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Fire protection design for composite lattice sandwich structure

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Abstract: Composite lattice structures are of considerable mechanical property and multifunctional design flexibility. However, the relatively low operating temperature of polymer composite prevents its application in high temperature or fire-proofing structures. Here, we propose a type of lightweight composite lattice sandwich structure that is capable of fire proofing as well as load bearing. In our design, the composite lattice sandwich structure is filled with heat insulation materials to interdict the thermal radiation and convection between its two facesheets. The top facesheet of the structure is covered with intumescent coating to isolate fire. Moreover, thermoresistant resin or flame retardant is adopted in manufacturing the top facesheet to improve its thermoresistance. A design procedure has been developed for such kind of fire-proofing structure, by which the material and geometry of the structure can be determined according to the fire-proofing effect. It was demonstrated by experiment that a 30-mm-thick structure, designed by the present procedure, was able to isolate 945°C fire load on the exposed surface for 3600 s, keeping the unexposed surface temperature rise below 139°C.

Keywords: composite lattice sandwich structure; fire protection design; heat transfer.

1 Introduction

With the advancement of technology, structural materials in industry are being required to become lightweight and multifunctional besides load bearing [1–4]. For example, in aerospace [5] and marine industries [6], structures are always needed to be able to sustain harsh thermal load [7], such as aerodynamic heating [8], intense fire, and gun-powder explosion [9]. Composite lattice structure is characterized by its multifunctional design flexibility as well as high specific stiffness and strength [10], which makes it prospective for structures in advanced industry. However, the relatively low operating temperature of polymer composite prevents its application in high temperature or fire-proofing structures [11]. Therefore, it is of great significance to improve the heat insulation and fire-proofing performance of composite lattice structure.

Fire-proofing structure is not only capable of isolating fire, but also insulating the heat flux so as to control the unexposed surface temperature rise (USTR). In the design of fire-proofing composite lattice structure, covering the surface exposed to fire with intumescent coating is one of the irreplaceable procedures. When exposed to fire, an intumescent coating undergoes several reactions forming multicellular chars as the temperature increases, which acts as thermal barrier. Numerous models have been developed to evaluate the heat transfer performance of intumescent coatings [12–14]. Di Blasi and Branca [15] proposed a 1-D transient mathematical model to study a composite system consisting of a substrate (steel) with intumescent coating exposed to radiant heating. A good agreement was found between the predicted and measured data of the substrate temperature profiles. Taylor et al. [16] studied systematically the factors influencing the fire-proofing performance of intumescent coating, including the substrate thickness, the coating dry film thickness, and levels of radiant heat flux. Another important procedure to improve the fire-proofing performance, or more accurately the heat insulation performance of the composite lattice sandwich structure, is to suppress the thermal conductivity of the lattice core. Similar to cellular foams, lattice structures, themselves, are of considerable heat insulation performance due to high porosity [17, 18].

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Wei et al. [19] studied the heat transfer mechanism of C/SiC ceramic pyramidal lattice structures at high temperature up to 1600°C and found that thermal cavity radiation plays a significant role in heat transfer. Wen et al. [20] studied heat transfer characteristic of sandwiched metallic honeycomb structures with one face-sheet heated by constant heat flux and cooled by forced air convection. They found that the overall heat transfer rate is a function of surface area density, cell configuration and dimensions, and the thermal conductivity of the parent material. Nevertheless, to our knowledge, there is still no literature published on composite lattice structures acting as fire proofing or even heat insulation structures.

In this paper, we propose a type of lightweight composite lattice sandwich structure that is capable of fire proofing as well as load bearing. The construction and fire-proofing mechanism of such kind of structure is introduced at first. Then, a design procedure for the present composite lattice sandwich structure is clarified, by which the material and geometry of the structure can be determined according to the fire-proofing effect. Samples of fire-proofing composite lattice sandwich structure were prepared according to the design, and fire resistance tests have been conducted to evaluate their fire-proofing performance.

2 Heat insulation mechanism of fire-proofing composite lattice sandwich structure

The fire-proofing composite lattice sandwich structure proposed in this study mainly consists of four parts, namely, the bottom facesheet, the lattice core (which consists of core truss and insulation material), the top facesheet, and the intumescent coating that covered the top facesheet, as shown in Figure 1. As the fire-proofing structure is designed not only for isolating fire but also for insulating the heat flux, heat transfer control of such kind of structure is a key factor in its design procedure.

