Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

COMPRESSIVE RESPONSE OF STRUT-REINFORCED KAGOME WITH POLYURETHANE REINFORCEMENT

Rinoj Gautam[1], Vijay Shankar Sridharan[2], Wee Lee Teh[3], and Sridhar Idapalapati[1,2,3]

[1]Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

[2]Rolls-Royce@NTU Corporate Lab, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

[3]School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

Abstract

Lattice structures find immense application in lightweight structures for their high specific strength, modulus, and energy absorption. Strut-reinforced Kagome (SRK) structures provide better compressive performance compared to many existing lattice structures. In this study, the performance of acrylonitrile butadiene styrene (ABS) SRK lattice structures, fabricated by fused deposition modeling, under compression loading is investigated. Further, SRK structures were filled with different polyurethane in the empty space and their effect on the compressive performance was examined. The SRK structure demonstrated abrupt failure at the joints in the vicinity of face sheet, thereby reducing the energy absorption of the structure. The SRK with flexible foam (low-density polyurethane foam) had no significant effect on peak failure load and moduli, whereas energy absorption per unit mass was higher by 16.5%. The SRK with the rigid foam (high-density foam) displayed not only the better energy absorption per unit mass (116%) but also different failure behavior than SRK only.

Introduction

Sandwich panels consist of lightweight core material in between two stiff and strong face sheets. The superior bending stiffness, high specific strength, and energy absorption of the sandwich structures give them a good potential in aerospace, marine and automobile industries [1]. The cellular core structures are either bending dominated or stretching dominated depending on their architecture [2]. Stochastic foam structures deform by the bending of the cell walls whereas the lattice structures deform either by the stretching or bending. The stretch dominated structures have higher stiffness and strength than the bending dominated structures [3]. The low relative density lattice structure collapses either by elastic or plastic buckling and the structure with high relative density fail by yielding. The foam structures have superior energy absorption ability and commonly used in energy absorption applications [4, 5].

Additive manufacturing is an innovative technology which made possible to fabricate different lattice structures with complex designs. The performance of Kagome structure fabricated through additive manufacturing under compression loadings has been investigated. Ullah et al. studied the performance of Kagome structure fabricated by selective laser melting and found that Kagome structures exhibited higher compressive strength than the conventional honeycomb structure [6]. The structures also showed similar effective modulus and energy absorption of conventional honeycomb structures [7]. Gautam et al. investigated the effect of part-built orientation and surface roughness on the compressive performance of Kagome structure fabricated by fused deposition modeling [8]. The graded relative density design of multi-layer Kagome structures exhibited higher energy absorption than the uniform density [9]. On their further studies, they studied the compressive performance of the modified Kagome structures. For the same relative density, modified Kagome exhibited higher strength and stiffness than Kagome structures [10, 11].

Different foams have been utilized as fillers in hollow cores to have better energy absorption of the sandwich panels. A study on the use of polyurethane foam on the circular cell honeycomb exhibited the stable collapse of the structure leading to the amplification of energy absorption [12]. Similarly, the composite egg box panels filled with the foam improved the energy absorption capacity [13]. Zhang et al. investigated the response of the pyramidal core structure filled with polyurethane foam under compression [14]. The foam has a synergetic effect on load carrying capacity and the structure filled with higher density foam exhibited superior energy absorption than unfilled structures. Kao et al. studied the effect of foam on the impact performance of bi-material structures [15]. The inclusion of the foam structure with high ductility improved energy absorption due to excessive local and global deformation.

In literature, we found that Kagome and SRK lattice structures demonstrated excellent strength and stiffness and foam structures exhibited tremendous energy absorption capacity. Hence, the study on the use of foam in the lattice structures under compression loading is needed. This study focuses on the use of polyurethane foam as the filler material to enhance the energy absorption capacity of the sandwich structure with strut-reinforced Kagome core. Strut reinforced structures were fabricated through fused deposition modeling with ABS material. Two different polyurethane foam with different densities were used as the fillers in the SRK core and their effect on the compressive performance of the structure was investigated.

Experimental Methods

Strut-reinforced Kagome is an improvised version of Kagome with a vertical strut in the center as shown in Figure 1. The performance of the lattice structures depends on the relative density of the structure. Thus, unit SRK structure is fully defined by the geometric parameters: strut diameter (d), the inclination of the slant strut (θ) and the height of the core (h). In this study, the strut diameter was designed as 2.3 mm, the core height of 13 mm, the inclination angle of 54.74° and face sheet thickness was 2 mm. SRK core structures, with 5 x 5 units, were designed for the compression test of sandwich structure. The arrangement of the unit structures is illustrated in Figure 2.

