. This research will contribute to minimizing accidents during transportation,

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ensuring the safety of LPG cylinder usage, and ultimately promoting the adoption of advanced materials in the design of pressure vessels [1] [2] [8].

2. Methodology

In this study, the focus is placed on analyzing the impact behavior and fatigue life of various materials using ANSYS simulation. However, it involves various materials using structural steel, along with aluminum alloys (Al 6061 T6, Al 7075 T6) and stainless steel. The following flow sheet outlines the methodology and detailing the steps.

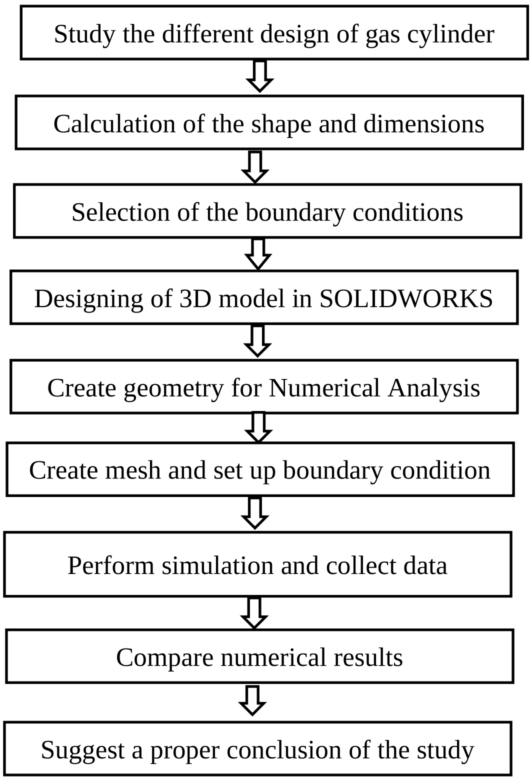


Fig.1 Flow chart of the study

2.1 Solid work design of LPG cylinder

The size and the meshing of a 2:1 semi-ellipsoidal head cylinder is shown in Figure 3.1. The stress analysis is done based on thickness. The ASME Boiler Pressure Code, Section-VIII is used to measure and calculate stresses in the cylinder [17]. Using SOLIDWORKS software a commercial LPG cylinder was constructed.

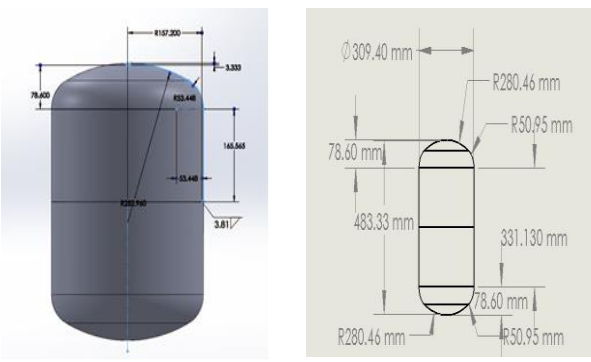


Fig.2 Solid work design of the LPG cylinder

2.2 Meshing of the design

Meshing is a process that breaks down any model into smaller manageable parts to allow for accuracy in the results. Free mesh was considered due to the sharp curves in the LPG cylinder geometry and an edge length of 6mm was selected for accuracy. On the other hand, smaller mesh sizes stretching from 9mm to 4.25mm were employed in a mesh independence test. Stress test results between the above sizes showed great variations between the 9mm and 6mm sizes while the smaller sizes did not greatly affect the results but rather consumed more time. Consequently, 6mm was found to offer the best mesh size for this research work. The simulation model consisted of 18102 nodes and 49605 elements respectively. Mesh is generated in ANSYS Student 2023 R1. Fig 3 shows the meshed model of the LPG cylinder commercialized system.

