Experimental Study on Failure Mechanism of Hierarchical Corrugated Structures with Second-order Core

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Abstract. Based on the sample experiment and ANSYS simulation, the experimental verification of the failure mode prediction model under compression load is completed, and the experimental results are compared with the theoretical analysis results. Among them, the sample experiment is carried out on the universal testing machine, including base metal experiment and uniaxial compression experiment. The experimental model is made of UV Curable Resin by 3D printing technology. And the buckling mode numerical simulation is completed on the ANSYS Workbench, using the plate and shell model of the pumping surface. By comparing the failure mode and yield stress of theory, experiment and simulation, the results show that the accuracy of the prediction model based on plate theory is higher. It can provide theoretical reference for structural design.

1. Introduction
Hierarchical structure has been researched continuously since it was proposed in the last century. It has the characteristics of small apparent density, high specific strength and specific rigidity[1][2], and is used in aerospace, marine, civil engineering, vehicle engineering, etc. The field has a wide range of application prospects. With the continuous development of large-span and super high-rise structures, the research on hierarchical structures has become more and more extensive. As a kind of hierarchical structure, the sandwich structure has been studied a lot, and different core materials and structural forms have been discussed based on different theories. Côté F studied and compared the mechanical properties of square honeycomb, rhombic column and folded corrugated sandwich structures with different relative densities, established the elastic-plastic buckling analysis model of square honeycomb, and considered that rhombic is more applicable in sandwich beams [3]. Russell B P discussed the three-point bending failure mechanism of a honeycomb sandwich beam, and gave analytical expressions for four failure mechanisms[4]. Wu Q studied the mechanical properties of the corrugated grid structure under lateral compression and shear in the out-of-plane direction, constructed a failure mechanism diagram, and performed a compression experiment by making prototypes by 3D printing[5]. Haldar A K has studied the mechanical properties of egg-shell sandwich panels under static compressive loads and their energy absorption performance under impact and explosion loads. Studies have shown that such sandwich panels not only have good mechanical properties, but also have excellent energy absorption effect under extreme load[6].

Kooistra G W applied the sandwich structure to the hierarchical structure, proposed the hierarchical sandwich structure, and studied its mechanical properties, gave six failure modes, and constructed its failure mechanism diagram. Under the same density, the compressive strength of this two-level sandwich structure is increased by an order of magnitude compared with that of the first level structure,
which indicates that this kind of sandwich structure has a wide application prospect[7]. However, the structure of this structure is more complicated, and the failure mechanism and mechanical properties are more sensitive to geometric parameters. Therefore, Li G has carried out a series of studies on this hierarchical fold structure, and based on the thin plate theory and Mindlin plate theory, its failure mechanism is analyzed to obtain 6 failure modes and the corresponding equivalent normal stress and equivalent shear stress formulas are given[8][9][10]. However, due to the difficulty of making the model, these studies are all partial to the theory, only numerical simulation, lack of experimental comparison and verification. With the advancement of science and technology, especially the maturity of 3D printing technology, the manufacture of complex experimental models has become more convenient. In this paper, the model is made of UV Curable Resin material and 3D printing technology is used to perform uniaxial compression experiments on a universal testing machine. Through experimental and numerical simulations, the failure mechanism of the layered fold structure is experimentally studied and compared with each other. The layered fold structure is made of the same material. The structure diagram is shown in figure 1. The properties of the base material are obtained through the base material experiment.

![Diagram of Hierarchical Corrugated Structures](image)

Figure 1. Diagram of Hierarchical Corrugated Structures

2. Experiment

2.1 Base material experiment

The base material experiment was performed on a microcomputer controlled universal testing machine, using displacement loading and a loading rate of 5mm / min. The original data was recorded by the testing machine's own system and the JM3812 multifunctional static strain test system. Five sets of experiments were performed on the base material in the tensile and compression tests. The damage picture is shown in figure 2. The properties of the UV Curable Resin 900 are shown in table 1.

