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A Numerical Study for Novel Thin-Walled Compound Structures Made of PPR Material Reinforced with AL Shells

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ABSTRACT

Thin-walled compound structures are usually utilized as improved impact energy-absorbing members in the structures of aircraft and automobiles because of their high energy absorption capacity via progressive plastic deformation. Although these thin structures have outstanding impact performance, high manufacturing costs are a big issue that has the potential to increase vehicle prices. High quality and lightweight are also important fundamentals in the manufacture of absorber devices. Hence, in this numerical and experimental study, novel thin-walled compound structures made of polypropylene random copolymer (PPR) and aluminum alloy (AL 6082 T6) were proposed to provide a reasonable solution for these issues as possible. Static Structural Analysis in ANSYS Workbench was utilized to simulate three types of thin-walled structure models made of these suggested materials under static axial loads and full plastic conditions, namely PPR, AL, and the novel PPR-AL-PPR. The purpose of that is to compare crashworthiness properties among each model and investigate the mechanical behavior of a failure, crush force efficiency and energy absorption capacity for each model. The results observed that the novel model (PPR-AL-PPR) is the optimal type in terms of improvements in crashworthiness properties in comparison to other traditional models, where the crush force efficiency and energy absorption capacity increased numerically by approximately 26% and 107%, respectively. The data have been validated with experimental results, and most of these findings were rather compatible. In conclusion, the PPR material reinforced by AL shells can significantly improve the crush force efficiency and the energy absorption capacity of thin-walled structures. Hence, the novel model suggested could be applied to vehicles and aircraft structures as a good absorber device.

Keywords: Axial crushing, Composite tubes, Energy absorption, Thin-walled structures, Shock absorbers

INTRODUCTION

It is acknowledged that thin-walled structures can be utilized as shock absorbers in many industrial engineering applications, particularly in transportation. However, these components can be affected by accidental overloads or harsh environmental conditions. Thus, the mechanical performance of thin geometric structures can decrease over time. To promote the mechanical crashworthiness properties (e.g., crush force efficiency, energy absorption capacity, peak and mean loads, modes of deformation) and environmental resistance of thin structures, researchers utilized multiple geometric shapes and multiple traditional materials for this purpose [Chahardoli and Nia, 2017; Naveed et al., 2017; Yao et al., 2019; Song et al., 2013; Bai et al., 2021; Xiaolin et al., 2021; Praveen, 2019; Dionysius et al., 2022]

Thin-walled engineering structures made of conventional composites play a significant effect on the mechanical performance of such structural components due to their high strength and stiffness properties, high corrosion resistance, lightweight and affordable prices [Degenhardt et al., 2010; Draidi et al., 2018; Xing et al., 2011; White et al., 2015; Zhu et al., 2018; Ude et al., 2019]. The experimental and numerical studies in this area focused on the behavior of these thin structures under axial loads for multiple geometric shapes. Thin-walled circular tubes were one of the most desirable geometric shapes that could be utilized to absorb shock energy. Thin-walled circular tubes, whether made of metals (e.g., aluminum alloys or steel alloys) or nonmetals (e.g., polymers, fibres), contributed to improving the crashworthiness properties, particularly energy absorption capacity and crush loads [Chahardol et al., 2019; Li et al., 2021; Chahardoli et al., 2019].

Interestingly, a combination of metallic tubes (e.g., aluminum shells) and nonmetallic tubes (e.g., glass or carbon fibres) can lead to more increments in the improvement of crashworthiness properties and sustainability of performance [Bai et al., 2021; Draidi et al., 2018]. Although studies in this area have been limited, these have achieved remarkable successes; however, there were some obstacles relating to the high costs and mechanical properties of these fibres, in particular their brittleness [Sun et al., 2016; Atthapreyangkul and Prusty, 2017]. To solve these problems, the use of alternative tough and ductile materials, for instance, advanced polymers, especially polypropylene (PPR) compounded with metals such as aluminum alloy (AL), could be a reasonable solution in the manufacture of absorber devices.

