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The Strength Behavior of O-Core Sandwich Pipe

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The Strength Behavior of O-Core Sandwich Pipe

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Abstract. Due to the characteristics of light weight, high specific strength, high specific stiffness and multi-function, sandwich structure is widely used in automotive industry, aerospace, offshore platform, construction, wind power generation and other fields. In recent years, the preparation and properties of new high-performance sandwich structures are the frontier research topics in the field of materials engineering. The research on the preparation method and mechanical properties of the sandwich pipes is favored by researchers at home and abroad. This paper, the O-core metal sandwich pipes is taken as the research object. The material is 304 stainless steel. By designing the orthogonal experiment, the sandwich pipes with 3 core pipes and 4 core pipes is prepared by laser welding. The tensile test of the sandwich pipes was carried out by Z250SNS electronic universal testing machine. At the same time, the finite element model of the sandwich pipes was established by using ANSYS finite element analysis software, and the strength of the sandwich pipes was further numerically simulated. Results show that the curves of the simulation and experiment data are in good agreement. Besides, when compare with an empty pipe, the carrying capacity of the sandwich pipe during stretching is significantly improved. The number of cores has a visible effect on the strength of the sandwich structure pipe, and the elastic limit is approximately proportional to the number of cores. In this paper, the mechanical properties of O-core metal sandwich pipe are studied, and the research method is clarified, which provides a new idea for the future research of sandwich pipe.

Keywords. O-core metal sandwich structure pipe; Finite element; Strength

1. Introduction

Sandwich structure has been widely used in the automotive industry, aerospace, architecture, and wind power generation due to its advantages of simple design as well as high specific strength and stiffness [1-4]. Figure 1. shows several typical sandwich structures. As show figure 1, the sandwich structure comprises of two layers of plates and middle core layers. The upper and lower layers are thinner panels with greater strength and stiffness, while the middle core material is thicker, and the density is lower. The plates and core can be either bonded through adhesive or welding. For the case of the same mass, increasing the thickness of the sandwich structure will increase the moment of inertia of the structure local. Therefore, the sandwich structure has higher bending stiffness and stability when compared with the single solid structure of the same material and weight.

In recent research, the study of sandwich structure is mainly about the sandwich plate. However, the research on the preparation of sandwich plates by laser welding is relatively small. Related to it, the sandwich steel pipe is used more in engineering practice. A traditional steel sandwich structure pipe consists of an inner and outer pipe with a sandwich layer. The sandwich layer can be filled with thermal insulation materials where it is a typically polymer or cement-based, while the inner and outer pipe act as integral support [5].

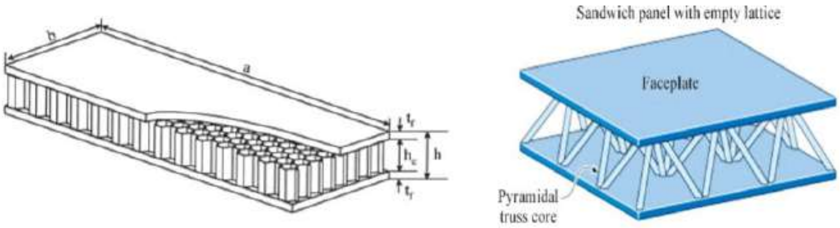


Figure 1. Typical artificial sandwich structures

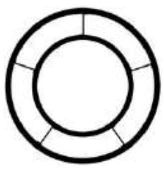
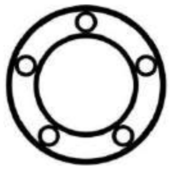
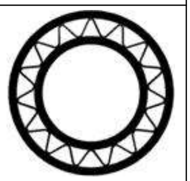
Although metal sandwich pipe has a particular structural strength and good thermal insulation effect, yet structural theory and mechanical properties deliver important research conducted by researcher [6]. However, there are still issues that need to be analyze:

a. Analytical method to study the mechanical properties of metal sandwich pipe- In engineering practice, the laminated steel pipe is generally buckling in plastic form, resulting in instability. However, in the research process, the analytical method is based on the elastic buckling of the laminated steel pipe without considering the plasticity of the material. Therefore, the results obtained by analytical methods in previous studies have significant errors, limiting the design of sandwich steel pipes in practical applications

b. Connection mode of metal sandwich pipe- Sandwich layer material and bonding method for sandwich steel pipe has essential effects on the mechanical properties of the elastic modulus of sandwich layer materials that put forward higher requirements. This is because both sandwich layer material provide heat preservation effect, which limits the development of interlayer steel pipe to a certain degree