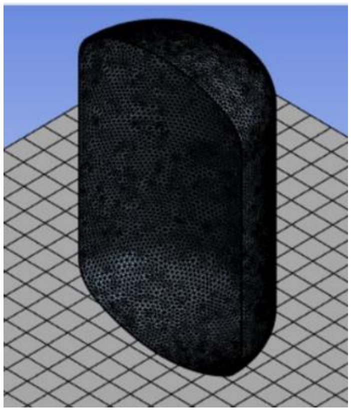


Fig.3 Meshing for semi-ellipsoidal head (2:1) cylinder

2.3 Boundary Condition

The model was initially created in SOLIDWORKS and later modified in Ansys Design Modeler. To ensure smooth simulation, the cylinder body was suppressed in two parts along the XY plane. Symmetry was applied to both the horizontal and vertical sections of the cylinder. The cylindrical body, which bears the load, is constrained to move only along the negative Y-axis, with all other movements restricted. For the free-fall condition, standard gravitational acceleration was applied, and a critical pressure of 2.5 MPa was exerted on seven inner faces of the cylinder. Therefore, a fixed horizontal plate was introduced for impact loading, with initial velocity of 7.5 m/s used for simulation cases.

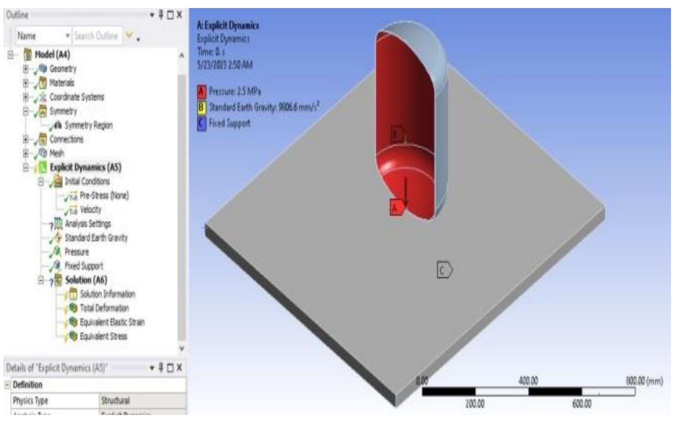


Fig.4 Boundary condition for the simulation

Comparing the results of the software to the previous numerical solution serves to validate the results. Equivalent stress (σv) of the current study and the previously simulated [18] equivalent stress is compared for validation for same boundary condition that is used for the simulation.

The following fig.5 shows the comparison of equivalent stress between current study and previous study.

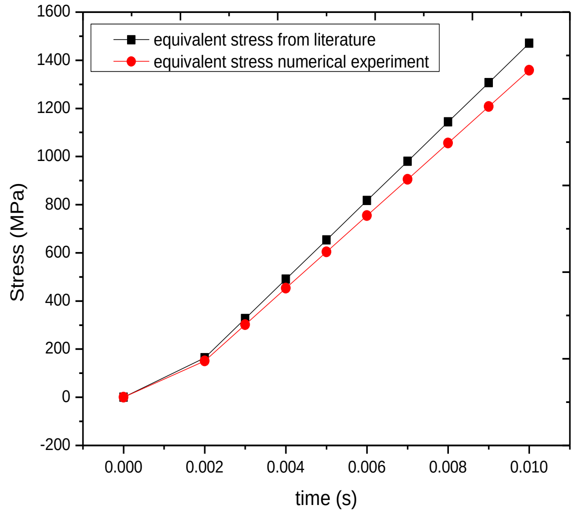


Fig.5 Graphical representation of equivalent stress with literature

According to the graph the average % of equivalent stress is 7.73 % which is accepted. By this calculation the following simulation is validated.

3. Result and Discussion

In this context, a comparison was made between three specific materials: Al 6061 T6, Al 7075 T6, and stainless steel. These materials were analyzed alongside nonlinear structural steel to assess and compare their deformation and equivalent (von Mises) stress responses when applied to an LPG cylinder. The following Fig.6 shows the deformation change of different materials with respect to change of impact time.