2.1 Heat transfer in intumescent coating

Intumescent coatings are composed of three active constituents: a swelling agent, an acid source, and a carbon source [21]. Generally, physical-chemical transformations occur when the coating reaches 250°C. Carbonization starts at about 300°C [11, 22], which generates a

Figure 1: Schematic of the fire-proofing composite lattice sandwich structure.

nonreactive char layer to isolate fire. On the other hand, thickness of the thoroughly reacted coating becomes several times thicker than the original one and, thus, improving the heat insulation performance. The photographs of intumescent coating before and after fire hazard are shown in Figure 2. For fire load above 900°C, the char layer is generated within 30 min. Therefore, for a long-time fire-proofing test, such as a test lasting for 1 h, the steady heat transfer process can be supposed. The thermal conductivity of the porous char layer dominated the heat insulation effect of the coating.

The thermal conductivity of a porous material can be divided into three parts, namely, conduction through solid and gas, convection within the cells, and radiation through the cell walls and across the cell voids. However, the cell size of the char layer is <1 mm, resulting in the Grashof number smaller than 1. As heat transfer by convection is comparable with the other two parts only when the Grashof number is no <1000, heat convection in the char layer can be omitted. Therefore, the thermal conductivity of the char layer is only contributed by conduction and radiation, which can be expressed as [23]:

$$\lambda_{ch} = \frac{\lambda_{sl} \lambda_{ga}}{\lambda_{sl} f_{ga} + \lambda_{ga} f_{sl}} + \lambda_{Tr} \quad (1)$$

where λ represents the thermal conductivity, and f denotes the volume fraction. The subscripts 'ch', 'sl', and 'ga' denote char, solid, and gas, respectively. λ_{Tr} is the thermal conductivity contributed by cell radiation that can be written as:

$$\lambda_{Tr} = 13.5\sigma T^3 \frac{d_{ch}}{\varphi\omega} \quad (2)$$

Figure 2: Photographs of intumescent coating before (A) and after (B) fire hazard.

where σ is the Stefan-Boltzmann constant, T is the temperature, φ and ω are the porosity and pore emissivity, respectively. d_{ch} denotes the average diameter of pores in the char layer.

2.2 Heat transfer in composite lattice sandwich structure

The char layer generated in fire test serves as the first heat insulation layer, which protects the structure from suffering high temperature as well as causing combustion reaction. However, as the temperature right behind the char layer may still be higher than the design requirement, the composite lattice sandwich structure is taken as the second heat insulation layer that further brings down the unexposed surface temperature. Similar to cellular foams, lattice structures are of considerable heat insulation performance due to high porosity. In our design, to further suppress its effective thermal conductivity, high temperature heat insulation materials is filled into the lattice core, as shown in Figure 3.

The effective thermal conductivity of composite lattice sandwich structure is taken as the parallel-serial model of top facesheet, lattice core, and bottom facesheet, which can be computed as:

$$\frac{1}{\lambda_{ss}} = \frac{f_{tf}}{\lambda_{tf}} + \frac{f_{lc}}{\lambda_{lc}} + \frac{f_{bf}}{\lambda_{bf}} \quad (3)$$

where the subscripts 'ss', 'lc', 'tf', and 'bf' denote sandwich structure, lattice core, top facesheet, and bottom facesheet, respectively. The two facesheets are made of carbon fiber-reinforced resin matrix composites, in which the fiber bundles are uniformly distributed without

Figure 3: Schematic of the composite lattice sandwich structure and heat transfer process.

contact with each other. The effective thermal conductivity of fiber-reinforced composite with low fiber volume fraction (take top facesheet as example) can be estimated by the Maxwell-Eucken model (adapted in 1940 by Eucken):

$$\lambda_{tf} = \frac{\lambda_{mt}f_{mt} + \lambda_{cf}(1-f_{mt})[3\lambda_{mt}/(2\lambda_{mt} + \lambda_{cf})]}{f_{mt} + (1-f_{mt})[3\lambda_{mt}/(2\lambda_{mt} + \lambda_{cf})]} \quad (4)$$

