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Investigation of blast resistance of cladding with square dome-shaped Kirigami folded structures as core

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Abstract. This study examines the response of Square Dome-shaped Kirigami (SDK) structures when used as a core in cladding systems under blast loading conditions. A numerical model of the SDK foldcore is developed on the commercially available software ABAQUS. The SDK foldcore made of an aluminium sheet is placed between two rigid plates. The model is put under a quasi-static compression test to simulate the crushing effect and the results are used to calibrate the simulation with the experimental data from the literature. To evaluate the blast resistance of the system, four different levels of blast loading conditions are applied to the top of the top plate using Trinitrotoluene (TNT) explosive, with a distance of 1500 mm from the centre of the top plate. The structural response of the SDK foldcore is then compared with that of a traditional Square Honey Comb (SHC) core under the same blast loading conditions. This study aims to evaluate the relative performance of the two different cores in terms of their ability to mitigate the effects of blast loading. The SDK foldcore demonstrated the capability to disperse blast energy over a wider area, thus decreasing the stress the cladding system experienced. The results of the study show that SDK foldcore provides a significant improvement in energy absorption, with a maximum reduction of 70% in the peak load transmitted compared to the case with no cladding. The peak load transmitted by the SDK foldcore is much more consistent than the SHC core, even under different blast loading conditions. This is due to its favourable plastic deformation, which prevents complete densification. These results suggest that the SDK folded structure has better performance in mitigating the effects of blast loading.

Introduction

Sandwich structures are commonly used in various fields, including transportation (such as vehicles, aircraft, and ships), packaging, and protective structures, due to their light weight and ability to absorb a large amount of energy [1]. Sacrificial cladding is used to withstand significant blast and impact loads, resulting in a large change in the geometry of the structure. Its failure is primarily caused by deformation, which is brought on by a combination of bending and stretching of the materials. Therefore, most of the energy absorbers are made of ductile material [1]. It is essential that the cladding should convert the input kinetic energy from the blast into inelastic energy. This should occur through plastic deformation or other dissipation processes, rather than simply storing it elastically. The maximum elastic deformation is reached when the initial kinetic energy is converted into elastic strain energy. The elastic strain energy then is released, potentially causing subsequent damage to the structure and those it is designed to protect.

Sacrificial cladding typically consists of two layers: an inner core and an outer skin panel. Most of the energy from the blast load is absorbed by the inner core, which deforms gradually. The outer skin panel distributes blast pressure uniformly over the inner core. The sacrificial layer absorbs energy from a nearby explosion and as a result, it experiences a significant deformation in a very short time interval. The strength of sacrificial cladding depends on various factors, such as the material properties, thickness, design of the cladding, and type of core. Various types of cores have been developed which include lattices [2], polymeric foams [3], aluminium honeycombs [4] and metallic foams [5].

A folded structure can serve as the core for sacrificial cladding. It has several advantages such as being lightweight, having a high strength-to-weight ratio, and having the ability to fold into a compact configuration. Miura introduced the folded energy-absorbing structures [6]. It is constructed from a single, unbroken sheet of material that is folded along predetermined creases without stretching or twisting the faces. It makes them suitable for use in solar panels in satellites [7]. It is relatively simple to fabricate, as it requires just a single sheet of material and a folding process, making them cost-effective. In foldcore construction, the open design of the cells allows moisture to escape through the channels, preventing it from being trapped. However, the Miura-type origami core is not as efficient in terms of crushing resistance and energy absorption capacity when compared to other core materials with similar densities [8, 9].

