

Effect of Adding Expanded Polypropylene and Polyurethane Foams on Crashworthiness Response of the Aluminium-Reinforced Honeycomb Structure



Vaibhav Saptal, G. Tiwari, and T. Thomas

Abstract This chapter aimed to find the effects of adding Expanded Polypropylene and Polyurethane foams on the crashworthiness response of reinforced aluminium honeycomb structures. Cell size and cell wall thickness were taken as 20 mm and 0.11 mm respectively for a honeycomb of node length 25 mm. Expanded Polypropylene (EPP) foams of densities of 20, 40, 60 kg/m³ and Polyurethane foams (PU) of densities 16, 29 and 42 kg/m³ were added to either side of the reinforced sheet. Finite-element simulations for foam-filled reinforced honeycombs were performed under quasi-static loading conditions using finite element code LS-DYNA. The effect of varying foam-filling percentages in reinforced honeycomb on crashworthiness parameters was also studied. The effect of varying PU foam density by keeping EPP foam density constant showed an increase in crashworthiness parameters peak load, mean load and specific energy absorption but crush force efficiency showed fluctuating behaviour in all the cases. Crashworthiness of both distinct type of structure showed superior performance as foam density increases.

Keywords Honeycomb core · Reinforced honeycomb · Quasi-static crushing

1 Introduction

One of the primary goals of the aerospace and automotive industries is to design lightweight and superior energy-absorbing crash-worthy structures to ensure occupant's safety. In recent years, honeycombs and foams got the attention of researchers due to their lightweight and energy absorption capabilities. Meran et al. [1] numerically studied the effect of varying foil thickness, cell size, cell expanding angle and impact velocity on the crashworthiness parameters of aluminium honeycomb under out-of-plane stress conditions. Results showed that as foil thickness and cell

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size increased; crush force efficiency and total energy absorption decreased. Crashworthiness parameters were unaffected by impact mass and velocity. Yin et al. [2] used a new approach for estimating the mean crushing stress of honeycomb structures with varying cell specifications under axial loading based on the super folding element theory and had a better agreement with the numerical simulation results. Tao et al. [3] studied the effect of strain rate on aluminium honeycombs to perform the crushing with quasi-static and dynamic loading and found that the rate-dependent shock theory yields more accurate predictions. The strain rate effect made a considerable contribution to the dynamic enhancement of metallic honeycombs across a wide velocity range. Pietras et al. [4] conducted static and low-velocity compression testing on polyurethane foam-filled aluminium honeycombs. The strength and energy absorption of the honeycomb structure was increased by more than 41% with the addition of 0.02 per cent reduced graphene oxide flakes. Due to the interaction effect, the foam-filled honeycomb showed better properties (up to 61%) than the bare honeycomb. The in situ foam-filling method was better than the ex-situ foam-filling method and the composition of foam greatly influences the collapse mechanism of the honeycomb. Nia and Sadeghi [5] conducted studies to determine the impact response of foam filling on the plastic behaviour and mechanical characteristics of honeycomb. Experimentation showed that foam filling enhanced the mean crushing strength and energy absorption capacity of panels up to 300 per cent. Moreover, the sum of the mean crush strengths of bare honeycomb and foam alone is lesser than the mean crush strength of foam-filled panels. Zhou et al. [6] studied the lateral crushing response of concrete foam-filled auxetic honeycomb made of aluminium under low velocity and quasi-static loading conditions. It was found that as foam density increases; modes of failure shift from crushing failure to failure under shear with high peak load. Zhang et al. [7] performed static and dynamic impact tests on expanded polypropylene foam-filled aluminium honeycomb and found higher peak and mean force but Specific Energy Absorption (SEA) was decreased. The initial peak strength, mean strength and SEA of filled specimens increased with increasing impact velocity. Compared to the static compression test, the initial peak strength in the dynamic impact test rose, however, the mean strength and SEA dropped. When different types of filling were compared, it was discovered that single-cell filling was an excellent choice for improving load resistance while utilising the least amount of filler material. Mahmoudabadi and Sadighi [8] theoretically and experimentally studied the aluminium honeycomb's crushing behaviour under quasi-static and low-velocity impact loading conditions. A novel static model was developed for determining the crushing strength and modes of failure of honeycomb structure by employing the energy method. Khan et al. [9] used Digital Image Correlation and performed experiments to crush aluminium honeycomb both axially and laterally and discovered that the honeycomb's crushing strength in the axial direction is greater than in the lateral direction. The ribbon direction strength was two times stronger than the transverse direction in lateral crushing. The deformation nucleated from the shear band at 45 degrees in the sample, according to the results of Digital Image Correlation. The deformation was restricted to the shear band's areas and the local plastic strain in the core was substantially larger for a given global strain