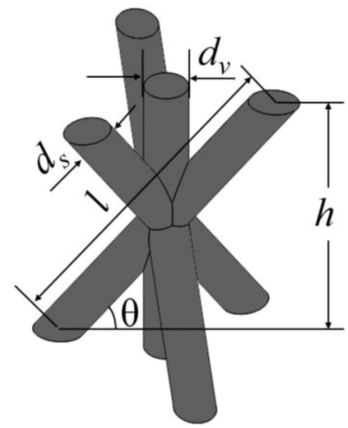


Figure 1: Unit SRK structure with its geometric parameters

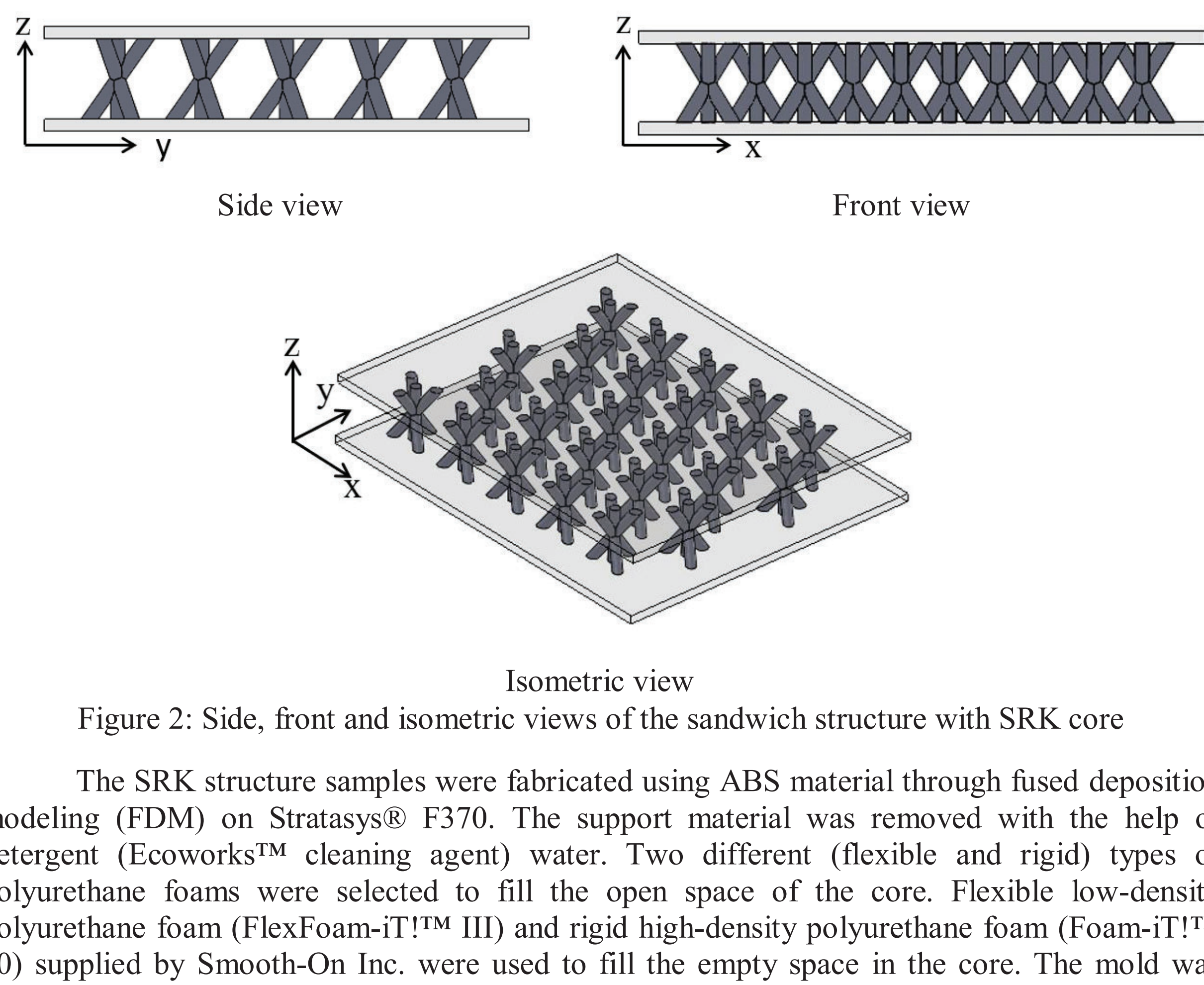


Figure 2: Side, front and isometric views of the sandwich structure with SRK core