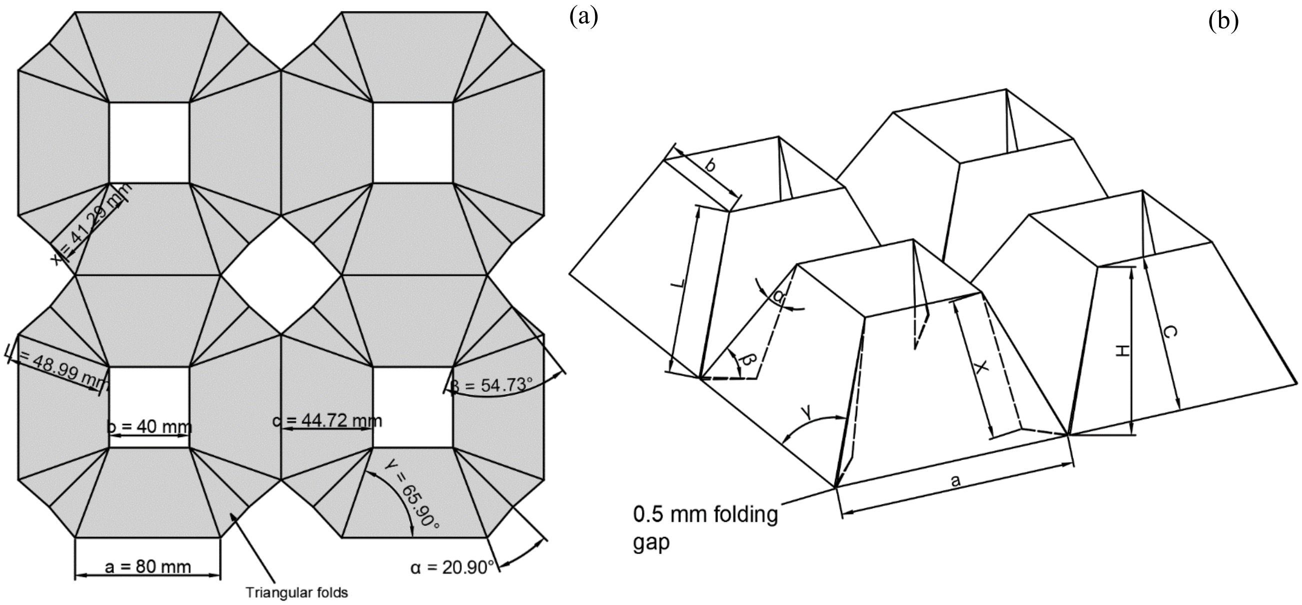

Figure 1: *(a) crease patterns and geometric parameters and (b) isometric view of folding configuration.*

Kirigami foldcore provides a way to create more efficient energy-absorbing structures. It is a variation of origami which includes folding as well as cutting to create a complex 3D structure from a single sheet of material. A study comparing the performance of the diamond strip core (kirigami foldcore) with that of the Miura-type foldcore revealed that the diamond strip core exhibited an increase in peak and average stresses of 74% and 92%, respectively [9]. Previous studies have demonstrated the potential use of a kirigami structure as a core in sacrificial cladding. However, further research is required to fully understand the various kirigami fold cores and their applications.

This study focuses on the performance of the kirigami foldcore under blast loading condition and how it compares to that of the honeycomb core. Square Dome-shaped Kirigami (SDK) foldcore is used as a core for sacrificial cladding using a single piece of aluminium sheet. Fig. 1 shows the crease patterns and the geometric properties of the foldcore. The energy absorption and crushing resistance of the foldcore increase as the vertical edges are connected since it is made from a single sheet of material. This connection provides more constraint against the out-of-plane crushing of the foldcore. This research examines the ability of the core to reduce the impact of a blast, the energy absorption capacity, and the peak load transmitted to the protected structure.

Geometry and Material Properties

The examined sandwich panels consist of top and bottom plates with a thickness of 5 mm and an aluminium SDK foldcore of 0.94 mm, giving the core a 5% relative density. The core's height is considered to be 40 mm. The material properties and true stress-strain data of Aluminium 1060 are shown in Table 1 and Table 2 respectively. Both the top and bottom plates have a density of 2400 kg/m^3 and Young's Modulus of 200 GPa.