The goal of this study is to investigate the effect of axial loading on the crashworthiness properties of a novel thin-walled circular compound structure numerically and experimentally. The novel compound tubes proposed are made of PPR material strengthened with AL shells. In this study, crashworthiness properties such as modes of deformation, crush loads, crush force efficiency and energy absorption capacity have been investigated and evaluated. In summary, the novel thin-walled compound structure is beneficial for improving crashworthiness properties, particularly crush force efficiency and energy absorption capacity.

EXPERIMENTAL WORK AND RESULTS

Material Characterization

In this study, the traditional thin-walled circular structures were manufactured from an aluminum alloy 6082 T6 rolled sheets. The aluminum alloy 6082 T6 was selected because of its common applications in automotive parts and aeroplane structures. A chemical analysis test was performed in accordance with the ASTM-E1251 standard for verifying the presence of various constituents in the as-received aluminum shell. The chemical composition and mechanical properties of the tested aluminum alloy 6082 T6 samples are presented in Tables 1 and 2.

Table 1. Chemical composition of 6082 T6 alloy

Constituents	**Si**	**Mg**	**Mn**	**Cu**	**Fe**	**Cr**	**Zn**	**Ti**	**Al**
Weight (in %)	0.9	0.68	0.43	0.09	0.45	0.22	0.08	0.03	97.12

Table 2. Mechanical properties of 6082 T6 alloy

Density (g/cm^3)	**Tensile yield strength (MPa)**	**Ultimate tensile strength (MPa)**	**Modulus (GPa)**	**Elongation (%)**	**Poisson ratio**
2.7	260	285	68	11	0.32

Other traditional thin-walled circular structures were made from polypropylene (PPR) material. The thermoplastic PPR is a random copolymer polypropylene, that is created via random co-polymerization of propensity monomer and a little amount of ethylene monomer under the action of pressure, heat and catalysts. Polypropylene comprises chains of hydrocarbons arranged in a chemical composition that provides the material with the characteristic of being tough and everlasting. The polypropylene-random material (PPR) selected in this study consists of a mixture of long chains and short chains. It was utilized to generate a material that is both elastic and tough, see Fig. 1.

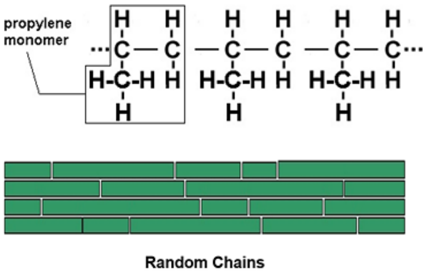

Figure 1. Chemical chains of PPR material

The elasticity assists in protecting the thin-walled structures from external damage, such as impact. In addition, it permits the thin-walled structures to absorb stress that might damage other components. While the toughness assists in improving the mechanical performance and capability of thin-walled structures to resist fracture [Yu et al., 2014]. As a result, it was selected to improve the efficiency of absorber devices. The mechanical properties of the tested PPR samples are presented in Table 3.

Table 3. Mechanical properties of PPR material

Density (g/cm^3)	Tensile yield strength (MPa)	Ultimate tensile strength (MPa)	Modulus (GPa)	Elongation (%)	Poisson ratio
0.9	23	40	0.7	50	0.4

A novel thin-walled compound structure was manufactured via a combination of these materials above. The purpose of utilizing aluminum alloys as reinforced materials with polypropylene is to fully benefit from their seductive properties, particularly strength, toughness, elasticity and ductility.

Preparation of Samples

Three types of commercial samples were prepared for the present work. Each sample was produced via the extrusion technique. The first sample is a thin circular structure made of polypropylene random copolymer (PPR) material only. The second sample is a thin circular structure made from aluminum (AL) shell only. The third sample is a compound of thin circular structures made of polypropylene random copolymer reinforced with aluminum shell (PPR-AL-PPR). The reinforced aluminum shell was placed at the midpoint of novel, thin circular structures. The geometric configuration and layers distribution for the novel thin-walled compound structure are illustrated in Fig. 2. The geometric dimensions for the prepared samples are listed in Table 4.