level. Aminanda et al. [10] crushed honeycomb specimens made of paper, Nomex and aluminium under quasi-static loading conditions and found that all the honeycombs showed similar kinds of force–displacement curves. For Nomex honeycombs indented by various indenters, an analytical model was developed and compared results with experiments. Both analytical and experimental results were found close.

From the literature study, it is observed that reinforced honeycombs got less attention than conventional honeycombs. Very few studies are available on foam filled reinforced honeycomb structures. In this chapter, finite-element analysis for quasi-static crushing of foam-filled reinforced honeycomb in out of plane direction was performed using finite element code LS-DYNA. The effect of the addition of expanded polypropylene (by varying densities of 20, 40 and 60 kg/m³) and polyurethane (by varying densities of 16, 29 and 42 kg/m³) foams together on reinforced honeycomb was studied. The effect of varying foam filling percentages on crashworthiness parameters such as peak load, mean load, specific energy absorption and crushing efficiency were calculated and analysed.

2 Material Modelling

2.1 Mat 024 (Piecewise_linear_plasticity)

MAT 024 (PIECEWISE_LINEAR_PLASTICITY) was used to simulate the honeycomb material's behaviour i.e., aluminium under numerical simulation [11, 12]. This material model is a nonlinear constitutive model based on Von Mises yield criteria, which considers the nonlinear behaviour of aluminium until a fracture takes place [13].

The yielding function for the model is defined as follows [14],

$$\phi = \frac{1}{2} S_{mn} \times S_{mn} - \frac{S_y^2}{3} \leq 0 \quad (1)$$

where

$$S_y = \beta \times [S_0 + f_h(\epsilon_{eff}^p)] \quad (2)$$

ϕ = Yield function, S_y = Yield Surface's current radius, S_0 = Flow stress.

$f_h(\epsilon_{eff}^p)$ = function for hardening, β = Strain rate effect parameter, S_{mn} = Deviatoric stress

Elasticity modulus, mass density, Poisson's ratio and yield strength for aluminium were taken as 69 GPa, 2.72 kg/m³, 0.3 and 98.147 MPa respectively. To determine the strain rate effect parameter two options were available, the first one was the Cowper-Symonds model and the second one was the use of the stress–strain curve obtained

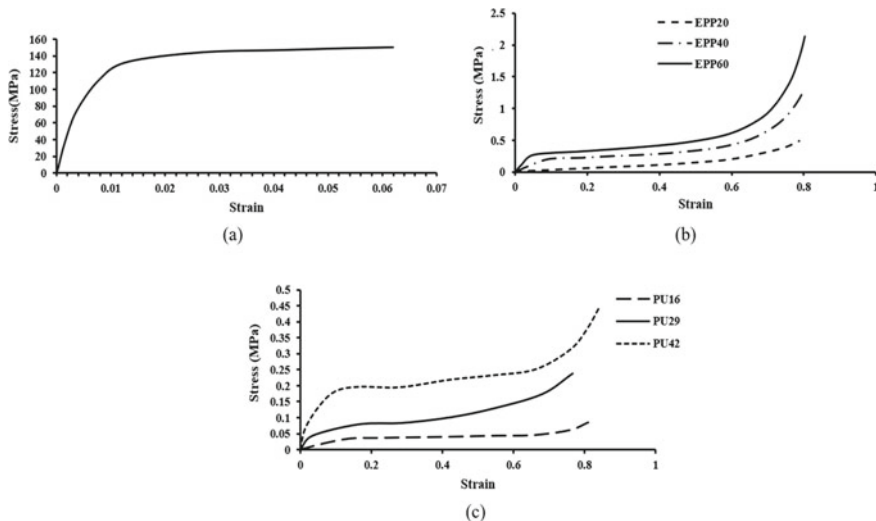


Fig. 1 Stress vs Strain curves for **a** Aluminium **b** Expanded polypropylene **c** Polyurethane

from the uniaxial tension test [14]. The stress–strain curve used in the simulation for aluminium was shown in Fig. 1a.