Table 1: *Material properties of Aluminium 1060*

Parameter	Young's Modulus (GPa)	Poisson's Ratio	Yield Stress (MPa)	Density (kg/m^3)
Value	69	0.33	67.7	2710

Table 2: True stress-strain data of Aluminium 1060

Strain	0	0.002	0.005	0.013	0.063	0.121
Stress (MPa)	0	67.7	112.3	120.1	125.8	130.6

The SDK foldcore has a dimension of 80×80×40 mm. Fig. 1 shows the geometric parameters and crease pattern of foldcore. A 2 mm high boundary strip is considered on the bottom plate to constrain the outer edges of the foldcore under out-of-plane crushing and to restrict the horizontal movement of the foldcore outer edges. The foldcore and top plate are simply supported and no tie constraint is defined between the foldcore and the plates.

The geometry of the foldcore is determined by three parameters only, i.e., the length of the bottom edge (*a*), the length of the top edges (*b*), and the height of the core (*H*). The parameters are illustrated in Fig. 1(a). Other parameters can be expressed in terms of a, b and H as follows:

$$c = \sqrt{\left(\frac{a-b}{2}\right)^2 + H^2} \quad (1)$$

$$L = \sqrt{\left(\frac{a-b}{2}\right)^2 + c^2} \quad (2)$$

$$\gamma = tan^{-1}\left(\frac{2c}{a-b}\right) \quad (3)$$

$$\alpha = \gamma - \frac{\pi}{4} \quad (4)$$

$$\beta = cos^{-1}\left(\frac{\sqrt{2}a-\sqrt{2}b}{2l}\right) \quad (5)$$

$$X = \frac{sin\beta.l}{\sin(\pi-\alpha-\beta)} \quad (7)$$

The total surface area of each SDK cell,

$$A_{surf} = 4.\frac{1}{2}c(a+b) + 8.\frac{1}{2}sin\alpha.Xl \quad (8)$$

The relative density,

$$\rho_{\vartheta} = \frac{A_{surf}.T}{a^2H} \quad (9)$$

The performance of SDK foldcore is compared to that of a Square Honey Comb (SHC) Core structure made of the same material (Aluminium 1060). The SHC core has a thickness of 0.87 mm. Both cores have the same height (40 mm) and the relative density of the core is kept the same for a fair comparison.

Numerical Modelling

A finite element analysis was performed on sacrificial cladding with SDK foldcore and SHC core as the inner core on a commercially available software ABAQUS/Explicit. A quasi-static compression test was conducted in an experiment, and it was determined that the core did not tear [10]. Therefore, an isotropic-hardening plasticity material model was used with no damage initiation or evolution behaviour. The aluminium sheet is modelled as an S4R 4-noded shell element having a linear geometric order, while the top and bottom plate are modelled as a C3D8R 8-noded solid element with linear geometric order as shown in Fig. 2. The inclusion of geometric imperfections in the model improves the accuracy of predictions for the performance of the core [8, 10, 11]. Therefore, a small folding gap of 0.5 mm is considered near the corner of the unit cell for the numerical modelling to account for any imperfections that may occur during the manufacturing of the SDK foldcore.

The top and bottom plates are modelled as rigid parts. The top plate is only allowed to move in the z-direction (towards the bottom plate) while the bottom plate is fixed. The mesh size of the outer plates is not critical, as they are considered to be rigid, i.e. no stress will be developed on them. The coefficient of friction for tangential contact behaviour is set at 0.3, while the normal contact behaviour is set as hard.

Table 3: Mesh convergence study

Mesh Size (mm)	Peak Load Transmitted (kN)	Average Force Transmitted (kN)
4	127.07	12.48
2	104.97	12.62
1	100.90	12.62
0.75	100.10	12.62
0.5	103.27	12.62

A mesh convergence study was conducted using the SDK foldcore cladding model to evaluate the effects of a 1 kg Trinitrotoluene (TNT) explosion at a stand-off distance of 1.5 m. The results showed that the peak and average transmitted force on the protected structure were similar when using mesh sizes of 0.5 mm and 2 mm, as shown in Table 3. As a result, a mesh size of 2 mm, which results in 66,000 elements, was deemed sufficient for further numerical studies. The same mesh size was used for the SHC core.