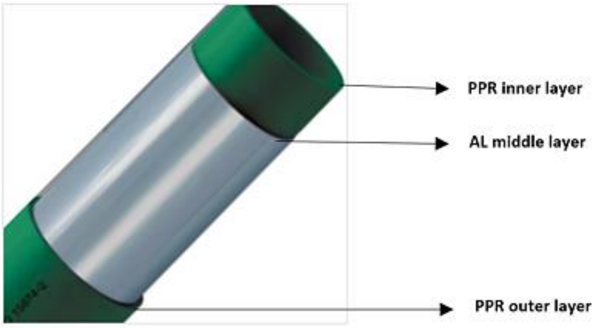

Figure 2. Geometric configuration of novel compound circular structure (PPR-AL-PPR)

Table 4. Geometric dimensions for three types of samples

Sample	External diameter (mm)	Internal diameter (mm)	Total Thickness (mm)	Length (mm)
PPR	25.4	18.4	3.5	40.1
AL	22.9	21.9	0.5	40.2
PPR-AL-PPR	26.4	18.4	4.0	40.1

Quasi-Static Tests

The thin-walled circular samples were statically tested by utilizing a compression test machine at a constant strain rate (0.02 s^{-1}). The sample was placed and constrained between two rigid plates, see Fig. 3. All samples were compressed axially to obtain a complete failure for each sample, and then the crashworthiness properties were calculated from the load-deflection curve for each of the tested samples. Three samples were tested for each type, and the average values for crashworthiness properties have been recorded in Table 5.

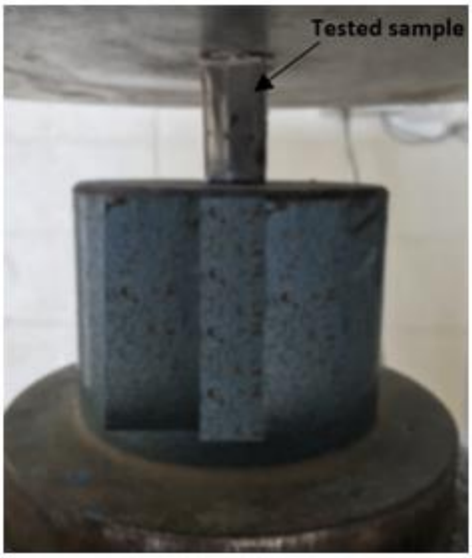

Figure 3. The mechanism testing of samples

Crashworthiness Criteria

To estimate the crashworthiness properties of an energy absorber, a number of criteria are often utilized. The information necessary to assess these parameters can be derived from the load-deflection curve for each sample, as shown in Fig. 4.

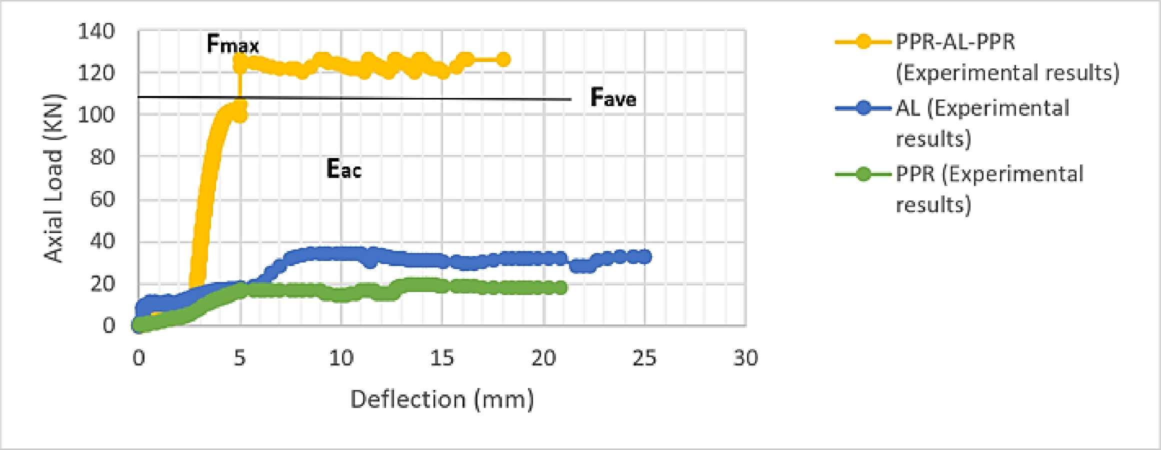

Figure 4. Load-deflection curves for experimental samples tested

- Failure mode (*FM*): It can be defined as the geometric deformations that appears on the sample during the loading process.