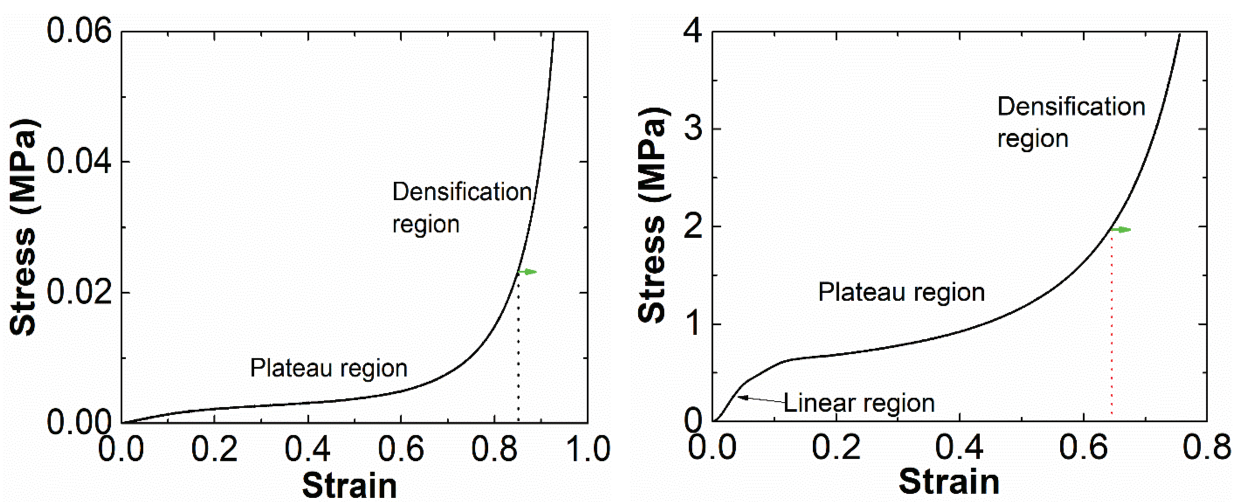
The SRK structure samples were fabricated using ABS material through fused deposition modeling (FDM) on Stratasys® F370. The support material was removed with the help of detergent (Ecoworks™ cleaning agent) water. Two different (flexible and rigid) types of polyurethane foams were selected to fill the open space of the core. Flexible low-density polyurethane foam (FlexFoam-iT!™ III) and rigid high-density polyurethane foam (Foam-iT!™ 10) supplied by Smooth-On Inc. were used to fill the empty space in the core. The mold was designed to snugly fit SRK core sandwich and fabricated using the FDM. The foam was filled in the mold-sandwich assembly such that the filling was homogenous and contained within the assembly.

The compression test on all unfilled and foam filled SRK samples were carried out on Instron 5569 universal testing machine (UTM) with 50 kN load cells with the crosshead speed of 0.2 mm/min. An external linear variable differential transformer (LVDT) was used to record the displacement of cross head of the machine. The displacement recorded by LVDT and the force recorded by data acquisition system of UTM was used to calculate the compressive stress and strain of the sandwich structures, respectively.

The properties of the foam materials were obtained by the compression test on the cube samples of 30 x 30 x 30 mm. The compression test on low-density polyurethane foam samples was carried out on 500 N load cell whereas the test on high-density polyurethane foam was carried out on 50 kN load cell.

Results and Discussion

The stress-strain curves of both flexible foam and rigid foam polyurethane are shown in Figure 3. Rigid polyurethane foam demonstrates distinct linear region whereas it is difficult to notice the linear region in the flexible foam due to its inferior load carrying capacity in the low strain. The linear region is due to the elastic deformation of the foam which occur by the cell wall bending of the foam. The near-plateau region formed due to the loss of stability of the foam and compacting drastically with almost no response to the applied load. The plateau region is followed by the densification region where the cells of the foam completely flatten, and the load increases considerably with little deformation. The rapid increase in the stress with a small increase in the strain is due to the densification (contact of cellular surfaces with each other). The onset of the densification in stress-strain curve is the strain to densification. The rigid foam has high plateau stress and the strain to densification is less than that of flexible foam as shown in Figure 3.



