International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:9, No:8, 2015

Research on Static and Dynamic Behavior of New Combination of Aluminum Honeycomb Panel and Rod Single-layer Latticed Shell

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Abstract—In addition to the advantages of light weight, resistant corrosion and ease of processing, aluminum is also applied to the long-span spatial structures. However, the elastic modulus of aluminum is lower than that of the steel. This paper combines the high performance aluminum honeycomb panel with the aluminum latticed shell, forming a new panel-and-rod composite shell structure. Through comparative analysis between the static and dynamic performance, the conclusion that the structure of composite shell is noticeably superior to the structure combined before.

Keywords—Combination of aluminum honeycomb panel and rod latticed shell, dynamic performance, response spectrum analysis, seismic properties.

I. Introduction

WITH the increasing advance of both material and civilization [1], people need much wider covering space to meet the standard of various activities, for example, large-large-scale places of assembly, gymnasium, hanger, convention centre, swimming pool, waiting room, industrial plant, etc. In the sense, spatial structure can live up to the standard required by such large-scale public buildings in span and style, and among spatial structures. The spherical latticed shell is one of the typical that being widely applied.

Due to the advantages of light weight, resistant corrosion as well as ease of processing [2], aluminum latticed shell is favored by architects. With its relatively lower elastic modules, however, the strength, stiffness and stability remain to be improved. In this paper, comparative analysis will be made between aluminum single-layer spherical latticed shell and new honeycomb panel composite latticed shell in terms of the static and dynamic performance, providing certain reference value for future research and application of such new type of structure.

This study is sponsored by the National Natural Science Foundation (No. 51578136)

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II. Analysis of Model

A. Introduction to the Structure Model

This model adopts single-layer spherical latticed shell with edges all simply supported. The grid form is Kiewitt-type, with its span 60 meters and rise 10 meters. For the sake of simplicity, this paper equates honeycomb panel with a piece of homogeneous one based on the equivalence theory [3], [4], and assumes that the panel is in sufficient connection with the rod.

The finite element analysis software will be imported after the buildup of spherical latticed shell with MST. The truss structure employs I-shaped aluminum section, with the specification of 178×114×5.84×9.65mm. There are 469 joints as well as 1332 trusses in this model. The sketches of it are shown in Figs. 1 and 2.

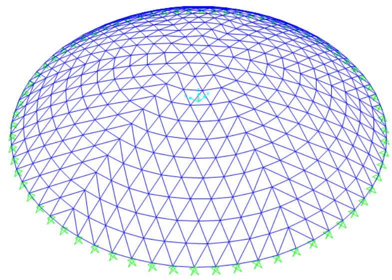

Fig. 1 The model of the single-layer spherical latticed shell

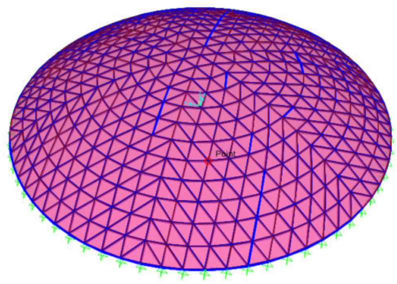

Fig. 2 The model of the panel-and-rod composite spherical shell structure

B. Structural Load

1. Dead load: 0.5KN/m^2 is employed. Through building a virtual section and through which induces load to the

The weight of the structure is calculated by the software automatically.

2. Live load: 0.5KN/m^2 is employed. The way to put pressure is same as that of dead load.
3. Wind load: The basic wind pressure w_0=0.45kN/m^2 is employed, and the shape coefficient will be valued according to similar models in *architectural structure load standards* [5]. The wind load then is calculated automatically by the procedure after specifying the parameter.
4. Seismic impact: This engineer adopts response spectrum method to carry out seismic analysis. In consideration of the vertical seismic impact, 8degree is selected as the seismic precautionary intensity, and 0.20g the basic seismic acceleration, 0.4s the characteristic cycle.