- Peak force (F_{max}): this force refers to the maximum magnitude on the load-deflection curve for each sample.

- Mean crushing force (F_{avg}): the magnitude of the average crushing force is defined analytically as:

$$F_{max} = \frac{1}{L_f}\int_0^{L_f} F(y)\, dy$$

Equation 1

Where L_f is the axial crush distance, and $F(y)$ is the instantaneous axial crush force.

- Crush force efficiency (*CFE*): defined as the proportion of the average crushing force (F_{avg}) to the magnitude of the peak force (F_{max}):

$$CFE = \frac{F_{ave}}{F_{max}}$$

Equation 2

- The increment ratio (*Inc.%*) for crush force efficiency of the novel thin-walled compound structure can be calculated by this formula

$$Inc.\% = \frac{CFE_{Novel-}CFE_{AL}}{CFE_{AL}} \times 100$$

Equation 3

A higher magnitude of CFE refers to better loading homogenously and superior crashworthiness performance. Ideal energy absorbers thus have *CFE* = 1.0.

- Energy absorption capacity (*Eac*): gained by integrating the load-deflection curve during the loading synthesis for each type of samples. It can also be defined as is the area under the curve. The greater the energy absorption capacity (*Eac*), the better the crashworthiness [Xiao et al., 2015].

$$Eac = \int_0^{L_f} F(y)\, dy$$

Equation 4

- The total energy absorption capacity (*TEAC*) of the novel thin-walled compound structure can be estimated by the following formula

$$TEAC = Eac_{PPR} + Eac_{AL}$$

Equation 5

- The increment ratio (*Inc.%*) for the total energy absorption capacity of the novel thin-walled compound structure can be calculated by this formula

$$Inc.\% \ = \frac{Eac_{Novel-}(Eac_{PPR} + Eac_{AL})}{Eac_{PPR} + Eac_{AL}} \times 100$$

Equation 6

Table 5. Experimental results of crashworthiness properties for tested samples

Sample	***FM***	**L_f (mm)**	**F_{max} (KN)**	**F_{ave} (KN)**	***CFE***	***Inc.* (%)**	***Eac* (J)**	***TEAC* (J) (Eac_{PPR}+ Eac_{AL})**	***Inc.* (%)**
PPR	Concertina	20.7	18.11	11	0.60	-	228	798	-
AL	Diamond	25.1	34.2	22.7	0.66	-	570		
PPR-AL-PPR	Concertina	17.8	127	105	0.82	24.5	1869	1869	134.2

NUMERICAL SIMULATION AND RESULTS

Three models of thin circular structures: PPR, AL and a novel PPR-AL-PPR were digitally simulated to compare with the experimental samples, utilizing Static Structural Simulation in ANSYS Workbench 20 R2, see Fig.5.

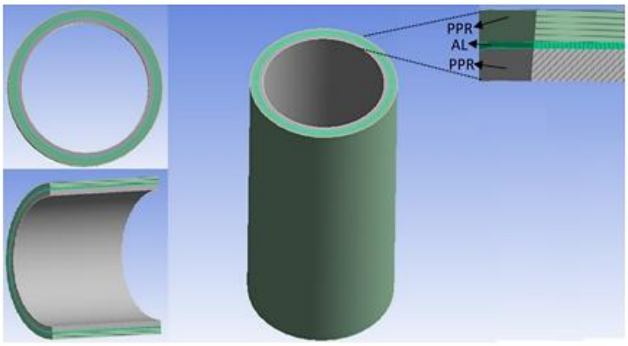

Figure 5. Geometric configuration of novel model (PPR-AL-PPR)

The novel PPR-AL-PPR model was constructed in three different layers utilizing SPACECLAIM software. The geometric dimensions of the three models are previously listed in Table 4. The mesh size for all models was refined to 1 mm. The plastic behavior was assumed to be analyzed for each model under static conditions. The model was vertically mounted on a rigid support plate. The support plate was fixed on the top of the model to prevent any movement of the pattern through a period of loading, as shown in Fig. 6. Each of the models was axially compressed to obtain a complete failure. To simulate the AL model and the PPR model separately, suppress body was activated for this purpose, and then the same steps have been applied to the models.