Sandwich pipes are divided into I-core, Z-core [7], O-core, V-core [8] (refer table 1. for reference). Considering the laser welding of thermal deformation and material processing defects, Z-core and V-core manufacturing is complex. I-core plate thermal deformation is more prominent, while O-core metal sandwich pipe manufacturing is convenient. When welding, O-core thermal deformation is relatively small, hence, O-core is preferable. The symmetrical O-core design contribute in reducing the overall deformation.

Table 1. Example of type of core available in sandwich structure pipe

Type of core	I	Z	O	V
Illustration				

Sandwich structure is a unique form of modern composite material. In the 1840s, the first fibreglass fishing boat with composite materials manufactured by hand paste was successfully launched. In the 1960s and 1970s, resin-based composite materials were widely used in aviation, machinery, construction, and chemical industries. In the 1950s, it was proposed that the metal sandwich structure should be a new branch of the industry because laser power generator was expensive, and laser welding cost was too high, so it was not easy to be accepted in the market. With the development of modern technology, high power laser welding makes it possible to weld sandwich structures. Since the beginning of the new century, the laser-welded sandwich structure has been mainly about the sandwich plate. The sandwich pipe is more about sandwich steel pipe applied in construction engineering [9].

Kerwin et al. [10] made a sandwich structural beam by adding viscoelastic damping material to the composite plate. Sine function was used to represent the transverse displacement of the beam, and the bending stiffness of the beam was expressed in the plural form. Mazuri et al. [11] analyzed the stress caused by the thermal expansion coefficient of different materials and calculated the stress of sandwich structure, which was verified by experiment test. N.Paydar et al. [12, 13] proposed a small deflection theoretical research method for symmetrically distributed sandwich structures through analyzing and comparing a large number of studies and experiments. Baruch and Frosti et al. [14] studied the mechanical properties of the upper and lower panels of the sandwich structure under different and the same loads. Reddy et al. [15] presented the influence of sandwich structure deformation on energy absorption under different loads. They detect the energy absorption of deformation under static load was smaller than that of dynamic load. Darko Frank et al. [16] experimented the relationship between the fatigue performance of laser-welded T-joints and the weld shape. They also analyzed the failure position and form of sandwich plates under multiple loads. Jani Romanoff et al. [17-19] developed the interaction theory between the panel and the core plate of the laser-welded sandwich plate under bending loads, evaluated its overall deformation under multiple loads, and studied the local deformation theory of the panel.

Initially in the 1980s, research have begun to explore the possibility of using sandwich steel tubes for support columns of offshore platforms, large diameter columns in buildings and structural columns subjected to loading. In these cases, sandwich pipes are used as members in buildings or structures to withstand axial force, shear force and bending moment alone or in combination [20]. S. Wei et al. [21] conducted a short column axial compression test of sandwich steel pipe where he continued his previous study to analyze the load-displacement curve relationship of axial compression members on sandwich steel pipes [22]. Po-Chien Hsiao et al. [23] investigated an experimental study on eight metal sandwich tube specimens. They proposed a simplified calculation formula based on the concept of the superposition strength method, which can accurately predict the ultimate bending moment of component. Yagishita et al. [24] and CAI Kequan et al. [25] conducted relevant experimental studies on the hysteretic performance of hollow sandwich concrete-filled steel tubular flexural component.Tao Zhong et al. [26, 27] experimented on 12 metal sandwich pipes specimens and finally obtained the design calculation formula of the specimen’s axial pressure and flexural bearing capacity through analysis and discussion.