III. Honeycomb Sandwich Plate Equivalence Theory

As a sandwich composite material characterized with high specific strength and stiffness, metal honeycomb core sandwich plate is widely used in many fields. It is composed of metal skin diaphragms with core sandwich in. Because of complexity of such structure, finite element software is often used to help analyze and design it. However, since honeycomb unit is not available in existing software, honeycomb sandwich core needs to be transformed into equivalent parameter before being input. Equivalence theories commonly used are Sandwich Core Theory, Honeycomb Plate Theory and Equivalent Plate Theory, among which the last one will be briefly introduced in this paper.

The equivalence plate with its elasticity modulus as E_{eq}, Poisson's ratio μ_{eq}, thickness t_{eq}, can bear both horizontal and vertical load. As a bending panel, it corresponds to the Kirchhoff hypothesis on small deflection of thin plates. Its bending stiffness is

$$D_{eq}^{B}=\frac{E_{eq}t_{eq}^{3}}{12(1-\mu_{eq}^{2})} \tag{1}$$

Besides, as a plane stress plate, it only undertakes in-plane load, and its stiffness of plane stress is:

$$D_{eq}^{P}=\frac{E_{eq}t_{eq}}{1-\mu_{eq}^{2}} \tag{2}$$

To avoid stretching bending coupling effects as well as bucking deformation caused by solidity, both the upper and lower plates are identical in their material and thickness, and are much shorter in height compared with that of the core. Two theories will be used to make equivalence on the structure of honeycomb sandwich plate respectively.

A. The Method of Equivalent-Stiffness in Reissner Theory

In Reissner's theory, honeycomb sandwich plate employs following assumptions: (1) Because of the plate being quite thin, it is assumed that the stress is uniformly distributed according to its thickness, that is to say, the plate is in the membrane stress mode. (2) With the softness of the sandwich core, its stress distribution paralleled to the xy plane can be negligible that $\sigma_x=\sigma_y=\tau_{xy}=0$ is assumed. (3) Stress components σ_z between the sandwich core and the plate is pretty small that $\sigma_z=0$ and $\varepsilon_z=0$ is assumed. According to the above-mentioned assumptions and knowledge about elastic mechanics, its bending stiffness is:

$$D_{R}^{B}=\frac{E_f(t+h)^2t}{2(1-\mu_f^2)} \tag{3}$$

h and t represent the thickness of the core and the plate respectively, while μ_f and E_f the Poisson's ratio of the material of the plate and elasticity modulus.

When receiving in-plate load, the upper and lower plate of honeycomb sandwich plate are even in bearing it. Its in-plate stiffness is:

$$D_{R}^{P}=\frac{2E_f t}{1-\mu_f^2} \tag{4}$$

B. The Method of Equivalent-stiffness in Hoff's Theory

In Hoff's theory, he assumes that the plate to be a common sheet and takes its bending stiffness into consideration, with other assumptions identical to the latter two assumptions in Reissner's theory. Likewise, the bending stiffness and in-plate stiffness drawn from Hoff's theory are:

$$D_{H}^{B}=\frac{E_f(t+h)^2t}{2(1-\mu_f^2)}+\frac{E_f t^3}{6(1-\mu_f^2)} \tag{5}$$

$$D_{H}^{P}=\frac{2E_f t}{1-\mu_f^2} \tag{6}$$

In accordance with the principle of equivalence, the bending stiffness of honeycomb sandwich core plate is identical to that of the equivalent plate, so is the in-plate stiffness. Thus, the parameter formulas of the equivalent plate can be achieved as in Table I.

TABLE I
Parameter Formulas of Equivalent Plate

	Reissner's theory	Hoff's theory
Equivalent thickness	$t_{eq}=\sqrt{3}(h+t)$	$t_{eq}=\sqrt{t^2+3(h+t)^2}$
	$E_{eq}=\frac{2E_f t}{t_{eq}}$	$E_{eq}=\frac{2E_f t}{t_{eq}}$
Equivalent elastic modulus	$G_{xeq}=\frac{G_{cxz}(h+t)^2}{ht_{eq}}$	$G_{xeq}=\frac{G_{cxz}(h+t)^2}{ht_{eq}}$
	$G_{yeq}=\frac{G_{cyz}(h+t)^2}{ht_{eq}}$	$G_{yeq}=\frac{G_{cyz}(h+t)^2}{ht_{eq}}$
Equivalent Possion's ratio	$\mu_{eq}=\mu_f$	$\mu_{eq}=\mu_f$
Equivalent density	$\rho_{eq}=\frac{\rho_c h+2\rho_f t}{t_{eq}}$	$\rho_{eq}=\frac{\rho_c h+2\rho_f t}{t_{eq}}$