![Base material experiment](image)

Figure 2. Base material experiment.

| Table 1. UV Curable Resin 9000 Material property table. |
|------------------|------------------|------------------|------------------|------------------|
| Elastic Modulus | Poisson ratio    | Density          | Tensile yield strength | Compressive yield strength |
| UV Curable Resin 9000 | 2018.8MPa     | 0.41             | 1.17g/mm³            | 37.3MPa           | 51.6MPa           |
2.2 Compression experiment
Compressed experimental samples were created by AutoCAD three-dimensional modeling, converted to STL format, and manufactured with Lite800HD 3D printer using UV Curable Resin 9000. The produced sample was allowed to stand for a period of time for further curing, and the main dimensions of the measured sample were recorded in table 2.

Table 2. Compression experiment sample original record table.

| Serial number | t1(mm) | l1(mm) | t(mm) | l(mm) |
|---------------|--------|--------|-------|-------|
| A1-1          | 1.05   | 20.6   | 2.07  | 94.3  |
| A1-2          | 1.06   | 20.5   | 2.08  | 94.6  |
| A1-3          | 1.03   | 20.6   | 2.05  | 94.6  |

The uniaxial compression test was performed on a microcomputer-controlled electronic universal testing machine, and the failure process of the experiment was recorded by camera. The data was collected through the testing machine's own system. The loading rate was 5mm / min displacement loading, and the test piece was damaged or severely deformed.

2.3 Ansys finite element simulation
The simulation is based on the Ansys Workbench platform, and the shell and shell model Shells 181 are used to perform linear buckling analysis of the structure. The solid model created by 3D modeling of AutoCAD software was imported into Ansys Workbench, and the model was extracted by SpaceClaim. Each size of the model is the same as the experimental sample design size. Material properties are added in Table 1. The mesh element size is set to 2mm, and the average Element Quality is 0.993. The lower panel uses the Fixed Support constraint, and the upper panel applies the Fixed Rotation constraint to control the rotation but guarantees that it can move with the substructure as a whole under the action of the force. The unit force 1N acts on the upper surface. By linear buckling analysis, the first-order buckling mode is the failure mode of the structure, and the first-order buckling load factor is the critical load of the structure.

3. Results and analysis
The position of the experimental group A1 on the failure mechanism diagram is shown in figure 3. The failure modes of the plate group and the beam theory are plastic yielding of the larger struts (YL).

Figure 3. Position of A1 in failure mechanism diagram of beam model and plate model.

The failure modes of experimental groups A1-1, A1-2 and A1-3 under compressive load are Plastic yielding of the larger struts. Simulation results show that it is also for Plastic yielding of the larger struts. As shown in figure 4. Through experimental and simulation analysis, the correctness of the failure mode theoretical prediction model is verified.
The experimental groups A1-1, A1-2, and A1-3 have buckling limit loads of 4.82KN, 4.77KN, and 4.68KN, respectively, taking an average of 4.757KN. The buckling pressure of the structure obtained by Ansys simulation is 4.566KN. With a difference of 4.2%, the critical buckling loads are very similar. It shows that the accuracy of the simulation analysis of the structure using Ansys workbench is very high, and that the experimental results of the prototype model made of UV Curable Resin by 3D printing technology are reliable.

4. Conclusions

3D printing is used to make prototypes for experiments. Through analysis of base material experiments and compression experiments, it is believed that the accuracy of 3D printing technology for making experimental models is reliable. Selecting suitable materials can observe the damage characteristics of the structure and achieve the production of some small models of special structures.

The comparative analysis between the simulation results and the experimental results shows that the plate and shell model using the shells181 element has higher analysis accuracy and reliable results, which can be used to replace the sample experiments to verify the theoretical analysis results by finite element simulation.

This article through prototype experiments and Ansys numerical simulations show that the theoretical failure mode of the thin plate theory can accurately predict the failure mode of the structure, and the failure mode of the designed structure can be controlled by the failure mechanism diagram for purposeful design. In addition, by controlling the failure mode of the structure, the failure can occur in the part that causes the least damage to the structure. In addition, through the failure mode of the structure, the parts that are prone to failure can be checked and repaired regularly to eliminate the hidden dangers of the structure and achieve the effect of disaster prevention and reduction.

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