Nie Jianguo et al. [28] analyzed the sandwich steel pipe and obtained the theoretical calculation formula for calculating the bearing capacity of the specimen. The calculation results obtained by the formula were in good agreement with the test results. Li Yongjin et al. [29] studied the bearing capacity and failure mode of sandwich pipe specimens under the action of sustained load. Liu Xiao et al. [30] presented the flexural mechanical properties of sandwich steel tubes at high temperature treatment by conducting test on 24 flexural members (parameters such as axial compression ratio, temperature and hollow ratio). Ouyang Peng et al. [31] conducted experiment research on sandwich steel tube axial compression short columns. They investigated the changes of bearing capacity of specimens under axial compression by taking the diameter to thickness ratio of steel tube as the main parameter.

In this paper, the mechanical properties of O-core sandwich steel pipe are analyzed and studied by means of experiment and simulation process. This study used the manufacturing technology of laser-welded sandwich plates. In order to analyze the strength, stiffness and stability of sandwich pipe, experiment such as tensile test was designed, respectively. Moreover, the rationality of metal sandwich structure pipe was determined through comparing with empty pipe. Besides, the finite element calculation was established by ANSYS where the model was modified and optimized according to the test results, and the mechanical properties were simulated and analyzed. Then, the simulation data were validated by comparing the experiment with simulation results. The metal sandwich pipe can be used as a new type of sandwich pipe which can replace the traditional sandwich pipe and has a very good development prospect.Through this experiment, the tensile mechanical properties of o-core metal sandwich pipe can be determined.At the same time, a new feasible scheme is provided for the study of mechanical properties of metal sandwich pipe by combining experiment and simulation.It lays a good foundation for the future research of metal sandwich pipe.

2. Methodology

This experiment can divide the test into sandwich pipe preparation, tensile test, and finite element analysis and test equipment. From this distribution, the reader can grasp the concept of operation and procedure control during the experiment. Therefore, deliver a better understanding of the study on the strength of O-core sandwich steel pipe.

2.1. Sandwich Pipe Preparation

The steel used in this test is 304 stainless steel pipe, and the dimensions are (32 x 2) mm for outer pipe, 12×2mm for inner pipe, and 8×2mm for core pipe, as shown in figure 2. The chemical composition is shown in table 2.

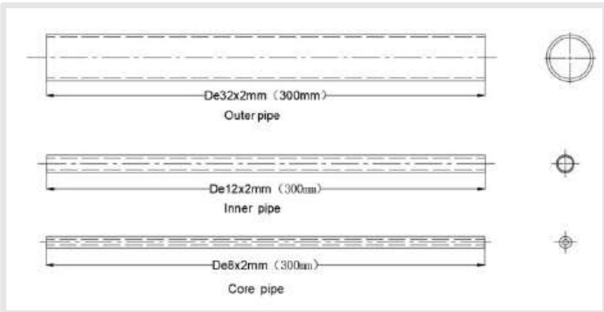


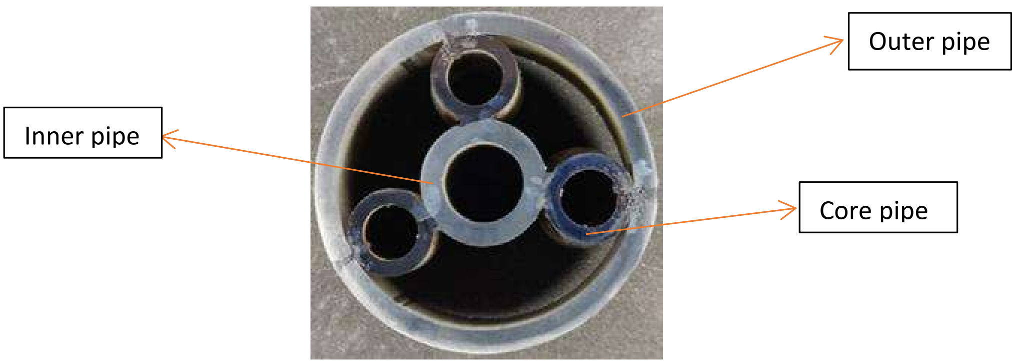
Figure 2. Different dimension for 304 stainless steel pipes

Table 2. Chemical composition of 304 stainless steel (wt.%)

Chemical composition	C	Mn	Si	Cr	Ni	P	S	Fe
Percentage	0.07	0.78	0.46	18.32	8.10	0.032	0.006	Bal.