As can be seen in the table, G_{cxz}, G_{cyz} represent the shear modulus of the two directions of the honeycomb core respectively, ρ_f, ρ_c are the mass density of the surface and core materials respectively, and other parameters can be referred in the above.

IV. Static Analysis

A. Structural Performance under Dead Load

The No.469 joint on the vertex of latticed shell is selected to conduct comparative analysis, and the deformation of the two under dead load can be seen in Figs. 3 and 4.

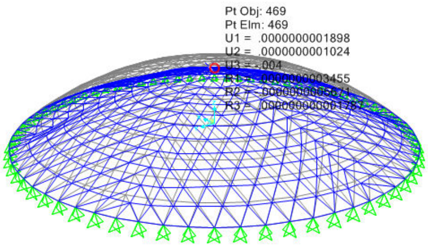

Fig. 3 Diagram of the deformation of latticed shell under dead load

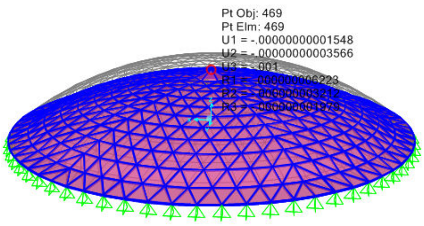

Fig. 4 Diagram of the deformation of honeycomb panel-and-rod latticed shell under dead load

Under the dead load, while the deflection of the spherical latticed shell's vertex is 4mm, that of the panel-and-rod composite latticed shell is only 1mm, 25 % of the former.

It can be observed that the axial force of the spherical latticed shell reaches its maximum -38.745kN ("-" indicates compression of the truss) at No. 38, 47, 57, 67, 732 and 742 truss. Meanwhile, at No.554, 587, 621, 655, 1240 and 1247 truss of the panel–and–rod counterpart reaches its maximum axial force -6.03kN, 15.56 % of the former.

B. Structural Performance under Live Load

Under live load, while the deflection of the spherical latticed shell's vertex is 3.3mm, that of the panel-and-rod composite latticed shell is only 0.6mm, 18 % of the former.

The spherical latticed shell reaches its maximum axial force -32.063kN at No. 38, 47, 57, 67, 732 and 742 truss, while its panel-and-rod composite counterpart reaches its maximum -3.953kN, which is 11.2 % of the former, at No. 554, 587, 621, 655, 1240 and 1247 truss.

C. Structural Performance under Wind Load

Deformation of the two structures under wind load is as in Fig. 5 and 6.

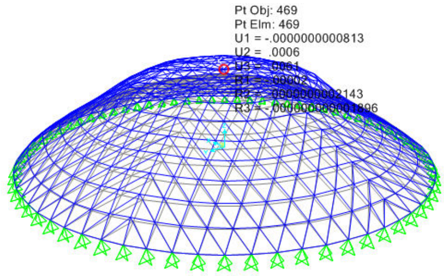

Fig. 5 Diagram of the deformation of latticed shell under wind load

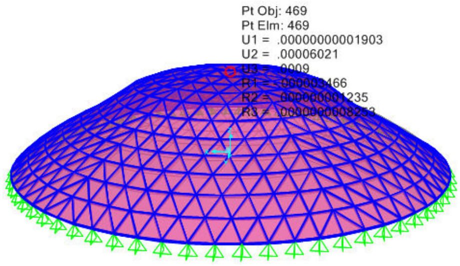

Fig. 6 Diagram of the deformation of honeycomb panel-and-rod latticed shell under wind load

Under wind load, while the deflection of the spherical latticed shell's vertex is -6mm, the data of its panel-and –rod composite counterpart is -0.9mm, 15 % of the former.