where the subscripts 'mt' and 'cf' denote the matrix of facesheet and carbon fiber bundles. Regarding to the lattice core, as the cell size is about 20 mm, the contribution of convection to the heat transfer is unignorable. Therefore, to avoid the convective heat transfer, insulation materials should be filled into the lattice core, which also interdicts cavity radiation between the two facesheets. As a result, the heat transfer in the lattice core mainly consists of heat conduction via lattice rods and the heat insulation fillers. The lattice rod with diameter of d_{lr} is made of carbon fiber. The carbon fiber is surrounded by resin,

with its cross section shown in Figure 3. The inclined angle between the lattice rod and the facesheet is θ . As the thermal conductivity of resin is much lower than that of carbon fiber, it is assumed that the heat conduction process of carbon fiber is not interactive with the filler material. Thus, the thermal conductivity of the lattice core can be computed as:

$$\frac{1}{\lambda_{lc}} = \frac{f_{lr}}{\lambda_{lr} \sin \theta} + \frac{1-f_{lr}}{\lambda_{fl}} \quad (5)$$

where the subscript 'fl' denotes the filler material.

During the fire-proofing test, the top facesheet with coating is exposed to fire, while the bottom facesheet is exposed to air at room temperature. When the steady-state heat transfer is reached, the heat flux can be computed as:

$$q = \frac{T_{fr} - T_{ar}}{\frac{L_{ch}}{\lambda_{ch}} + \frac{L_{ss}}{\lambda_{ss}} + \frac{1}{h}} \quad (6)$$

where q is the heat flux, T is the temperature, L is the thickness. h is the convection heat transfer coefficient between the bottom facesheet and the adjacent air. The subscripts 'fr' and 'ar' denote fire and air, respectively. With room temperature and given the USTR of the bottom facesheet, a heat flux can be figured out. When the heat flux is computed, the temperature of each interface of the lattice sandwich structure can be figured out in turn. Hence, when the upper limit of the USTR, namely, the maximum temperature difference of the bottom facesheet before and during the fire hazard, is determined, each part of the sandwich structure can be designed accordingly. Similarly, with room temperature and the highest temperature of the top facesheet, another heat flux can be figured out. Hence, we can make another design case of the sandwich structure. Last, according to these two design cases, the safer proposal should be chosen as the right plan.

3 Design procedure of fire-proofing composite lattice sandwich structure

The proposed design procedure of a fire-proofing composite lattice sandwich structure is as follows, as shown in Figure 4:

1. Determine the temperature of fire load as well as the maximum and minimum environment temperatures according to the actual operating condition of the fire-proofing composite lattice sandwich structure.

Determine the upper limit of the USTR and the top facesheet temperature according to the required fire-proofing performance.

2. Design the lattice topology and dimensions according to the requirement of mechanical performance.
3. Choose the proper resin and fire retardant according to heat resistance, economy, and manufacturability when manufacturing the facesheets (the thermal resistance properties of the panel in front of the fire must not be worse than the panel at the back of the fire). Choose the proper heat insulation materials to fill into the lattice core. Compute the thermal conductivity of the lattice sandwich structure by Eqs. (3)–(5).
4. Choose intumescent coating and estimate the thermal conductivity of the char layer by Eqs. (1)–(2) according to the type of coating and the temperature of fire load.
5. Compute the steady heat flux q_1 by $q_1 = h \cdot \Delta T$, where ΔT is the upper limit of USTR. Then, substitute the effective thermal conductivity λ_{ss} and λ_{ch} , the thickness of the sandwich structure L_{ss} , the temperature of the fire load T_{fr} into Eq. (6), and adopt the maximum or minimum environment temperature as T_{ar} ; two candidate values of char layer thickness L_{ch1} , L_{ch2} can be estimated. Similarly, compute the steady heat flux q_2 by

$$q_2 = \frac{T_{fr} - T_{ar}}{\frac{L_{ss}}{\lambda_{ss}} + \frac{1}{h}} \quad (7)$$

Hence, another two candidate values of char layer thickness L_{ch3} , L_{ch4} can be computed by constraining the top facesheet temperature below its upper limit. The maximum among the four candidate values is adopted as the right thickness of the coating char.

$$L_{ch} = \text{Max}\{L_{ch1}, L_{ch2}, L_{ch3}, L_{ch4}\}. \quad (8)$$

6. Manufacture samples according to the design result, and conduct the fire-proofing test to verify the fire-proofing performance, especially the USTR.