2.2 Mat 057 (Low_density_foam)

The material model of Mat 057 (LOW_DENSITY_FOAM) was used to simulate the expanded polypropylene and polyurethane foams behaviour under numerical simulation [15]. This foam model was used to simulate highly compressible low-density foams [14, 16]. It depicts compressive behaviour, which includes hysteresis during unloading [14]. Under the application of tensile stress, the material shows linear behaviour until it breaks. The low-density foam model was basically a Maxwell fluid consisting of a series of springs and dampers [14]. The modulus of elasticity and decay constant were used to characterise this in the input. For expanded polypropylene foams having densities of 20, 40 and 60 kg/m³, Young’s modulus values were taken as 0.667, 3.395 and 5.084 MPa, respectively. For polyurethane foams having densities of 16, 29 and 42 kg/m³, Young’s modulus values were taken as 0.2974, 1.2764 and 1.8405 MPa, respectively. As foam will not fail in tension in this application, the tension cut-off stress is left at the default value. The form of the unloading curve is controlled by two non-dimensional parameters, that is, the hysteric unloading factor and the shape factor, both of which are set to 0.101 and 25 respectively [16]. The damping coefficient of 0.5 is used to increase stability [16]. The default value of 0.0 is used for both Young’s relaxation modulus and the decay constant. Stress–Strain curves were shown in Fig. 1.

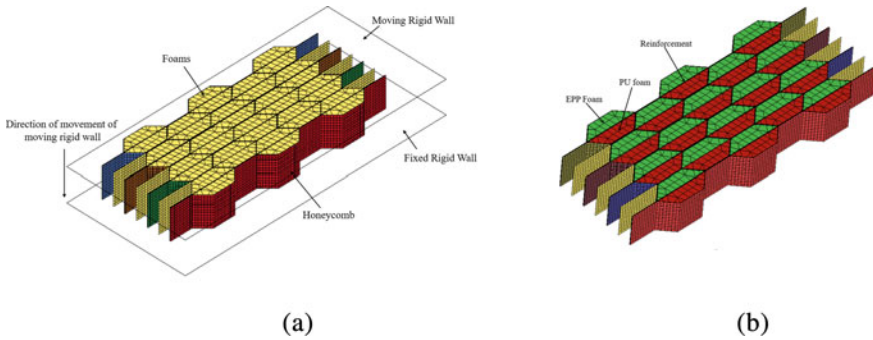


Fig. 2 **a** Typical boundary conditions for all honeycomb structures **b** Foam-filled reinforced honeycomb with two different foams together

3 Numerical Modelling Details

The honeycomb of node length 25 mm, cell size 20 mm and wall thickness 0.11 mm were used in the analysis. LS-DYNA was used to model the crushing behaviour of the aluminium honeycomb and foam. Santosa et al. [17] given concepts for quasi-static simulations, which states that the ratio of total kinetic energy to total internal energy must be very small throughout the simulation and the load–displacement curve should not be dependent on applied velocity when the rate of loading was increased to speed up the analysis were used for analysis. The completely integrated shell elements were used to model honeycomb structures [11, 12]. AUTOMATIC_SURFACE_TO_SURFACE_TIEBREAK contact was provided between two layers of honeycomb core with adhesive properties of normal stress and shear stress 45 MPa and 40 MPa, respectively [12]. The coefficient of friction between the surfaces was given as 0.3[12]. Between the aluminium honeycomb and expanded polypropylene foam AUTOMATIC_SURFACE_TO_SURFACE_CONTACT was used with a friction value of 0.2 [16]. The honeycomb model was put between two rigid planes. The top moving plane moved at 0.5 mm/s, whereas the bottom plane was fixed in all directions [12]. Typical Boundary conditions for all structures were shown in Fig. 2a.