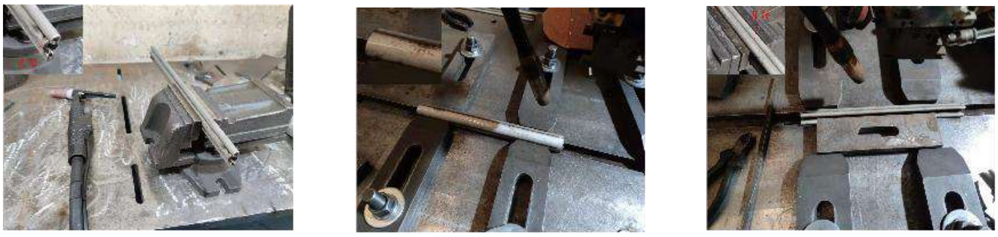
An O-core sandwich pipe is a new core topology of a sandwich pipe. There is no prefabricated sample in the past decade. Considering the sealing property of a round pipe, the welding method of a sandwich plate cannot be indiscriminately imitated entirely. Therefore, a new preparation method for sandwich structure pipe were developed. The preparation process is as follows:

a. preparation of internal and external pipes
b. core pipe relates to the inner pipe
c. core pipe relates to the outer pipe



Preparation process for a. need 304 stainless steel seamless pipe in line with the test requirements.

Wire cutting machine is used to cut 300mm short pipe and three-core pipes corresponding to the outer pipe along 0°, 120°, 240° is divided into three equal parts, the four-core pipe corresponding to the outer pipe along 0°, 180° and 90°, 270° is divided into four equal parts. As for b., we utilize spot welding to fix the core pipe and inner pipe in position (refer figure 3a). Next, the pipe is firmed on the welding slab and welded through fillet joining (refer figure 3b). Later in c., following the process a and b, it shall continue through connecting it with outer pipe. Essentially, 1/3 or 1/4 of the outer pipe is covered with the welded core pipe and inner pipe. Then, the core pipe and outer pipe are connected by laser deep penetration welding method. When an area has welded, the pipe was rotated to another area to weld the remaining part of 1/3 or 1/4 of the outer pipe (refer figure 3c).



a) b) c)

Figure 3. Welding process of O-core sandwich steel pipe

Welding technology has a significant influence on the performance of metal sandwich pipes [9]. The welding process mainly includes laser power, defocus and welding speed. Laser power and defocus have a great influence on the penetration depth, while welding speed has a significant influence on the fusion width and beam waist width ratio [10]. The quality of the welding process can directly affect the performance of welded joints and latter, affect the performance of the metal sandwich pipe. Given the selection of welding process parameters, the orthogonal experimental design method is adopted. Orthogonal experimental design is a method to study many factors and levels. It is based on the orthogonality of the comprehensive test to pick out some representative points for the test. These representative points have the characteristics of "uniform dispersion, homogeneous comparable". It is an efficient, rapid and economical experimental design method [11]. In this comprehensive test, nine groups selected three-phase factors and three linear levels for the comprehensive test design. By comparing the macroscopic morphology of the cross-section of three-core pipes and four-core pipes O-core sandwich pipes, it is found that the higher the laser power is, the slower the welding speed and the greater the defocus with better welding effect.

2.2. Tensile Test

Directly after holding the sandwich pipe, tensile easy to slip resulting in inaccurate results due the test machine fixture on the bar clamping range of the maximum diameter of 30mm, and O-core metal with outer pipe diameter of 32mm (hollow). For the convenience of clamping, weld the external thread sleeve to both ends of the sandwich pipe and use the clamping sleeve to facilitate clamping, as shown in figure 4.