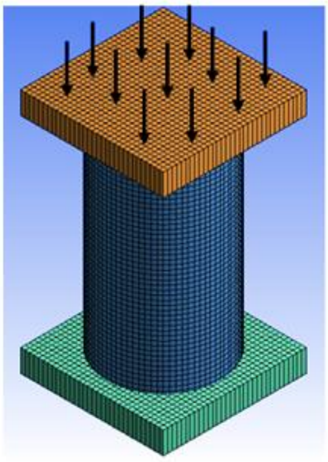

Figure 6. The preparation stages of finite element models

The plastic analysis for the models was performed to assess the energy absorption capacity in each model. The same plastic analysis settings were considered for all models. Constant steps have been assumed with each stage of loading to reach a plasticity region. The large deflection option was activated to consider the plastic state of the materials. The material nonlinearity (bilinear isotropic hardening) was considered for suggested materials (AL and PPR), and the plastic behavior was defined for both in the material library as stated in Tables 2 and 3. The crashworthiness properties in Table 6 were also estimated from the Load-deflection curve for each model, as shown in Fig.7.

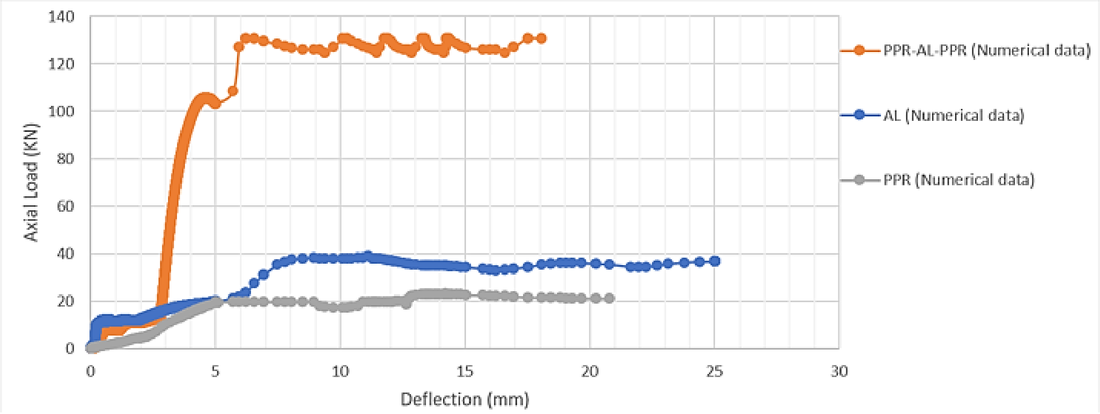

Figure 7. Load-deflection curves for numerical models simulated

Table 6. Numerical data of crashworthiness properties for simulated models

Model	FM	L_f (mm)	F_{max} (KN)	F_{ave} (KN)	CFE	Inc. (%)	Eac (J)	TEAC (J) (Eac_{PPR}+ Eac_{AL})	Inc. (%)
PPR	Mixed mode (diamond and concertina)	21	27.6	17.47	0.63	-	367	1030	-
AL	Diamond	25	38.66	26.52	0.68	-	663		
PPR-AL-PPR	Concertina	18	137	118.61	0.86	26.19	2135	2135	107.28