(a) (b)

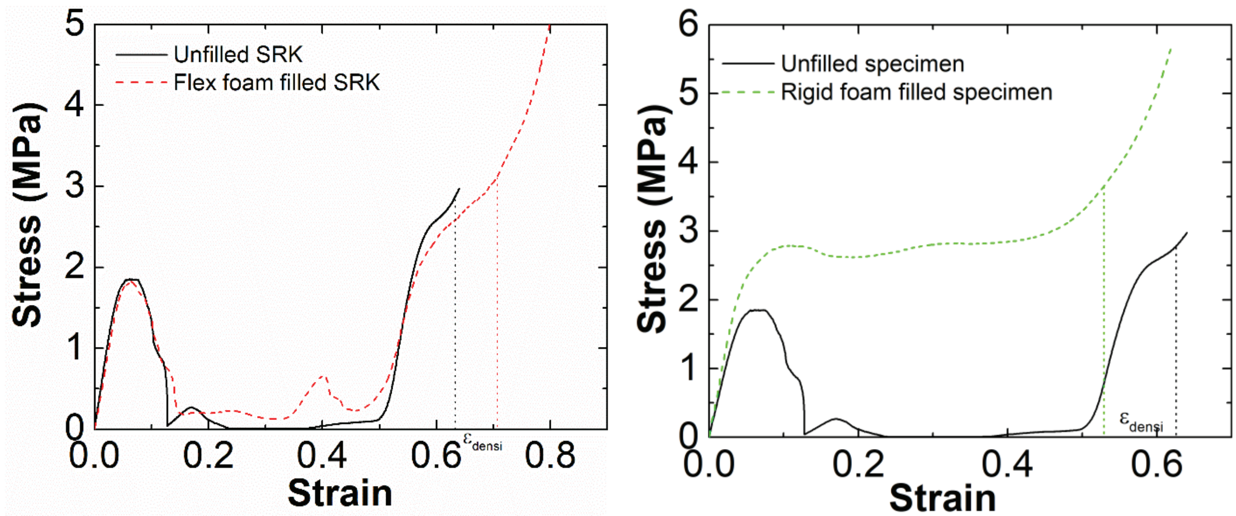
Figure 3: The compressive strain-strain curve for (a) flexible foam and (b) rigid foam

The average weight of the unfilled SRK samples, flexible foam (FF) filled, and rigid foam (RF) filled are listed in Table *1*. The increase in the weight of the SRK samples with the filling of flexible foam and rigid foam is 28.12% and 50.96%, respectively.

Table 1: Average weight of the unfilled SRK and foam filled SRK samples.

	Unfilled SRK	FF SRK	RF SRK
Average weight (g)	33.14 ± 0.07	42.46 ± 0.11	50.03 ± 0.21

The representative stress-strain curve of SRK structure under compression is depicted in Figure 4. The plot of unfilled SRK and flex foam filled SRK are presented in Figure 4 (a) to see the contribution of the flexible foam on the performance. FF SRK structure exhibited similar compressive behavior as the unfilled structure. The stress-strain curve of both unfilled SRK and FF SRK show the linear region to the initial peak stress followed by the rapid decrease in the stress. The presence of FF did not have any influence in the initial peak strength. The load supported by FF is negligible and the truss core supported the whole load. Once the truss started to fail, the structure did not support any load. The use of FF provided no support to the truss hence have the similar stress-strain curve as unfilled SRK.



(a) (b)

Figure 4: The compressive response of unfilled SRK and (a) flex foam filled SRK and (b) rigid foam filled SRK

The representative stress-strain curve of SRK and RF SRK under compression is shown in Figure 4(b). The use of rigid foam increased the initial peak strength of the structures by about 60%. This is because the RF has high density and they provided lateral support to the truss structure. After reaching the initial peak strength, the rigid foam filled displayed the plateau region. The stress continues to remain the constant, unlike the unfilled SRK structure. The cell walls of the foam began to collapse which progressed at the same constant load. The densification of the collapsed cell walls led to the densification of the structure. The densification of rigid foam filled structure occurred at lower strain than that of SRK structure.

The energy absorption per unit volume of the structure is obtained by the area under the stress-strain curve. It can be observed that the area under the stress-strain curve of RF SRK is bigger than that of unfilled SRK. The effect of the foam on the energy absorption of the structure can be compared with the energy absorption per unit weight of the structure, which considers the influence of added weight. The comparative performance of unfilled SRK and foam filled structure in terms of volumetric energy per unit mass is illustrated in Figure 5. There is a slight increase in the energy absorption to densification with the flexible foam filling in SRK core. The SRK with rigid foam filling exhibited higher (116%) energy absorption than unfilled SRK structure.