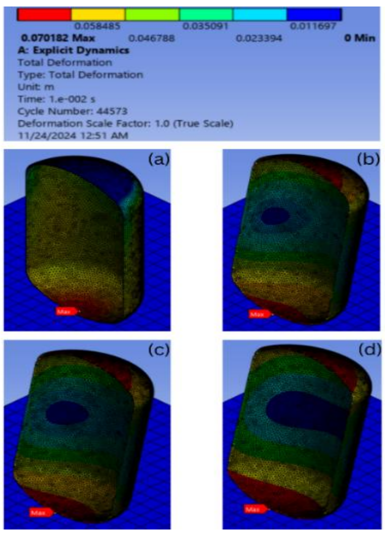
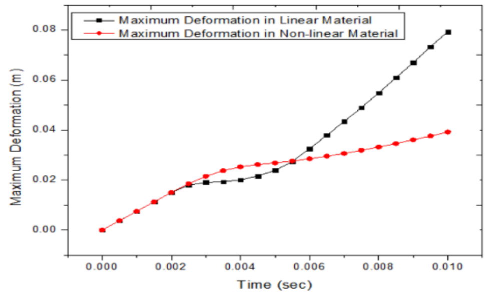
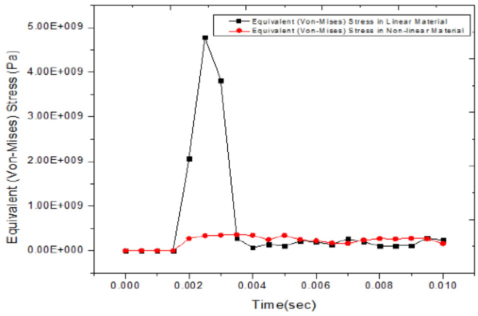


Fig.6 Deformation behavior for (a) nonlinear structural steel (b) Al 6061 T6 alloy (c) Al 7075 T6 alloy (d) Stainless Steel

The analysis of LPG cylinder deformation and stress under impact reveals key differences between linear and nonlinear structural steel. With increasing impact time, deformation rises in both materials, but linear steel shows a maximum deformation of 79.342 mm, much higher than 39.197 mm for nonlinear steel. Similarly, von-Mises stress peaks at 241.26 MPa for linear steel, compared to 159.51 MPa for nonlinear steel. Nonlinear properties effectively reduce deformation and stress, mitigating impact loads better than linear steel.



(a)



(b)

Fig.7 Graphical representation (a) of deformation behavior and (b) equivalent (von Mises) stress for linear and nonlinear structural steel for vertical impact velocity 7.5 m/s

Simulation results show that Al 7075 T6 had the highest deformation, followed by Al 6061 T6, stainless steel, and nonlinear structural steel, which exhibited the least deformation and highest resistance. Figure 7 indicates that total deformation of the LPG cylinder increased with impact time. Within the elastic limit, all materials behaved similarly, but deformation diverged beyond it, with Al 7075 T6 showing the greatest and nonlinear structural steel the lowest deformation.

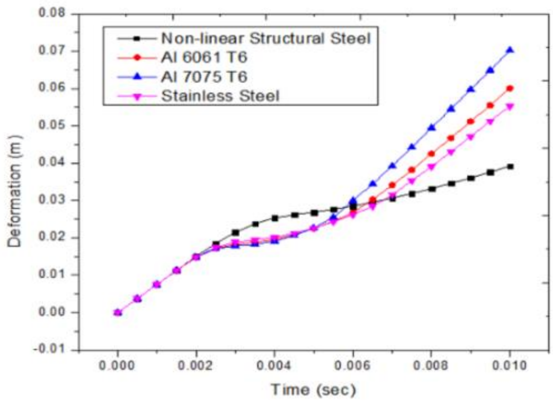


Fig.8 Comparison of the total deformation of the LPG cylinder

Again, ANSYS simulation was conducted to compare the equivalent (von Mises) stress in an LPG cylinder for different materials. The results showed that stainless steel experienced the highest stress, followed by Al 7075 T6, Al 6061 T6, and nonlinear structural steel, which exhibited the lowest stress. This comparison highlights the varying stress resistance of these materials, with stainless steel being the most stressed, while nonlinear structural steel demonstrated the greatest stress resilience under the same conditions.