DISCUSSION

Modes of Deformation and Axial Crush Distance

The failure modes of PPR, AL and PPR-AL-PPR models are shown in Fig. 8. The mode of plastic deformation for the PPR model is semi-similar to the PPR-AL-PPR model, but the number of folds and maximum axial crushing distance of the PPR model are greater than those of the PPR-AL-PPR model. This may be due to an increase in the strength properties and thickness of the novel thin circular structure reinforced with AL shell [Liu et al., 2015]. The PPR and PPR-AL-PPR models show concertina mode failure experimentally, but in numerical analysis, the PPR model shows mixed mode failure (diamond and concertina), and the PPR-AL-PPR model shows concertina mode numerically and experimentally. The reasons behind such different modes of failure could be due to defects in geometric sizes or materials utilized in the manufacture of samples. Whereas the AL model shows diamond mode failure numerically and experimentally, moreover, the value of the maximum axial crushing distance of the AL model is higher than that of the other models, as shown in Table 5. This behavior could provide convenient evidence about the effects of the ductility of aluminum on axial crushing distance [Naveed et al., 2017]. Thus, the combination of metallic and nonmetallic materials could affect the failure modes of thin circular structures. This may have more influence on the energy absorption capacity and other crashworthiness properties. These modes of deformation have been confirmed with experimental results, and the numerical data were rather close to the experimental results.

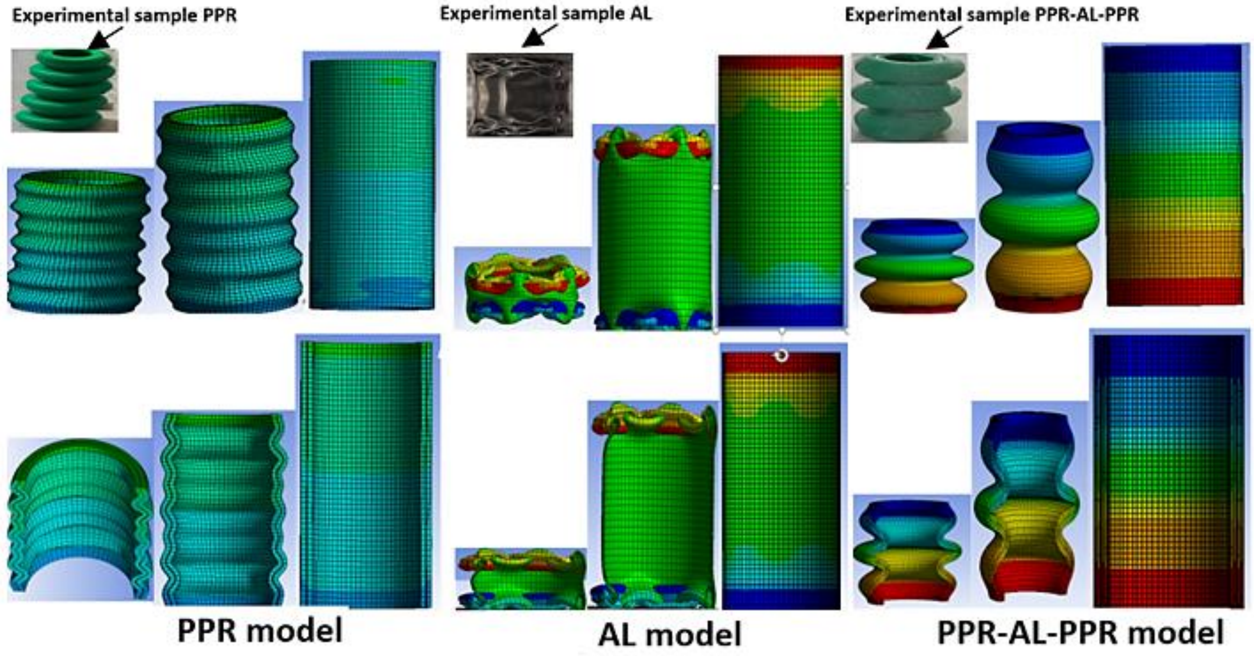

Figure 8. The failure modes for each indicated model: PPR, AL, PPR_AL_PPR

Load-Deflection Curves

The numerical simulation curves and experimental work curves have been presented for each model and sample, as shown in Fig. 9. The figure illustrates the mechanism of reduction in axial length with fluctuations in the magnitudes of crush loads precisely in the novel model (PPR-AL-PPR). These fluctuations could be due to the plastic behavior of materials, mode of deformation, geometric dimensions, as well as the effects of ductility and toughness [Naveed et al., 2017; Rabiee and Ghasemnejad, 2018]. The behavioral mechanisms of failure for the numerical models and experimental samples were rather compatible.