The spherical latticed shell reaches the maximum axial force 34.838kN at No. 27 and 34 truss, while its panel-and-rod composite latticed shell reaches its maximum 3.727kN, which is only 10.7 % of the former, at No. 6 and 701 truss.

V. Dynamic Analysis

A. Modulus Analysis

As the structure of the spherical latticed shell is regular-shaped, eigenvector method is employed to carry out the modulus analysis [6]. In light of the principle "the calculation of mode number is only available when the mode participation mass accounts for at least 90% of the total mass", this paper will select first 100 modes and abstract first 10 modes of each for comparative analysis. Tables II and III show the results of mass participation parameters on the basis of modal analysis.

Based on the first 10 modes and the vibration cycle of the structures, following conclusions can be drawn:

1. The fundamental cycle of the spherical latticed shell is 0.35s, while that for the panel-and-rod composite one is 0.13s. The two relatively low numerical values indicate that both of the two structures are in high stiffness. However, the overall stiffness of the latter is higher than that of the former.
2. The spectrum of the spherical shell is so dense that the cycle of each stage is continuously changing without noticeable fluctuation. This is caused by large numbers of structural joints, which also possess several symmetrical

International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:9, No:8, 2015

axes. In addition, the influence of mutual coupling between modes can be neglected.

3. As the mass participation coefficient of the two structures' first 10 modes are both small, it can be said that high mode plays a vital role in structure and cannot be overlooked. In terms of the 100th mode of the spherical latticed shell, the mass participation coefficient of accumulated mode is 1 in the UZ axis, 0.3 in the UX and UY axis, 0.2 in the RX and RY axis and 0 in the RZ axis. This indicates that this structure is mainly of vertical modes and its vertical stiffness if relatively weak. On the other hand, as for the 100th mode of the panel-and-rod composite latticed shell, the mass participation coefficient of accumulated mode remains 1 in the UZ axis. However, it is 0.6 in the UX and UY axis, 0.7 in the RX and RY axis and 0.83 in the RZ axis. Though still mainly of vertical modes, this composite structure is evener in all degrees of freedom as for stiffness and thus enjoys better bearing performance.

TABLE II
CYCLE AND MASS PARTICIPATION COEFFICIENT OF THE LATTICED SHELL

MODE	CYCLE(S)	UX	UY	UZ	RX	RY	RZ
1	0.35	0.07	0.02	0.00	0.01	0.04	0.00
2	0.35	0.02	0.07	0.00	0.04	0.01	0.00
3	0.33	0.00	0.00	0.00	0.00	0.00	0.00
4	0.33	0.00	0.00	0.00	0.00	0.00	0.00
5	0.32	0.07	0.02	0.00	0.02	0.05	0.00
6	0.32	0.02	0.07	0.00	0.05	0.02	0.00
7	0.32	0.00	0.00	0.00	0.00	0.00	0.00
8	0.32	0.00	0.00	0.00	0.00	0.00	0.00
9	0.32	0.00	0.00	0.00	0.00	0.00	0.00
10	0.32	0.00	0.00	0.00	0.00	0.00	0.00

TABLE III
CYCLE AND MASS PARTICIPATION COEFFICIENT OF THE COMPOSITE LATTICED SHELL

MODE	CYCLE(S)	UX	UY	UZ	RX	RY	RZ
1	0.13	0.00	0.00	0.01	0.00	0.00	0.00
2	0.13	0.01	0.01	0.00	0.01	0.01	0.00
3	0.12	0.01	0.01	0.00	0.01	0.01	0.00
4	0.12	0.00	0.00	0.00	0.00	0.00	0.00
5	0.12	0.00	0.00	0.00	0.00	0.00	0.00
6	0.12	0.00	0.00	0.00	0.00	0.00	0.00
7	0.12	0.01	0.00	0.00	0.00	0.01	0.00
8	0.12	0.00	0.00	0.00	0.00	0.00	0.00
9	0.12	0.00	0.00	0.00	0.00	0.00	0.00
10	0.12	0.00	0.00	0.00	0.00	0.00	0.00