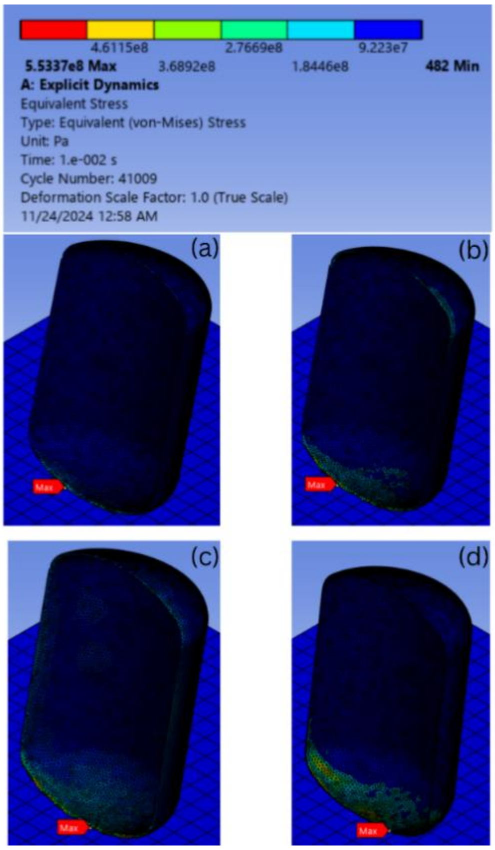


Fig.9 Equivalent (von-Mises) stress for (a) nonlinear structural steel (b) Al 6061 T6 alloy (c) Al 7075 T6 alloy (d) Stainless Steel

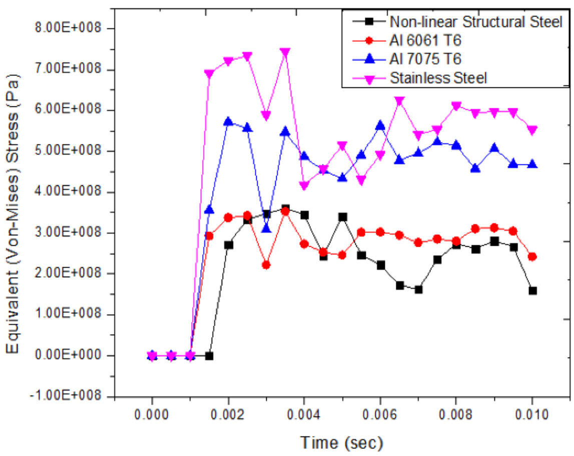


Fig.10 Comparison of the equivalent (von Mises) stress of the LPG cylinder

Similarly, fig.9 shows that stainless steel exhibits the highest stress values among the materials tested, followed by Al 7075 T6, Al 6061 T6, and nonlinear structural steel, which has the lowest stress. Each material shows a sharp peak in stress at the onset of impact, with stainless steel reaching the highest peak and nonlinear structural steel the lowest. This suggests that nonlinear structural steel has the greatest ability to withstand stress.

From S-N curve in fig. 11, structural steel can achieve finite life. It can sustain 10003 cyclic alternating loads where aluminum alloy is placed in low cycle region. Aluminum alloy can sustain 3042.4 cycle which is not sufficient enough.