4 Result and Discussion

4.1 Model Validation

Lu et al. [18] performed an experiment to crush bare honeycomb and Expanded Polypropylene foam-filled conventional honeycomb in the out of plane direction. Commercially available honeycomb structures having cell wall thickness, node length and cell width of 0.062 mm, 20 mm and 6.2 mm, respectively, were used

by them for experiments. They performed quasistatic crushing tests on conventional honeycomb structures and Expanded Polypropylene foam-filled honeycomb structures (of varying densities 20, 40 and 60 kg/m³) using a uniaxial tension testing machine. To validate the numerical model, conventional honeycombs and foam-filled honeycombs of the same dimensions and mechanical properties were used by Lu et al. [18] were used into LS-DYNA explicit FEA software. As shown in Fig. 3, the results obtained through the numerical model for both conventional honeycomb and EPP foam (of density 20 kg/m³) filled honeycomb were in accordance with the experimental results presented by Lu et al. [18]. Therefore, the numerical model can be used in further studies (Table 1).

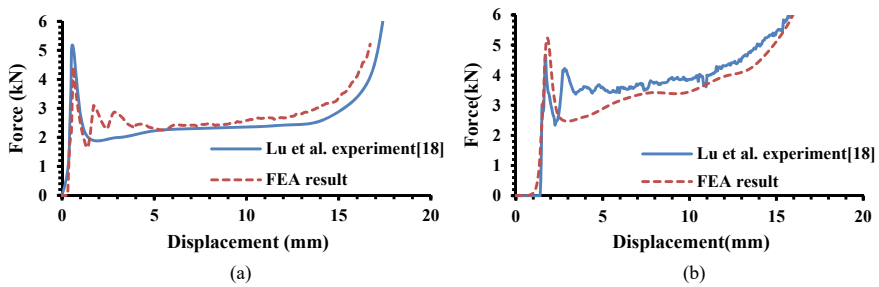


Fig. 3 Model validation **a** conventional honeycomb **b** EPP foam (of density 20 kg/m³) filled honeycomb

Table 1 Model validation

Parameters	Conventional honeycomb		Foam-filled honeycomb	
	Lu et al. experiment [18]	FEA result	Lu et al. experiment [18]	FEA result
Peak load (kN)	5.14	4.42	5.33	4.66
Mean load (kN)	2.34	2.61	3.69	3.91
Crushing efficiency	45.56%	59.19%	69.32%	83.95%
Energy absorption (kN-mm)	34.9	38.2	52.1	54.3
Maximum crush length (mm)	14.8	14.6	14.1	13.88

4.2 Effect of Filling Two Different Foams Together on Crashworthiness Response of Reinforced Honeycomb Structure

The reinforced honeycomb structure provides the feature to add two different foams into the same structure as shown in Fig. 2b. With the help of this feature, properties of two foams can be used to enhance the crashworthiness performance of the honeycomb structure. So, for reinforced honeycomb structure, keeping expanded polypropylene foam of densities of 20, 40, 60 kg/m³ on one side of the reinforced sheet and varying polyurethane foam of densities of 16, 29 and 42 kg/m³ on another side of the reinforced sheet different cases were formed and analysed. The load–displacement curve showed similar behaviour to any crashworthy structure during its crushing. It showed three regions: elastic region, plateau stress region and densification region.

4.2.1 Keeping EPP Foam Density 20 kg/m³ and Varying PU Foam Densities 16, 29, 42 kg/m³ in Foam-Filled Reinforced Honeycomb

Effect of filing Expanded Polypropylene foam of density 20 kg/m³ and varying Polyurethane foam of densities 16, 29, 42 kg/m³ on the other side of the honeycomb structure showed the following variations in crashworthiness properties. As the density of polyurethane foam increases peak load increases. Peak load showed a maximum value of 37.8 kN for EPP20_PU42 (see Fig. 4b). Mean load also showed similar behaviour as peak load. As the density of polyurethane foam increases mean load also increases as shown in Fig. 4b and it showed a maximum value of 19.89 kN for EPP20_PU42. Crush force efficiency showed a sudden increase when PU foam density changed from 16 to 29 kg/m³, but after that, it again decreased when the density of polyurethane foam changed from 29 to 42 kg/m³. Specific energy absorption also increased as the density of foam increased from 16 to 42 kg/m³.