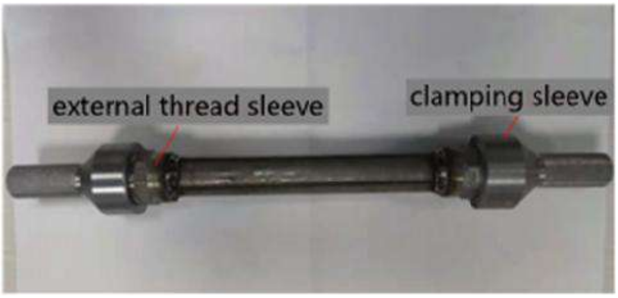


Figure 4. Tensile clamping device for O-core metal sandwich structure pipe

Universal tensile testing Z250SNS machine produced by Zwick Roell Company in Yinchuan Materials Research Institute of Shanghai Jiao Tong University (refer figure 5). The design and manufacturing requirements of the Universal tensile testing Z250SNS comply with ISO- 6892-1. All parts of the testing machine and the counting units of various measuring instruments are used in the International Counting Unit (SI) standard. The control system is equipped with more than 6 module slots, and the acquisition frequency of each channel can reach to 400kHz. The testing machine is equipped with the main test space and side test space. The rated load is 250kN and latter, 10kN, where the spaces test each other. The dynamic repetition function in the test process can be used to analyze and study the dynamic behaviour of force, displacement, deformation and time. Figure 6. display the clamping method of O-core sandwich steel pipe at the clamping area. A laser extensometer was used to measures the deformation of the sandwich pipe. The spacing between the two laser markers is 150mm and the tensile test speed was 1mm/min. The tensile test was stopped when the load-displacement curve of the sample decreased.

Figure 5. Z250SNS electronic universal testing machine

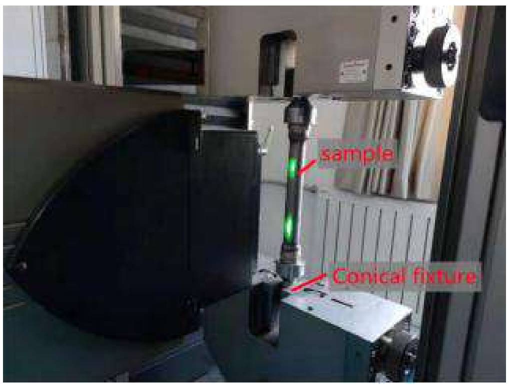


Figure 6. Tensile test clamping

Figure 7 illustrated the process of tensile testing for O-core sandwich steel pipe. Figure 7a show the initial loading, figure 7b show the tensile deformation morphology at loading time of 15min, whereas figure 7c show the tensile deformation morphology at loading time of 24min.This illustration and explanation are important to comprehend the mechanical strength of the material properties. The following are the description:

(1) The sandwich steel pipe is installed and clamp at both sides. The significant of this tensile test is the clamping where the clamp is a cornicle shape. Besides, the laser extensometer is fixed at height and a position.

(2) Start the testing machine, first preheat the testing machine for a period, and then pre add a small amount of load (these loads should be controlled within the elastic range of the sample) after the system of the testing machine is stable, to reduce and eliminate the gap between the sample and the fixture, and then remove the load

(3) As the loading increases, the data acquisition process and synchronous photography process are carried out at the same time, until the load-displacement curve decreases in the data acquisition process, hence, stop and unload the sample.