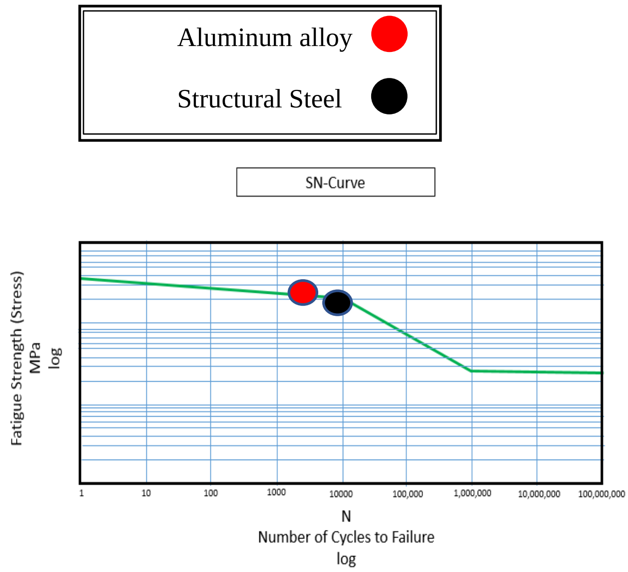


Fig. 11: SN curve for aluminum alloy and structural steel

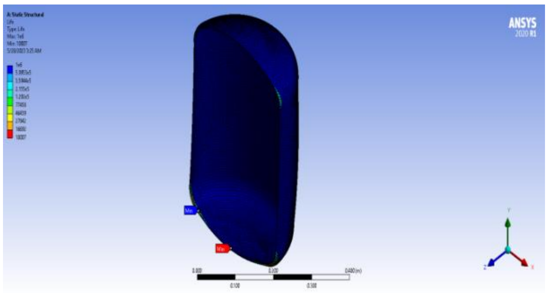
The study also investigates fatigue analysis to improve material durability by comparing structural steel and aluminum alloys in LPG cylinder applications. It emphasizes low cyclic fatigue due to high stresses and plastic deformation, highlighting the role of LCF in the required material performance under severe, short-term loads for increased safety and strength High fatigue was considered inappropriate because it tests lower sustained stress over long cycles. Fig.12 shows the regions where the lifetime of these elements is maximum and minimum.

The fatigue life characteristics for structural steel and aluminum alloy are presented in table 1 based on the simulation analysis.

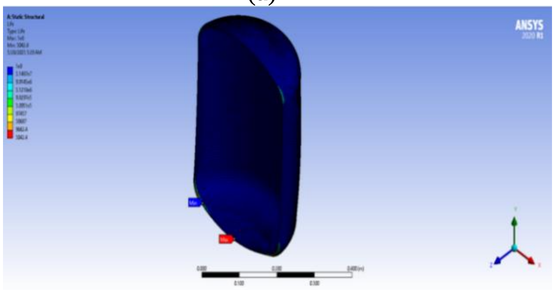
Table 1 Fatigue life behavior for structural steel and aluminum alloy

Material	Minimum cycle	Maximum cycle	Average cycle
Structural steel	10007.0	1E+6	9.942E+5
Aluminum alloy	3042.4	1E+8	9.928E+7

Looking into the table 1, it is witnessed that structural steel has a limited fatigue life, as shown by its lower minimum and average cycles, though it can endure many cycles at lower stress levels. In contrast, aluminum alloy demonstrates a much broader range of fatigue life, with significantly higher maximum and average cycle counts, indicating superior fatigue resistance. Overall, while structural steel is adequate under certain conditions, aluminum alloy offers greater endurance under cyclic loading, particularly at lower stress levels. Meanwhile, the safety factor region for fatigue analysis of LPG cylinders, using structural steel and aluminum alloy, was determined through simulation, as illustrated in fig.13.



(a)

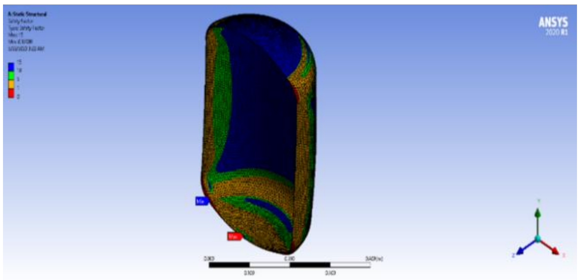


(b)

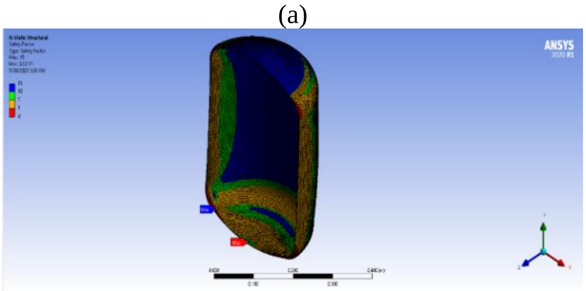
Fig.12 Maximum and minimum life region of an LPG cylinder for fatigue life analysis of (a) structural steel (b) aluminum alloy