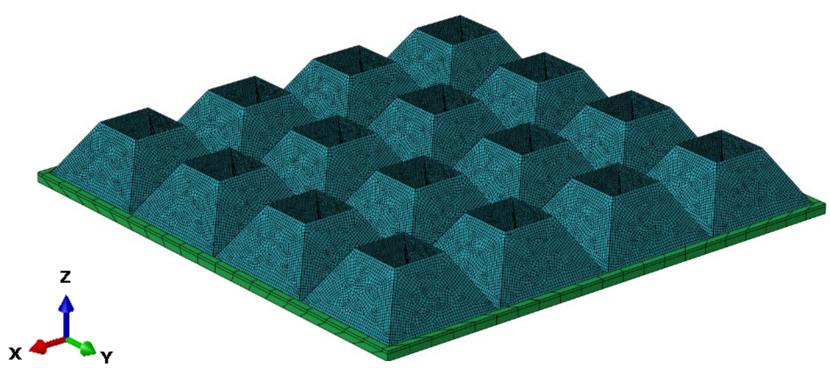

Figure 2: *Numerical model of the SDK foldcore and its base plate.*

Quasi-Static Compression Test

The numerical model considering a four-unit cell of the SDK foldcore is crushed under a quasi-static compression test. A boundary condition is applied to the top plate in which a constant loading rate of 50 mm/s is applied until 0.8H is reached. As shown in Fig. 3, the critical including plateau stress and densification strain is close for the two curves from the numerical simulation obtained in this study and the curve given by Li et al. (2018) [10]. In this study, the maximum stress achieved before complete densification is significantly higher than what was observed in experiments. This discrepancy is attributed to flaws in folding the sheet, such as not taking into account the appropriate folding gap and the initial stiffness of the foldcore. The high-pressure loading incident on the structure should be converted into a lower magnitude load with a much longer duration (due to conservation of momentum) and hence the core should provide predictable and constant load transfer up to densification. Once densification occurs, the load increase and the advantages of the cellular material are lost.

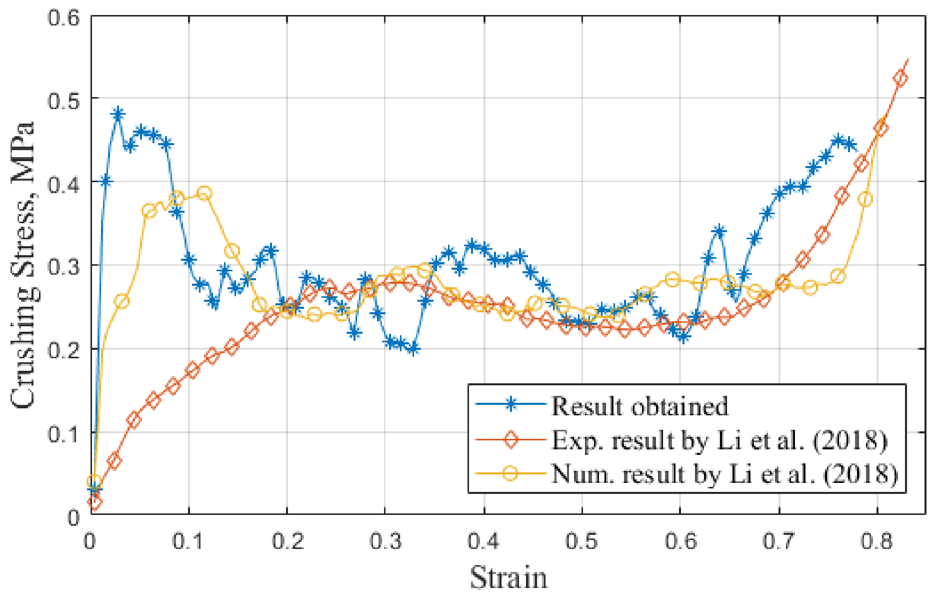

Figure 3: *Validation of Stress-Strain curve of numerical result with experimental results*

During the analysis, three distinct states of deformation can be observed. The first stage is when the peak stress is reached. This is the point at which the maximum stress is experienced by the core before it begins to deform. The second stage is when the faces of the SDK foldcore begin to bend. In the third stage, the load is consistently transferred throughout the core, resulting in a constant load transfer. In the final stage, densification of the core occurs. This is when the core becomes more compact, its relative density increases and it becomes more resistant to further deformation.