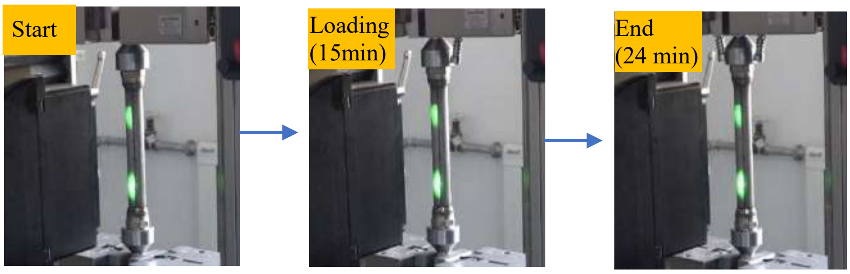


Figure 7. Tensile deformation morphology at loading time of 24min

2.3. *Finite Element Analysis*

This paper mainly focuses on the mechanical properties of O-core sandwich steel pipe. After welding, each pipe forms a whole structure. Therefore, taking metal sandwich pipe with 4 cores as an example, UG10.0 (3D graphic software) was firstly used to create an overall three-dimensional model of sandwich steel pipes during modelling. The model size is shown in table 3. and image in figure 8. Furthermore, export it as a Parasolid schema to import from UG10.0 into ANSYS software . In order to facilitate mesh division and get better mesh quality, further processing of the model is needed in ANSYS.

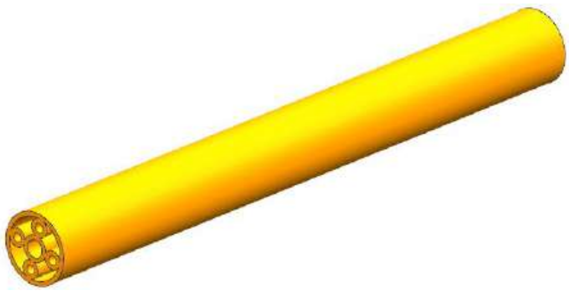


Figure 8. Diagram of 3D model of O-core metal sandwich pipe

Table 3. Finite element model size

part	Inner pipe	Core pipe	Outer pipe
size	12x2mm	8x2mm	32x2mm
length	300mm		

This paper uses ANSYS2020R2 version to further process the O-core sandwich steel pipe model in 'SpaceClaim' module. Considering the structural symmetry of the pipe, half of the model were produced along the axial direction. In the module, 3D model of the metal sandwich pipe was processed with translational symmetry. The origin coordinate was in the middle of global sandwich steel pipe. The main function of 'SpaceClaim' module was used to separate the outer pipe, inner pipe, and core pipe (refer figure 9.) for incomplex mesh division. Therefore, the segmented model could separate the outer pipe, inner pipe, and core pipe when dividing the mesh, thus obtaining a grid with high quality and relatively regular structure. Since the sandwich structure pipe is made by laser welding connection, it should be regarded in simulation analysis. The segmented components are set as a sharing topology, in case node sharing can be realized at the joint of all components when dividing the grid, and the simulation analysis carried out.

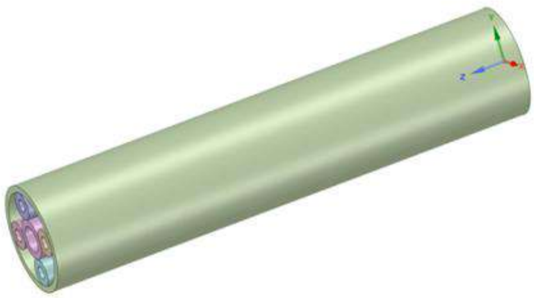


Figure 9. Model of a new metal sandwich pipe after treatment

2.4. Equipment

The new laser welding equipment used in this test is mainly a laser material welding equipment developed and manufactured by Wuhan Ruike Fiber Laser Technology Co., Ltd., China. The laser label as Raycus RFL-C6000H (refer figure 10a). This product series fiber laser mainly adopts a single coupler, 2, 4 fibre real-time fibre cutting, coupling operation efficiency increases ≥96%, switching operation duration is short, equipped with a safe laser mechanical, electrical, control and automatic monitoring function system.The detailed parameters are shown in table 4. The industrial robotic arm label as Panasonic LA-1800GIII six-axis articulated robot (refer figure 10b). Its maximum payload is 26kg, and its working range is 489 -1801mm.

a)

b)

Figure 10. Sandwich control equipment: a) RayCus RFL-C6000H laser and b) Panasonic LA-1800GIII Six-axis articulated robot