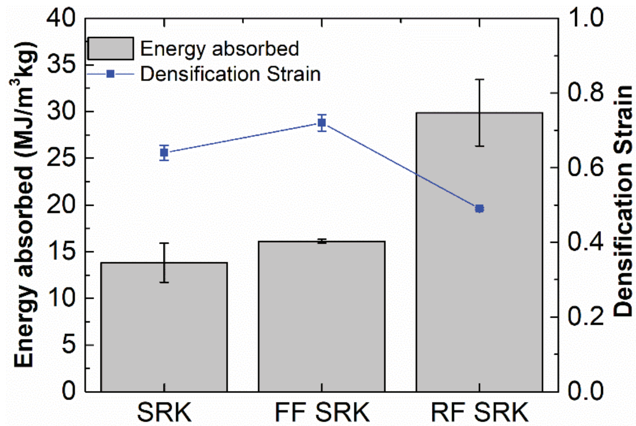


Figure 5: Total energy absorption to densification and densification strain of unfilled SRK, flex foam filled SRK and rigid foam filled SRK.

The cumulative energy of absorption per unit mass of unfilled and foam filled SRK is plotted against the strain in Figure 6. The curve for the rigid foam filled SRK is different from that of foam filled SRK and unfilled SRK. The area for the initial region of foam filled SRK is less than the unfilled SRK. In initial loading, the truss supports the applied load in the foam filled structures. Thus, the foam filled SRK have less energy absorption in the initial linear region because of the increased weight of the structures. The FF is very flexible and contributes negligibly in supporting the load, thus have similar energy absorption curve of unfilled SRK. The plateau region in the curve for FF SRK and unfilled SRK is due to the abrupt decrease in the load carrying capacity after the initial failure as shown in Figure 4(a). But the energy absorption curve of RF SRK increases almost linearly with strain. The plateau region of the stress-strain curve of RF SRK contributed to increasing the area under the curve, hence, increased the energy absorption. The rigid foam has provided the synergetic effect on the energy absorption capacity of the SRK structure.

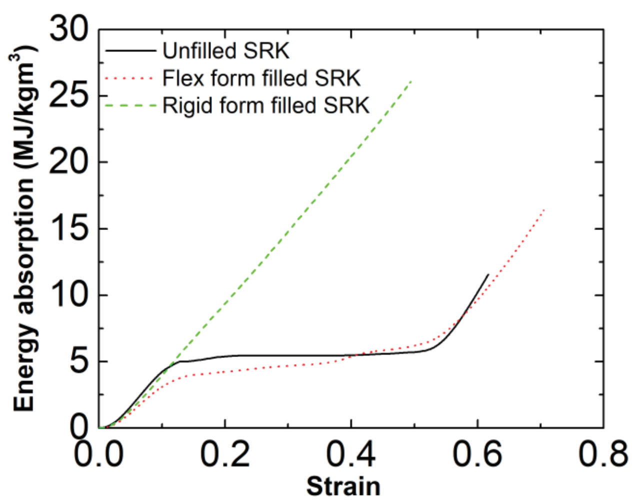


Figure 6: The energy absorption per unit weight of unfilled SRK and foam filled SRK against the strain.

Conclusion

In this study, the response of strut-reinforced Kagome core sandwich structure filled with different densities polyurethane foam under quasi-static compression loading was investigated. The compression test on unfilled SRK structure exhibited a rapid decrease in the load carrying capacity after reaching the initial peak strength. FF with SRK core could not resist the abrupt failure of the structure hence barely influenced the performance of the structure. The use of RF in the SRK core not only increased the peak load of the structure but constrained the rapid failure of the structure. The RF provided the lateral support to the SRK truss increasing the peak load. The RF with SRK truss demonstrated the synergetic effect on the energy absorption capacity of the structure. The volumetric energy absorption per unit weight (considering the increase in the weight) increased by 116% with the use of RF in SRK core structure. The selection of appropriate density foam and its use on the lattice core sandwich structure can be utilized to increase the performance of the sandwich structure.

Acknowledgments

This work is funded by Ministry of Education - Singapore (MoE) Academic Research Fund Tier 1 grant # MOE RG173/15 administered through Nanyang Technological University, Singapore.

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