Ideal Blast Wave Profile

After an explosion occurs, the pressure increases instantaneously and then decays exponentially. The blast pressure wave depends on the mass of charge, the distance of the centre of charge, and time. Fig. 4 shows an ideal blast wave resulting from an explosion in the air. The maximum pressure reached is known as peak positive pressure, P_{pos}. The time required for the pressure to become P_{pos} after the blast is called arrival time, t_a. In the decay phase, the pressure becomes lower than the ambient pressure (P_o), known as under pressure, P_{neg}. The blast wave profile is described by the Modified Friedlander Equation [12]. It depends on time, t which starts at the arrival of the pressure wave at this point, i.e. $t = t_o - t_a$ as,

$$P(t) = P_o + P_{pos}\left(1 - \frac{t}{t_{pos}}\right) e^{-b\frac{t}{t_{pos}}} \tag{10}$$

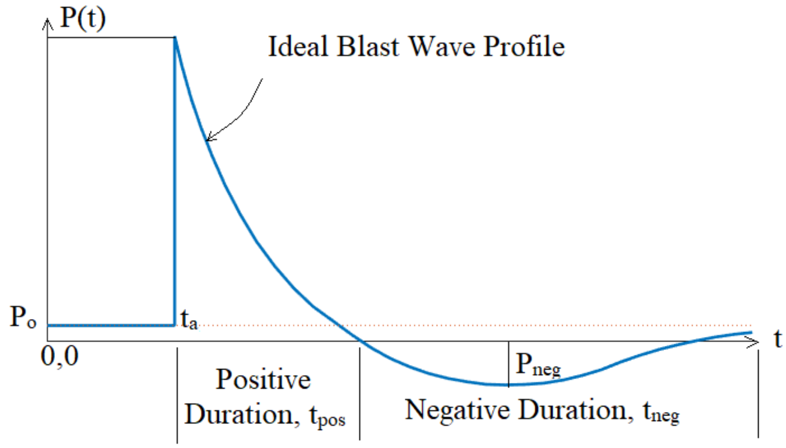

Figure 4: *Ideal Blast Wave resulting from an explosion in the air.*

Blast Loading

Sixteen SDK unit cells of dimension 80×80×40 mm are sandwiched between two rigid plates making the core 320×320×40 mm, as shown in Fig. 5(a). The unit cell size of the SHC has been established as 40×40×40 mm, resulting in a top-opening dimension that matches that of the SDK foldcore as shown in Fig. 5(b). The top and bottom plates are of dimension 330×330×5 mm with a 2 mm high boundary strip at the edges of the bottom plate. TNT of 1kg, 2kg, 4kg and 6kg is used as a spherical free airblast source at a distance of 1500 mm (scaled distance of 1500 mm/kg$^{1/3}$, 1190.55 mm/kg$^{1/3}$, 944.94 mm/kg$^{1/3}$ and 825.48 mm/kg$^{1/3}$ respectively referring to Eq. 11) from the centre of mass of the top plate. The expression for scaled distance is as follows:

$$Z = \frac{R}{M^{1/3}} \tag{11}$$

Where Z = scaled distance (m/kg$^{1/3}$)
R = distance to the structure of concern (m)
M = mass of blast charge (kg)

CONWEP [13] is used to calculate the pressure wave and the arrival time and is directly applied on the top surface of the rigid top plate. The force transmitted to the top of the bottom plate is observed for 3 ms. The transmitted force-time history curve of the protected structure under various blast loads is shown in Fig. 7. The peak load transmitted to the protected structure for the no-cladding case is 141.51 kN. The deformation of the cladding can be divided into three states i.e. (i) elastic state, (ii) plastic state and (iii) fully densified state. The elastic state is the temporary deformation of a structure that returns to its original shape when the stress or force causing the deformation is removed. This type of deformation can be observed when the transmitted force fluctuates multiple times. The SHC core is observed to be in an elastic state for initial cases of loading considered in this study. The maximum displacement of the top plate is 0.88 mm for the SHC core (2.2% of the depth of the core). As the strength of the blast wave increases while maintaining a constant distance from the structure, the arrival time decreases and the peak transmitted force increases.