4.2.2 Keeping EPP Foam Density 40 kg/m³ and Varying PU Foam Densities 16, 29, 42 kg/m³ in Foam-Filled Reinforced Honeycomb

Effect of filing Expanded Polypropylene foam of density 40 kg/m³ and varying Polyurethane foam of densities 16, 29, 42 kg/m³ on another side of the honeycomb structure showed the following variations in crashworthiness properties. As the density of polyurethane foam increases peak load increases. Peak load showed a maximum value of 38.5 kN for EPP40_PU42 (see Fig. 4d). Mean load also shows similar behaviour as peak load. As the density of polyurethane foam increases, mean load also increases as shown in Fig. 4d. It shows a maximum value of 19.89 kN for EPP20_PU29. Crush force efficiency showed a sudden increase when PU foam density changed from 16 to 29 kg/m³, but after that, it again decreased when the

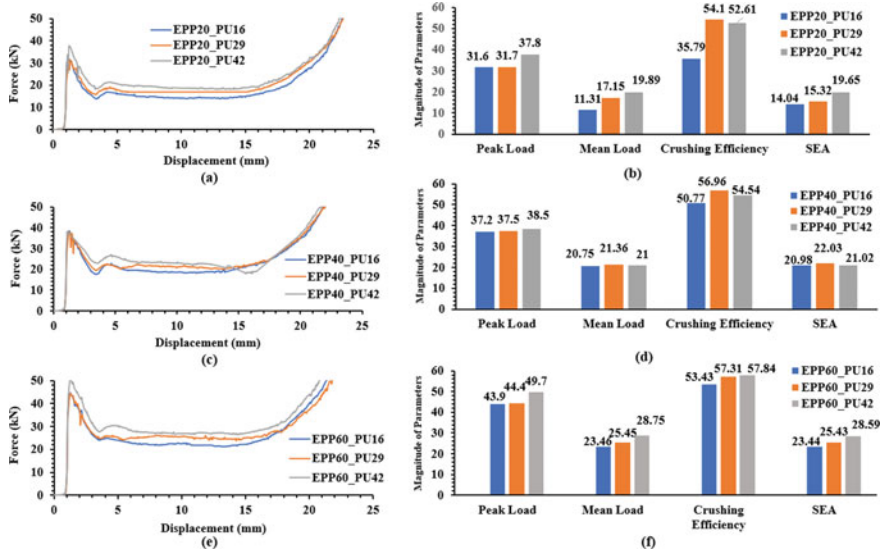


Fig. 4 Effect of filling two different foams together on crashworthiness response of reinforced honeycomb structure

density of polyurethane foam changed from 29 to 42 kg/m³. Specific energy absorption also increased as the density of foam increased from 16 to 29 kg/m³ but it showed decrement when the density of foam increased from 29 to 42 kg/m³.

4.2.3 Keeping EPP Foam Density 60 kg/m³ and Varying PU Foam Densities 16,29,42 kg/m³ in Foam-Filled Reinforced Honeycomb

Effect of filing Expanded Polypropylene foam of density 60 kg/m³ and varying Polyurethane foam of densities 16, 29, 42 kg/m³ on the other side reinforced sheet showed the following variations in crashworthiness properties. As the density of polyurethane foam increases, the peak load showed an increment. Peak load maximum value of 49.7 kN for EPP60_PU42. Mean load also shows similar behaviour as peak load as the density of polyurethane foam increases mean load also increases as shown the in figure and shows a maximum value of 28.75 kN for EPP60_PU42. Crush force efficiency showed an increase when PU foam density changed from 16 to 42 kg/m³. Specific energy absorption also increased as the density of foam increased from 16 to 42 kg/m³. SEA variation with density was shown in Fig. 4f.

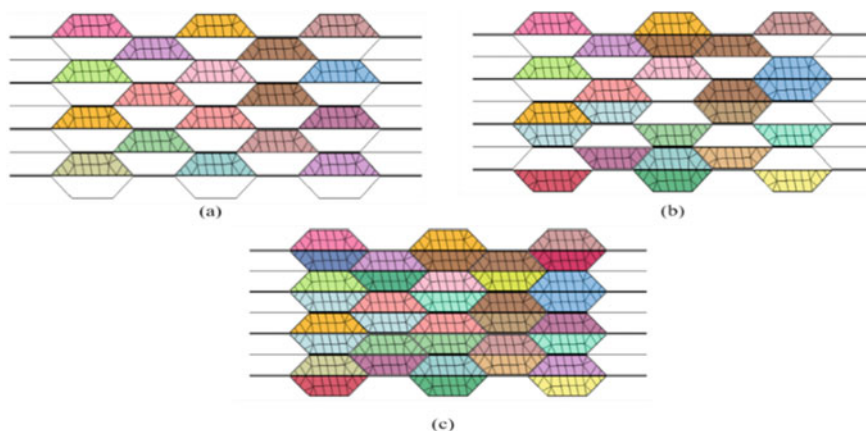


Fig. 5 Typical arrangement of honeycomb structure for **a** 50% foam filling **b** 66% foam filling **c** 100% foam filling