4 A design case

The temperature of fire load was determined to be 945°C, which was the highest temperature of the Standard Fire Curve, and the test duration was 3600 s. The maximum and minimum environment temperatures were 40°C and -30°C, respectively. During all the tests, the USTR must not be higher than 139°C, and the temperature of the top facesheet must be controlled under 200°C.

Figure 4: Design procedure of the fire-proofing composite lattice sandwich structure.

The topology of the lattice core was chosen to be pyramidal lattice, and the lattice rods were made of carbon fiber, which had been twisted and infiltrated into resin. Facesheets of the sandwich structure were made of carbon fiber-reinforced resin matrix composites, in which a thermal stable resin was required. Considering heat resistance, economy, and manufacturability, both top and bottom facesheets were made of the epoxy resin. Thus, the temperature of the top facesheet should be controlled under 200°C during all the tests. The dimensions of the lattice sandwich structure were determined by the mechanical design, as listed in Table 1. The polycrystalline mullite fiber was chosen as the heat insulation filler. Regarding the intumescent coating, the HM-1 ship fire-proofing coating developed by the Marine Chemical Research Institute was adopted. The inflated char layer of such coating can be eight times thicker than the original coating and is able to sustain 950°C of fire for a long time without losing strength and toughness. The gas phase in the char layer was assumed to be a mixture of the principal combustion gases [25], i.e. 50 wt% of CO₂ and 50 wt% of H₂O.

According to the aforementioned, the basic materials together with the geometry and physical parameters as listed in Table 1, we were able to design the thickness of the virgin intumescent coating. First, combining Eqs. (1) and (2), the thermal conductivity of the char layer was

Table 1: Material and geometry parameters in the design case.

Parameters	Value	References
Geometry parameters determined by mechanical property		
L_{tr}, L_{bf}	3 mm	Designed by need for mechanical performance [24]
L_{lc}	18 mm	Designed by need for mechanical performance [24]
d_{tr}	2 mm	Designed by need for mechanical performance [24]
θ	45°	Designed by need for mechanical performance [24]
Physical parameters		
f_{mt}	60 wt%	Measured
f_{cf}	40 wt%	Measured
$\lambda_{tr,ad}$	55 Wm ⁻¹ K ⁻¹	As quoted from manufacturer
$\lambda_{tr,rd}$	6.5 Wm ⁻¹ K ⁻¹	As quoted from manufacturer
λ_{CO_2}	0.017 Wm ⁻¹ K ⁻¹	As quoted from [25]
λ_{H_2O}	0.025 Wm ⁻¹ K ⁻¹	As quoted from [25]
$\lambda_{ch,sl}$	22.5 Wm ⁻¹ K ⁻¹	As quoted from [26]
λ_{fl}	0.25 Wm ⁻¹ K ⁻¹	As quoted from manufacturer
λ_{mt}	0.3 Wm ⁻¹ K ⁻¹	As quoted from manufacturer
ρ_{CO_2}	0.63 kg m ⁻³	As quoted from [25]
ρ_{H_2O}	0.26 kg m ⁻³	As quoted from [25]
ρ_{ch}	104 kg m ⁻³	Measured based on [26]
$\rho_{ch,sl}$	1670 kg m ⁻³	As quoted from [26]
H	16 Wm ⁻¹ K ⁻¹	Measured
σ	5.67e8 Wm ⁻² K	Based on literature values
ω	1	As quoted from [15]
d_{ch}	26e-3 mm	Measured based on [15]

calculated to be $\lambda_{ch}=0.0816$ Wm⁻¹ K⁻¹. The effective thermal conductivity of the lattice sandwich structure was also figured out to be $\lambda_{ss}=1.14$ Wm⁻¹ K⁻¹, using Eqs. (3)–(5). Then, the steady heat flux q_1, q_2 was calculated, and the four candidate values of char layer thickness were estimated to be 29 mm, 22 mm, 26 mm, and 32 mm following the procedure mentioned in step 5. Thus, the char layer thickness of 32 mm was adopted. As the expansion rate of the intumescent coating under 945°C of fire is around 8, the thickness of the original intumescent coating should not be <4 mm. When a safety factor of 1.5 was required, the coating thickness was finally determined to be 6 mm.