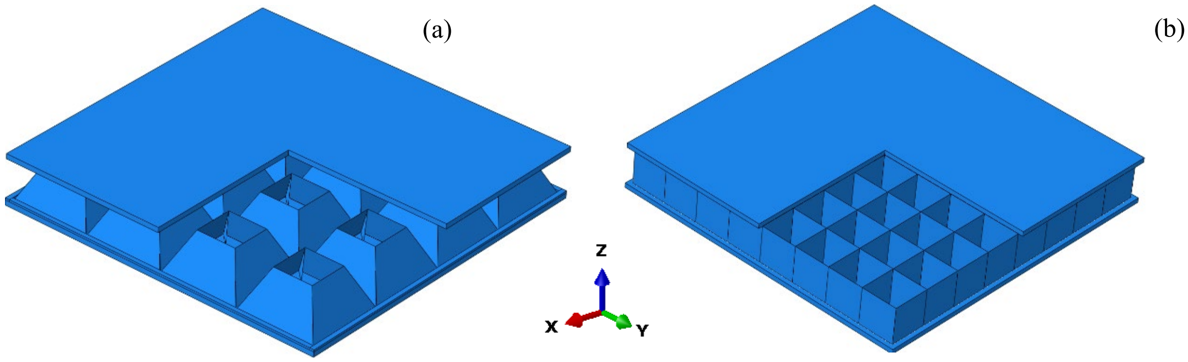

Figure 5: *Numerical model of (a) SDK foldcore for blast analysis and (b) square honeycomb core for blast analysis.*

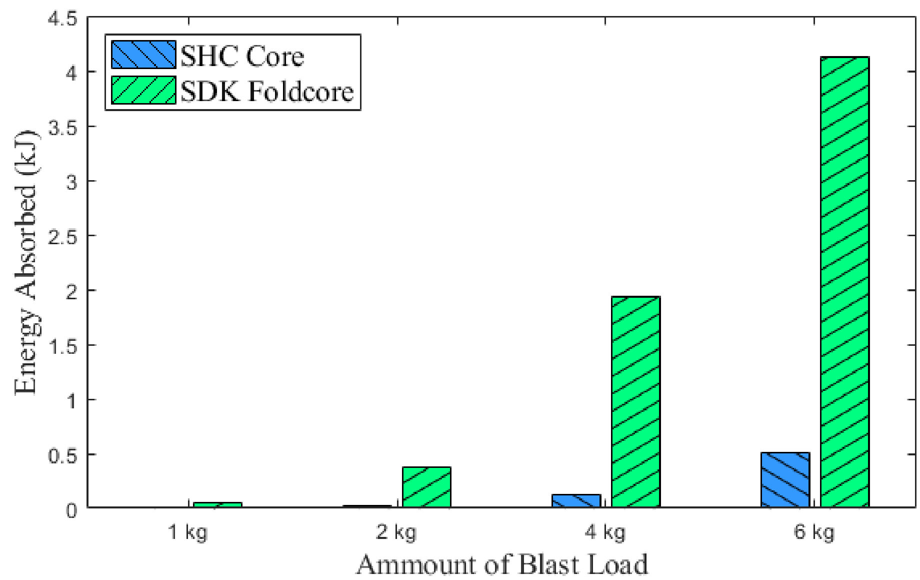

Figure 6: *Energy absorption by core for various blast loading*

The SDK foldcore exhibits a higher average transmitted force for all the loads considered in this study, which supports the presence of plastic deformation across all loading scenarios (as listed in Table 4). In contrast, the SHC core transmits more load than the no-cladding case for 1kg, 2kg, and 4kg of TNT blast load, which may result in greater damage to the protected structure. The SDK foldcore can reduce a maximum of 68.7% of the peak load in the no-cladding case. It demonstrates favourable energy absorption properties under both quasi-static and dynamic loading. This is evident through the higher plastic strain, avoiding full densification, low initial peak stress, and a small ratio of average stress to peak stress. The comparison of energy absorption by the two cores is shown in Fig. 6.