B. Response Spectrum Analysis

The response spectrum analysis of seismic impact is in essence a kind of simulated dynamic analysis. It goes by the calculation of seismic response of points using dynamic method. Then, a response spectrum is formed using statistics and finally the static method is employed for structural analysis [7]. In accordance with *Code of Seismic Design of Buildings* [8], the maximum seismic affecting coefficient of frequently occurred earthquakes is 0.16; the structure's dumping ratio 0.05 and characteristic period of ground 0.4s. In seismic analysis, vertical seismic impact is mainly focused on because of the vertical mode of latticed shell [9]. When calculating the mode decomposition response spectrum, the single impact of vertical earthquake as well as the CQC method is preferred. What's more, the vertical acceleration is generally 1/2 to 2/3 of its horizontal counterpart [10].

Deformation of the two structures under vertical seismic impact can be seen in Figs. 7 and 8.

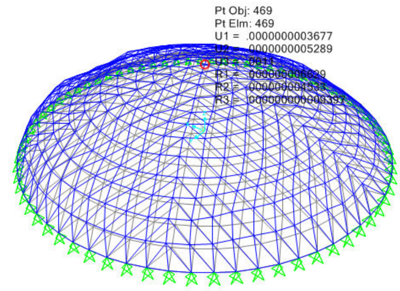

Fig. 7 Diagram of the deformation of latticed shell under seismic impact

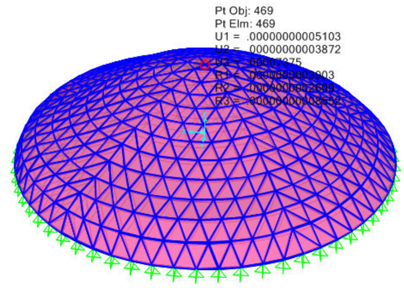

Fig. 8 Diagram of the deformation of honeycomb panel-and-rod composite latticed shell

1. Inner Force Analysis

Under vertical earthquake, the vertical counterforce towards basement in spherical latticed shell is 169kN, while that of the panel-and-rod composite one is merely 4.7kN, 2.8% of the former.

The maximum axial force of truss in the spherical latticed shell is 4.84kN, while in the panel-and-rod composite structure it is 0.27kN, 5.6% of the former one. Therefore, it is clear that the bearing force of composite latticed shell is much stronger than that of the spherical one.

2. Deformation Analysis

As before, the No.469 joint on the vertex of latticed shell is chosen for comparative analysis in terms of deformation. The structural deformation based on mode decomposition response spectrum can be seen in Table IV.

TABLE IV
STRUCTURAL DEFORMATION UNDER SEISMIC IMPACT

ITEM	TOP DISPLACEMENT(mm)		
	X	Y	Z
Latticed shell	0	0	1.1
Composite latticed shell	0	0	0.074

It can be seen from Table IV that the horizontal top displacements of both spherical latticed shell and the composite one are pretty close to 0. While as for vertical top displacement, the latter one is only 6.7% of the former one. So the stiffness of composite latticed shell is stronger than its spherical counterpart.

VI. Conclusion

Through finite element analysis between the single-layer spherical latticed shell, which is 60 meters in span, and the new honeycomb panel-and-rod composite counterpart, conclusions are as follows:

1. Under single influence of dead load, live load and wind load respectively, the vertex deflection as well as truss's maximum axial force of the latter one are both superior to the former one, which suggests that the latter structure is better than the former in terms of stiffness and strength.
2. From the analysis of their vibration characteristics, it can be seen that the overall vertical stiffness of the former one is relatively weak, while the latter one's stiffness in all degrees of freedom is even. That is to say, the latter structure is better in its bearing performance. Besides, both structures are virtually of vertical modes, with the frequency spectrum being quite dense and no continuous changes in each mode's cycle. In addition, the mutual coupling between modes can be negligible.
3. Under the influence of vertical earthquake, the results of response spectrum method indicate that the latter structure's vertical counterforce towards basement is far weaker than that of the former one, so are the latter's top vertical displacement as well as truss's maximum axial force. In short, both the overall stiffness and bearing force of the composite latticed shell show great advantages over its regular counterpart.

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