5 Materials and methods

5.1 Fire-proofing experiment

In the present paper, unidirectional carbon fiber supplied by Hengtong Carbon Fibres Co., Ltd (Jiangsu, China), was used to fabricate the facesheets and pyramidal lattice truss

core, and the polymer used as matrix was epoxy, supplied by Sino Polymer Co., Ltd (Shanghai, China). The mullite fibers are commercial products purchased from Bangni Refractory Fiber Co., Ltd. (Zhejiang, China). Intumescent coating plays the main role in fire proofing, supplied by the Marine Chemical Research Institute (Shandong, China).

Fire-proofing tests were carried out on three types of samples, namely, the aluminum alloy panel covered with intumescent coating, the lattice-reinforced sandwich structure without foam core, and the complete fire-proofing composite lattice sandwich structure as comparison. All samples were 100×100 mm in plane, as shown in Figure 5. The sample (A) was a 1.5-mm-thick panel covered with 6 ± 0.1 mm intumescent coating. The sample (B) was a composite lattice sandwich structure covered with 6 ± 0.1 mm intumescent coating, and the sample (C) was the same as (B) except the polycrystalline mullite fiber core. Thickness of the two facesheets and the lattice core were 3 ± 0.1 mm, 3 ± 0.1 mm, and 18 ± 0.5 mm, respectively. The diameter of the lattice rod was 2 ± 0.1 mm, and the angle between the lattice rod and the facesheet was

$45^\circ\pm 5^\circ$. Moreover, each value obtained represented the average of three samples.

The fire-proofing tests were carried out in the National Laboratory of Flame Retardant Materials in Beijing Institute of Technology with an environment temperature of 17°C . The sample was clamped vertically on a frame. The fire temperature was 1050°C , and the distance between the flame gun and the sample was adjusted to generate a 945°C fire load on the sample surface. During the test, the fire load on the sample surface was measured to be within the range of 935°C to 950°C , and the unexposed surface temperature was measured by temperature sensors on two points. A schematic and a photograph of the testing apparatus are shown in Figure 6.

5.2 Flat crush test

To study the effect of fire load on the out-of-plane compression behaviors of a lattice-reinforced sandwich composite, the quasi-static out-of-plane compression test were

Figure 5: Photographs of test samples: (A) aluminum alloy panel covered with intumescent coating; (B) lattice reinforced sandwich structure without foam core; (C) complete fire-proofing composite lattice sandwich structure. Sample (A) is tested to validate the thermal-proofing property of coating; sample (B) for the lattice reinforced sandwich structure and the coating but without foam core; while sample (C) for the whole structure, where 1 refers to virgin intumescent coating, 2 refers to substrate (aluminum alloy), 3 refers to the facesheet exposed to fire, 4 refers the polycrystalline mullite fiber core, 5 refers to the lattice truss core, 6 refers to the facesheet unexposed to fire.

Figure 6: The fire-proofing testing apparatus: (A) schematic; (B) photograph.

Figure 7: Test schematic of the sandwich composites subjected to quasi-static out-of plane compression loads.

performed with samples both without fire load and after fire load. The tests were performed with a testing machine named Zwick/Z005 (Germany) at a loading rate of 0.5 mm/min, and the test schematic of the sandwich composite panel is presented in Figure 7. The load and displacement of the flat cylindrical indenter were automatically recorded by a computer using data acquisition software. Three specimens were tested at each test temperature, and the average values of the experimental results were obtained.

6 Results and discussion

Under a high-temperature fire load, a chemical reaction occurred in the intumescent coating with releasing gases and generated a char layer rapidly, as shown in Figure 8. Pictures (A), (B), (C), and (D) were shoot at 0 min, 7 min, 13 min, and 23 min, respectively. The char layer grows continually at the first 25 min. Nearly all the virgin intumescent coating would transform into a char layer after 30 min. Then, the char layer stays in a steady state with the thickness unchanged and lasts for 30 min. After the

60-min fire load, the paragraph of the test sample shown in Figure 9, the char layer was about eight times that of the virgin intumescent coating. It can be seen that there is no virgin intumescent coating in the sample, only the char layer sticking on the composite lattice structure. Just a little deformation and delamination were observed on the top facesheet of the lattice structure. The bottom facesheet and the filler material stayed stable without any damage.