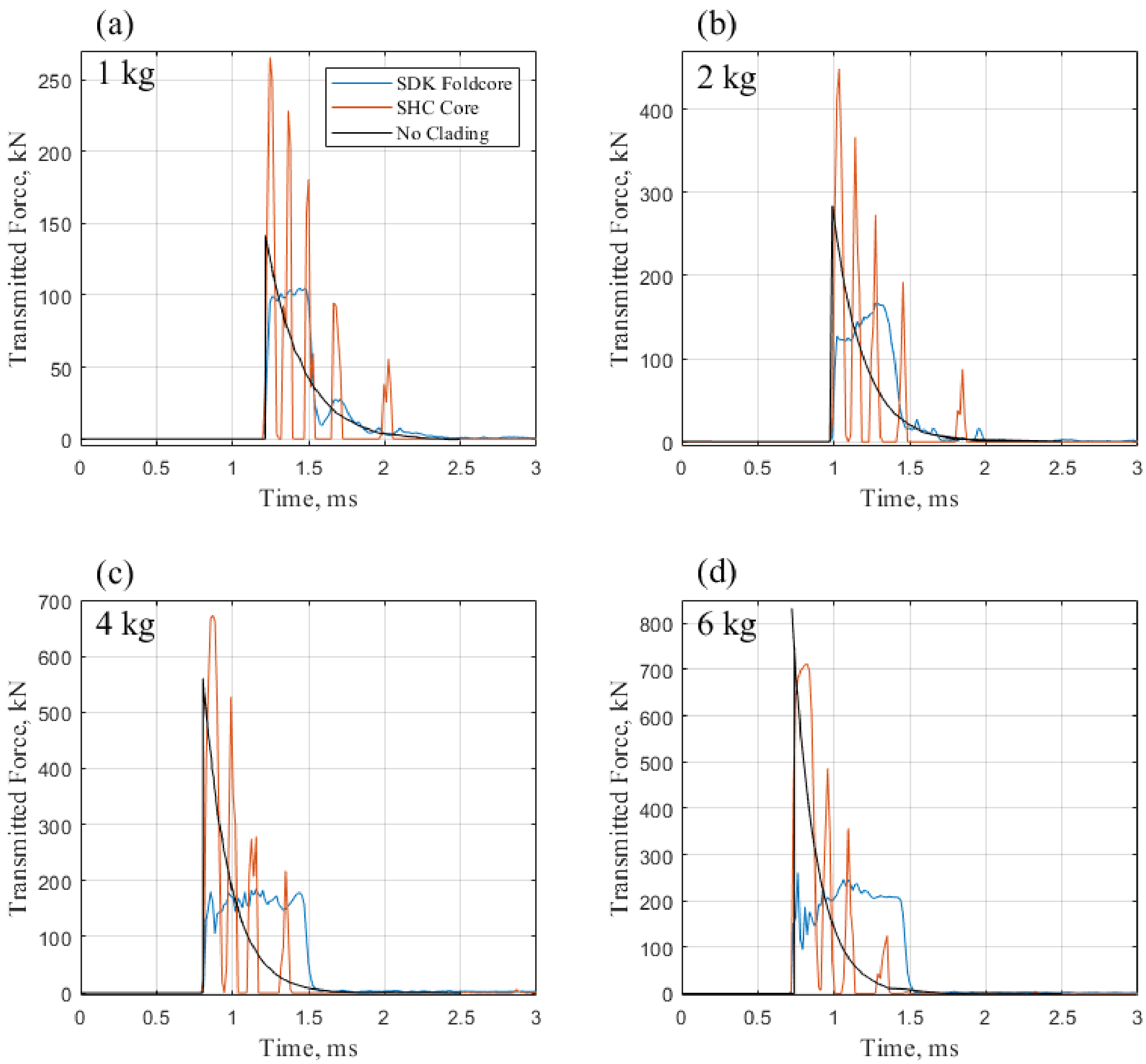

Figure 7: *Comparison of transmitted force-time history curves under different blast loads; (a) 1 kg TNT; (b) 2 kg TNT; (c) 4 kg TNT; (d) 6 kg TNT.*