Table 2 Fatigue safety factor for structural steel and aluminum alloy

Material	Minimum	Maximum	Average
Structural steel	0.32908	15	10.402
Aluminum alloy	0.32171	15	10.266



(a)



(b)

Fig.13 Maximum and minimum safety factor region of an LPG cylinder for fatigue factor of safety analysis for (a) structural steel (b) aluminum alloy

The results, summarized in table 2, indicate that structural steel has a minimum safety factor of 0.32908, a maximum of 15, and an average of 10.402. In comparison, the aluminum alloy shows a minimum safety factor of 0.32171, a maximum of 15, and an average of 10.266. These findings highlight that both materials maintain a maximum safety factor of 15, suggesting they can withstand significant stress. However, structural steel exhibits a slightly higher average safety factor, indicating it may provide a marginally better overall performance in fatigue scenarios compared to aluminum alloy.

Table 2 Fatigue safety factor for structural steel and aluminum alloy

Material	Minimum	Maximum	Average
Structural steel	0.32908	15	10.402
Aluminum alloy	0.32171	15	10.266

4. Conclusion

The study found that nonlinear structural steel outperforms other materials due to its high strength, low deformation, and long fatigue life. These properties make it ideal for LPG cylinders, where safety and reliability are crucial, especially in cases of movement or impacts. Therefore, nonlinear structural steel is a suitable candidate for improving LPG cylinder usage.

The performance of LPG cylinders depends on material behavior. Linear models, which relate stress to strain, are suitable for primary assessments but fail to capture complex phenomena like yielding, creep, fatigue, or damage. Nonlinear models, which account for inelastic actions such as permanent deformation, stiffness reduction, and premature yielding due to defects, offer a more accurate representation. To ensure more reliable analyses and designs, nonlinear material models are recommended.

Several conclusions can be drawn from the completion of this study. It demonstrates that:

- Nonlinear structural steel proves to be the most suitable material for impact scenarios, including at a velocity of 7.5 m/s, alongside other materials tested.
- Based on graphical explanation, nonlinear structural has the highest strength and lowest deformation among the three materials, followed by Al 6061 T6, Al 7075 T6 and then Stainless Steel.
- In the fatigue analysis, structural steel outperforms aluminum alloy by enduring up to 10,007 cycles, compared to the 3,042.4 cycles sustained by aluminum alloy, which exceeds its finite life limit. Moreover, structural steel demonstrates a significantly higher average safety factor of 10.402, further emphasizing its superior fatigue resistance.
- Clearly this study highlights how nonlinear structural steel outperforms traditional materials in impact resistance and fatigue life, paving the way for safer, more durable LPG cylinder designs and reducing accidents through advanced material models and simulations.

This study improves understanding of LPG cylinder structural behavior under impact loads, recommending nonlinear structural steel for its superior strength, minimal deformation, and extended fatigue life

References

[1] S. M. Tauseef, T. Abbasi, and S. A. Abbasi, “Risks of fire and explosion associated with the increasing use of liquefied petroleum gas,” *Journal of Failure Analysis and Prevention*, vol. 10, no. 4, pp. 322–333, Jun. 2010.

[2] T. Abbasi and S. A. Abbasi, “Dust explosions–Cases, causes, consequences, and control,” *Journal of Hazardous Materials*, vol. 140, no. 1–2, pp. 7–44, Nov. 2006.

[3] Y. Kim, C. Choi, C.-G. Kim, and Y.-D. Doh, “Ring burst test of filament wound composites for environmental resistance,” *Journal of Composite Materials*, vol. 50, no. 18, pp. 2507–2521, Oct. 2015.

[4] S. Kushwah, S. Parekh, H. Mistry, J. Darji, and R. Gandhi, “Analysis of cylindrical pressure vessels with dissimilar ends and material comparison,” *Materials Today Proceedings*, vol. 51, pp. 355–368, Jun. 2021.