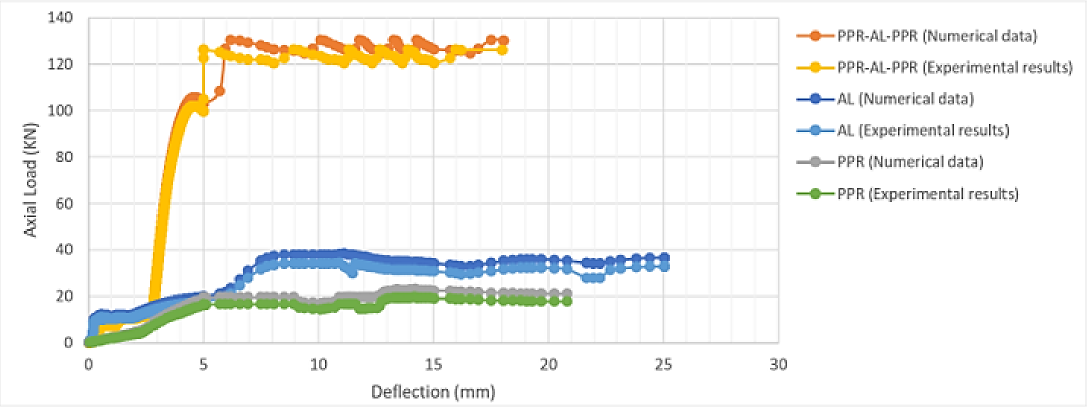

Figure 9. Load-deflection curves for the simulated models and tested samples: PPR, AL, PPR-AL-PPR

Crush Force Efficiency and Energy Absorption Capacity

It is apparent from Table 6 that crush forces and total energy absorption capacity (TEAC) of the PPR-AL-PPR model have increased after the combination of aluminum alloy and polypropylene material. It is also quite clear that the TEAC of the PPR-AL-PPR model is higher than the PPR and AL models. It is attributed to the addition of another material, such as aluminum shell to the polypropylene thin-walled structures, which leads to more improvements in the crush force efficiency and energy absorption capacity of the novel thin-walled structures, where these numerical CFE and numerical energy data grew up by approximately 26% and 107%, respectively. Table 7 shows that most of the numerical data is rather compatible with experimental results for three simulated models. The main reasons behind the differences in some statements could be because of imperfections in the geometric dimensions of experimentally tested samples, the properties of utilized materials or boundary testing.

Table 7. The difference in results between experimental samples and numerical models

Sample/Model	**Experimental *CFE***	**Numerical *CFE***	**Difference in *CFE* (Num-Exp)**	**Experimental *Eac* (J)**	**Numerical *Eac* (J)**	**Difference in *Eac* (Num-Exp) (J)**
PPR	0.60	0.63	0.03	228	367	139
AL	0.66	0.68	0.02	570	663	93
PPR-AL-PPR	0.82	0.86	0.04	1869	2135	266

CONCLUSİON

This study mainly described the effect of axial crushing loads on the novel thin-walled structure made of aluminum alloy 6082 T6 and thermoplastic polymer PPR. The results of modes of deformation, crush force efficiency, energy absorption capacity and crush loads were listed and compared for three types of models, namely PPR, AL and the novel PPR-AL-PPR. The results of this study clearly described that the novel PPR-AL-PPR model is superior in improving crush force efficiency and energy absorption capacity in comparison to the PPR and AL models, where crashworthiness criteria increased numerically by approximately 26% and 107%, respectively. Furthermore, the failure mode and maximum axial crush distance of each model have been affected by the combination of AL and PPR materials. The present study also showed that numerical data are rather close to experimental results.
In conclusion, the polypropylene PPR reinforced with aluminum alloy 6082 T6 could enhance the crashworthiness properties of thin-walled structures under quasi-static conditions. Thus, novel thin-walled structures could be beneficial in the engineering application of novel absorber devices.

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