As the blast load increases, the capacity for energy absorption also increases when subjected to higher blast loads. Significant improvement in energy absorption is observed for SDK foldcore. The low value of energy absorbed by the SHC core when subjected to 1 kg and 2 kg of blast load suggests that it remains in an elastic state. An energy-absorbing structure or material under impact must provide enough total energy-absorption capacity during the large deformation process, while also keeping the peak force (and thus the peak deceleration) below the level that would cause harm or injury. Additionally, the reactive force should remain stable or almost consistent to prevent an excessively high rate of deceleration, which is demonstrated by SDK foldcore.

When the core is completely densified, it should be able to absorb some of the energy from the blast. However, the peak transmitted force may increase to a value that is higher than it would be without cladding in some cases. The peak transmitted force in an elastic state will be observed immediately after the blast, but for a densified state, it will be observed near the end of the test after the material has undergone plastic deformation. As a result, the plastic state is the most desirable, which absorbs more energy and transmits less load to the protected structure.

Table 4: Peak transmitted load, duration and the crushed distance at the cladding centre by a core of different cladding configurations under various TNT blast loads.

Amount of TNT	Cladding type	P_{peak} (kN)	$P_{average}$ (kN)	Duration (ms)	Peak crushed distance at centre δ (mm)	Energy Absorbed by core (J)
1 kg TNT	No-cladding	141.51	-	0.78	-	-
1.5	SHC core	265.33	11.76	0.79	0.05	3
m/kg$^{1/3}$	SDK foldcore	104.97	12.62	0.75	0.74	51.45
2 kg TNT	No-cladding	284.05	-	0.79	-	-
1.19	SHC core	448.21	19.43	0.90	0.11	16.21
m/kg$^{1/3}$	SDK foldcore	167.07	21.62	0.84	3.21	368.12
4 kg TNT	No-cladding	560.59	-	0.80	-	-
0.94	SHC core	672.81	33.50	0.59	0.32	121.25
m/kg$^{1/3}$	SDK foldcore	184.90	37.82	0.81	13.16	1934.60
6 kg TNT	No-cladding	832.29	-	0.79	-	-
0.83	SHC core	711.67	45.39	0.62	0.88	503.34
m/kg$^{1/3}$	SDK foldcore	260.74	50.98	0.84	21.57	4128.50

Summary and Conclusions

The study presented in the paper focused on evaluating the performance of an SDK foldcore as the core of a sacrificial cladding system. The results were compared to those of an SHC core with the same relative density. SDK foldcore can be made from a single sheet of material, making it different from other high-performing cores. SDK foldcore can be made through stamping, but the thickness of the core needs to be reduced to minimize folding gaps and join the vertical edges more accurately. The SDK foldcore showed plastic deformation and prevented complete densification, which is a desirable type of failure, while the SHC core showed elastic deformation, leading to a higher peak transmitted load than without cladding. The other two states, elastic and fully densified, occur when the cladding is too weak or too strong with respect to the reflected blast pressure, resulting in reduced effectiveness of the cladding.

The square dome kirigami foldcore design shows effective energy absorption properties in both static and dynamic conditions, due to its high-density strain, low maximum stress, and a low ratio between average stress and peak stress. The unique blend of their strength and energy-absorbing abilities, combined with the capacity to fold and unfold, makes kirigami structures an optimal choice for situations where maintaining structural stability and resilience to impact are crucial. Further studies are needed to determine the optimal SDK geometry for various applications and to explore its potential use in sacrificial cladding, due to its uniform crushing resistance and insensitivity to strain rate.

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