Table 4. Parameters of the Raycus RFL-C6000H laser

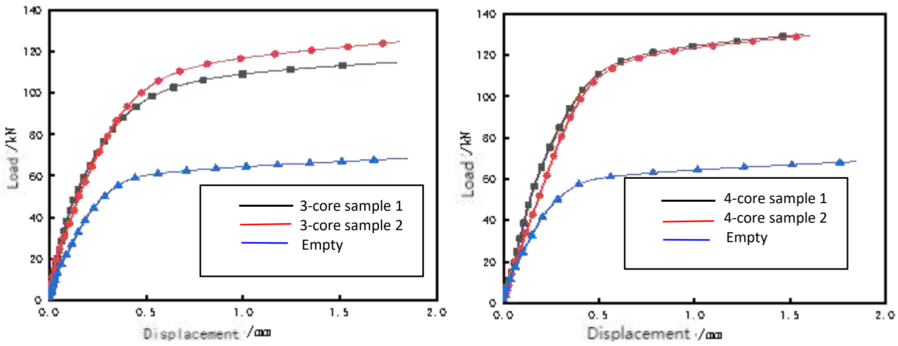
parameter	value
Maximum power	12kw
Input core diameter	100μm
Output core diameter	200-1000μm
Maximum NA	0.14
High coating through	1030-1090nm
Optical fiber Interface Type	QBH/QD
Type of cooling	water-cooling

3. Result and Discussion

According to the same test procedure, five tests were carried out (two groups of 3 core pipes and 4 core pipes and 1 group of empty pipes). The size of the empty pipes was the same as that of the outer pipes. The effect of the specimen after tensile is shown in figure 11. The outer thread sleeve is connected with the metal sandwich pipe by welding, and the fracture mainly occurs at the welding area. Before fracture, the samples have undergone obvious plastic deformation.

3-core sample 4-core sample Empty

Figure 11. Tensile test samples



a) b)

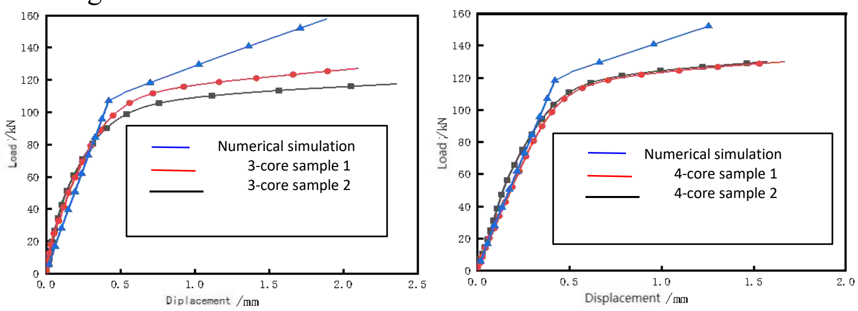
Figure 12. Load-displacement curve of sandwich structure pipe and empty pipe with a) 3 core pipes and b) 4 core pipes

Figure 12. display the load-displacement curves of sandwich steel pipes and empty pipes with a different number of core pipes. As shown in figure 12, the tensile bearing capacity of the sandwich structure pipe is doubled when compared with the empty pipe as well as when the number of sandwich core pipes increases from 3 core to 4 core pipes. The relationship between the tensile capacity of the core tube and the number of core tubes will be analyzed in detail later.

3.1. Comparison and Analysis of Simulation and Test Results

Kujala et al. [8] found that the error between the actual value and the analytic value of the sandwich structure was 30-50 %. Figure 13. shows the load-displacement curves of the test and simulation of 3 core pipes and 4 core pipes. This topic only analyzes and compares the elastic-plastic stage in the tensile process. It can be seen from the load displacement curve that the variation trend and value of the simulated curve and the experimental curve are relatively close.

This shows that the experimental curve is in good agreement with the simulation curve. It is proven from the material properties and mesh types of the finite element model used are reasonable. Therefore, this model can analyze the strength of O-core metal sandwich pipe and the effect of the number of core pipes on the strength.