The curves of the unexposed surface temperature *versus* test time are presented in Figure 10. It can be seen that the measured temperatures became nearly constant about 1800 s after applying the fire load, which is coincident with the assumption of the steady-state heat transfer process. For the aluminum alloy panel covered with intumescent coating, the maximum value of the measured temperature was around 160°C, and thus, the USTR was 143°C. Therefore, the design requirement on the upper limit of the USTR was not met by using the intumescent coating alone. For the lattice-reinforced sandwich structure without a foam core, the maximum value of the measured temperature was around 150°C, i.e. the USTR was 129°C, 10°C lower than the design requirement on the upper limit of the USTR, just meeting the requirement. On the other hand, the maximum temperature measured on the bottom facesheet of the fire-proofing composite lattice sandwich structure was only around 133°C, as shown in Figure 10, indicating that the USTR of 116°C, 23°C lower than the design requirement on the upper limit of USTR, greatly prevents mechanical properties from decreasing [27], and protects the people or things behind the lattice structure.

As shown in Figure 11, the failure load of the sample without fire load is 3.9 kN, while the failure load of the sample after the fire-load test is 2.8 kN, i.e. 72% of the former. What is more, the fire-load test also has a little effect on the compression modulus. From the linear part of the load-displacement curve in Figure 11, the slope of

Figure 8: Evolution of the intumescent coating during test.

Figure 9: Photographs of fire-proofing composite lattice sandwich structure after test.

Figure 10: Temperature versus time at the face unexposed to fire.

Figure 11: The typical load-displacement curves for lattice reinforcement sandwich structure between the sample without fire load and after fire load.

the sample without a fire-load test is 1.6 kN/mm, while the slope of the sample after a fire-load test is 1.4 kN/mm, i.e. 87% of the former. The effect of the fire-load test on the compression modulus is unapparent than that on the failure load. In a word, it can be found that the fire load has a remarkable effect on the flat crush property. This enlightens us that, in the lattice reinforcement sandwich structure design with mechanical properties, the effect of the fire load must be accounted for.

7 Conclusions

A novel type of lightweight composite lattice sandwich structure has been proposed, which is capable for both fire-proofing and load-bearing abilities. The design procedure was also developed for such kind of fire-proofing structure, in which the material and geometry of the structure can be determined according to the mechanical performance and fire-proofing effect. A design case was performed, and the designed structure was manufactured. Both of the fire-proofing test and quasi-static out-of-plane compression test were conducted. The fire-proofing test results showed that a 30-mm-thick structure designed by the present procedure was able to isolate 945°C fire load on the exposed surface for 3600 s, keeping the USTR below 139°C. The quasi-static out-of-plane compression test indicated that after suffering for 3600 s, 945°C of fire hazard, the strength (stiffness) of the designed structure was about 72% (87%) of the designed structure without a fire hazard. The findings in this paper are as follows:

1. Three methods can be used to improve the fire-proofing performance of the composite lattice sandwich structure: choosing a thermo-stable resin or adding a fire retardant to enhance the inherent fire resistance of composite material; adding fire protection devices such as the intumescent coating on the surface of the structure to protect the composite top facesheet from suffering from fire load; filling heat insulation materials into the lattice core to interdict the thermal radiation and convection between the two facesheets.
2. As the operating temperature of the composite top facesheet is limited, the intumescent coating plays an important role in insulating fire temperature.
3. The design procedure was also useful in the design of the metal lattice fire-proofing structures because the design procedure is not for a specific material system but for all the lattice sandwich structures.

Nomenclature

λ	Thermal conductivity
σ	Stefan-Boltzmann constant
T	Temperature
d	Diameter
φ	Porosity
ω	Pore emissivity
f	Volume fraction
q	Heat flux
L	Thickness
h	Convection heat transfer coefficient
θ	Inclined angle between the lattice rod and facesheet

Subscripts

ad	Axial direction
ar	Air
bf	Bottom facesheet
cf	Carbon fiber
ch	Char
fl	Filler filled in lattice core
fr	Fire
ga	Gas
lc	Lattice truss core
lr	Lattice rode
mt	Matrix
rd	Radial direction
sl	Solid
ss	Sandwich structure
tf	Top facesheet
Tr	Thermal radiation

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