4.3 Effect of Different Types of Arrangements of Foam Filling in Foam-Filled Honeycomb Structures

In order to analyse the effect of the arrangement of foams on the crashworthiness properties of foam-filled reinforced honeycomb structure, three arrangements with 50% foam filling, 66% foam filling and 100% foam filling were taken for the study. The arrangement of foams was shown in Fig. 5. While arranging, care has been taken that the effect addition of foams will distribute uniformly throughout the section. Two types of foams named expanded polypropylene and polyurethane were used for the analysis. Here also, the Load displacement curve showed similar behaviour to any crashworthy structure during its crushing.

4.3.1 Expanded Polypropylene Foams

As shown in Fig. 5, 50% foam filling, 66% foam filling and 100% foam filling were done for EPP foam. As the foam filling percentage increases peak load increases. The mean load also showed an increment with an increase in density. Crush force efficiency increases when the foam filling percentage increases from 50 to 66%, but it again decreases when the foam filling percentage increases from 66 to 100%. Specific energy absorption increases with an increase in foam filling percentage. Variation in parameters was shown in Fig. 6a and b.

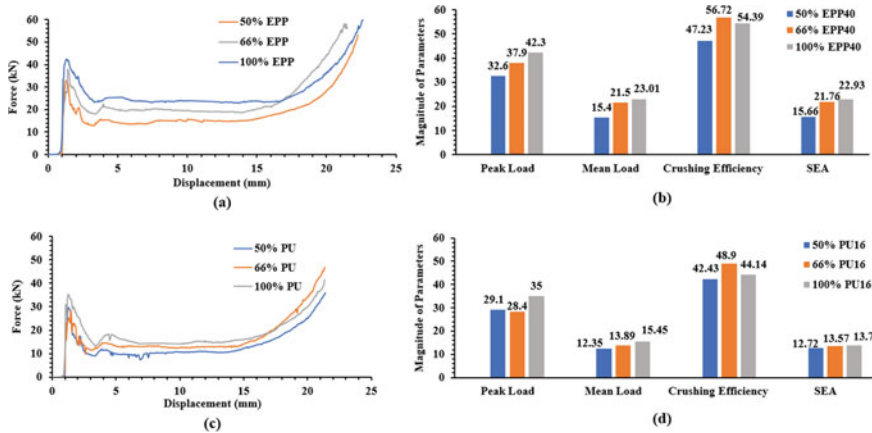


Fig. 6 Effect of different types of arrangements of foam filling in foam-filled honeycomb structures

4.3.2 Polyurethane Foams

PU foams showed similar trends in response as EPP foams. As shown in Fig. 5, 50% foam filling, 66% foam filling and 100% foam filling were done for expanded PU foam. As the foam filling percentage filling increases peak load increases. The mean load also showed an increment with an increase in density. Crush force efficiency increases when the foam filling percentage increases from 50 to 66%, it again decreases when the foam filling percentage increases from 66 to 100%. Specific energy absorption increases with an increase in foam filling percentage. Variation in parameters was shown in Fig. 6 c,d.

5 Conclusion

In this study, foam-filled reinforced honeycomb structures were crushed axially under a quasi-static loading condition using finite element simulation. The effect of filling expanded polypropylene foam (varying densities 20, 40, 60 kg/m³) and polyurethane foam (varying densities 16, 29, 42 kg/m³) in combinations on the crashworthiness of reinforced honeycomb structures was studied. Also, the effect of varying foam filling percentages of honeycomb cell (55%, 66%, 100%) on crashworthiness parameters was studied. From the study, it was concluded that as the density of PU foam filled into the reinforced honeycomb increased by keeping EPP foam density constant, crashworthiness parameters peak load, mean load and specific energy absorption was increased. In both EPP and PU foam-filled reinforced honeycombs, as foam filling percentage increased, parameters such as peak load, mean load and specific energy absorption also increased.

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