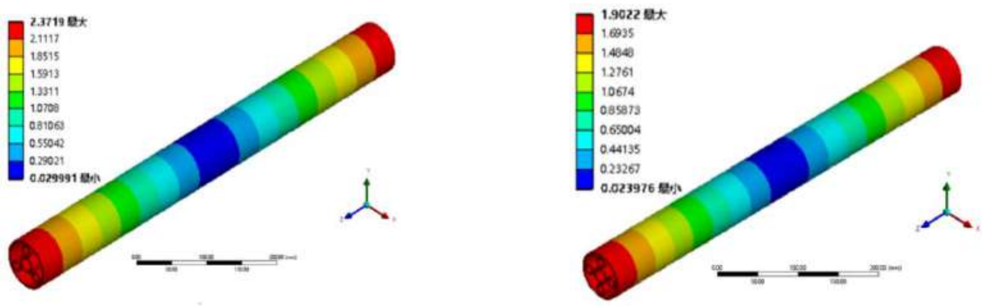


a) b)

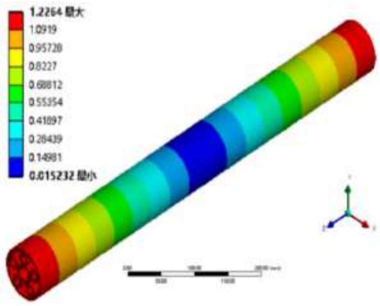
Figure 13. Load-displacement comparison curves between tensile test and simulation of O-core metal sandwich pipe for a) 3 core pipes and b) 4 core pipes

3.2. Influence of the Number of Core Pipes on the Strength of O-Shaped Metal Sandwich Pipes

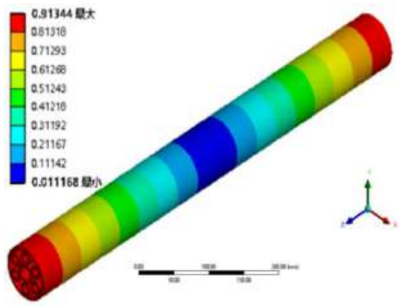
The o-core metal sandwich pipes with different numbers of core tubes (3, 4, 5, 6) were established, and the tensile test simulation was carried out for them respectively. The tensile load of the end face was 130kN, and the mesh division and boundary conditions were consistent. The finite element solution was carried out for them respectively figure 14. shows the displacement and deformation visualization of sandwich pipe with the different number of core pipes. It can be seen that the displacement and deformation of sandwich structure gradually decrease when the number of core pipes increases. Furthermore, when the number of core pipes is 3, the displacement of sandwich structure pipe is the largest with 2.3719 mm and when the number of core pipes is 6, the displacement of sandwich structure pipe is the smallest with 0.9134 mm.



a) b)



c)



d)

Figure 14. Displacement and deformation visualization of sandwich structure pipe with different number of core pipes for a) 3 core pipes, b) 4 core pipes, c) 5 core pipes and d) 6 core pipes

4. Conclusion

In this study, tensile test and finite element method were used to study the tensile strength of O-core sandwich steel pipe and the influence of the number of core pipes. The results showed that:

a) Compared with empty pipe, sandwich pipe can effectively improve its bearing capacity during stretching.When the tensile deformation of the empty pipe and the three-core pipe is 0.5mm, the load that the three-core pipe can bear is 100kN, about twice of the load that the empty pipe can bear 60.The ultimate load it can withstand has been increased by nearly two times.

b) For O-core sandwich steel pipe with a different number of cores has a significant effect on the strength of the sandwich structure pipe. When increasing the number of cores, it can effectively improve the strength of the sandwich structure pipe. The elastic limit of the sandwich structure is approximately proportional to the number of core pipes.

There are some interesting topics that can be conducted in the future about structure preparation and mechanical properties of O-core metal sandwich pipe. Further studies on thickness to diameter ratio for inner and outer pipe as well as material factor such as initial defect shall impact the performance of sandwich structure pipe. In accordance with development of modern information technology, researcher can design a software that function which meet the customers demand on sandwich structure pipe.

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