[5] E. Pasternak and A. V. Dyskin, “Materials and structures with macroscopic negative Poisson’s ratio,” *International Journal of Engineering Science*, vol. 52, pp. 103–114, Dec. 2011.

[6] T. Murphey and M. Mikulas, “Nonlinear effects of material wrinkles on the stiffness of thin polymer films,” *40th Structures, Structural Dynamics, and Materials Conference and Exhibit*, Apr. 1999.

[7] R. A. Ibrahim, “Assessment of breaking waves and liquid sloshing impact,” *Nonlinear Dynamics*, vol. 100, no. 3, pp. 1837–1925, Apr. 2020.

[8] M. Kuroda, S. L. Fok, B. J. Marsden, and S. O. Oyadiji, “Analyses of the multiple cracking behaviour of brittle hollow cylinders under internal pressure,” *Int. J. Impact Eng.*, vol. 32, no. 6, pp. 905–927, Jun. 2006.

[9] S. N. Khetre, P. T. Nitnaware, and A. Meshram, “Design and Analysis of Composite High Pressure Vessel with Different Layers using FEA,” *Int. J. Eng. Res.*, vol. 3, no. 11.

[10] K. Akkimaradi and A. U. B. Khadabadi, “DESIGN AND ANALYSIS OF COMPOSITE CYLINDER,” vol. 03, no. 02.

[11] G. R. Johnson and T. J. Holmquist, “Evaluation of cylinder-impact test data for constitutive model constants,” *J. Appl. Phys.*, vol. 64, no. 8, pp. 3901–3910, Oct. 1988.

[12] P. J. Maudlin, J. F. Bingert, J. W. House, and S. R. Chen, “On the modeling of the Taylor cylinder impact test for orthotropic textured materials: experiments and simulations,” *Int. J. Plast.*, vol. 15, no. 2, pp. 139–166, Mar. 1999.

[13] A. Tom, G. M. Pius, G. Joseph, J. Jose, and M. J. Joseph, “DESIGN AND ANALYSIS OF LPG CYLINDER,” *Int. J. Eng. Appl. Sci.*, vol. 6, no. 2, pp. 17–17, Jun. 2014.

[14] F. Zhou, H. Liu, and J. La, “Fatigue Analysis of Liquefied Petroleum Gas Cylinders for Safety Risk Assessment,” *J. Shanghai Jiaotong Univ. Sci.*, vol. 25, no. 3, pp. 394–397, Jun. 2020.

[15] Dr. A. Tripathi, A. Kumar, and M. Chandrakar, “Design and Analysis of a Composite Cylinder for the Storage of Liquefied Gases,” vol. 5, pp. 2321–613, Mar. 2017.

[16] N. K. Mahraur and N. K. Singh, “Household LPG Cylinder: Effects of different heads and Impact analysis using ANSYS,” *J. Phys. Conf. Ser.*, vol. 1240, no. 1, p. 012063, Jul. 2019.

[17] V. Payghan, D. N. Jadhav, G. Y. Savant, and S. Bharadwaj, “Design & Analysis of Steam Drum Based on ASME Boiler and Pressure Vessel Code, Section VIII Div.2 & Div.3,” *Applied Mechanics and Materials*, vol. 852, pp. 511–517, Sep. 2016.

[18] N. K. Mahraur and N. K. Singh, “Household LPG Cylinder: Effects of different heads and Impact analysis using ANSYS,” *Journal of Physics Conference Series*, vol. 1240, no. 1, p. 012063, Jul. 2019.

[19] N. Md. Sahiduzzaman, N. R. Raihan, N. Moksatara, and N. A. Hossain, “Study on the physiochemical properties of liquefied petroleum gas available by cylinders in Bangladesh,” *International Journal of Latest Technology in Engineering Management & Applied Science*, vol. 13, no. 5, pp. 186–194, Jun. 2024.

[20] H. Shinde, P. Kale, and S. More, “Finite element analysis of LPG cylinder,” *AIP Conference Proceedings*, Jan. 2022.