Numerical simulation on winding CFRP pipe axial compression stability

Bo Nan*, Yue Wu

School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China

Received 1 October 2014, www.cmnt.lv

Abstract

Because of the requirements of strict weight, airship structures are usually built by high strength and light-weight CFRP composite truss, CFRP composite tube is the basic unit of it. Winding CFRP tube ultimate bearing capacity has been further improved by combinations of various fiber directions, while stable bearing capacity is an important indicator that could influence the bearing characteristics. It concludes the destruction and deformation characteristics, as well as the relationship between stability factor Φ and slenderness λ, through analysing different CFRP tubes of slenderness ratio with The arc-length method, and drawing the Load-displacement curve, which provided a theoretical basis to better the truss design, and discussed the laws of how component defects affect its stability capacity via a large number of parameters.

Keywords: carbon fiber-reinforced plastic (CFRP), the arc-length method, stability coefficient, slenderness ratio

1 Introduction

Truss structure is a traditional form of large support structure, which is using rod or pipe to transfer load statically, because of big stiffness and saving material, which is a highly efficient structure form of supporting. From the use of material types, the existing truss structures are made of steel, aluminum alloy and CFRP composites, etc. Steel truss by the weight of material density, which cannot meet the requirements of aerospace lightweight structure; Quality of aluminum alloy truss structure is lighter and has been widely used in various kinds of large support structure in the field of aerospace. Along with the development of the large airship and space technology, advanced CFRP composite truss structure because of its significant weight loss effect and excellent mechanical properties have also been more and more applied to the satellite, airship, etc all kinds of aerospace structure (as shown in Figures 1 and 2).

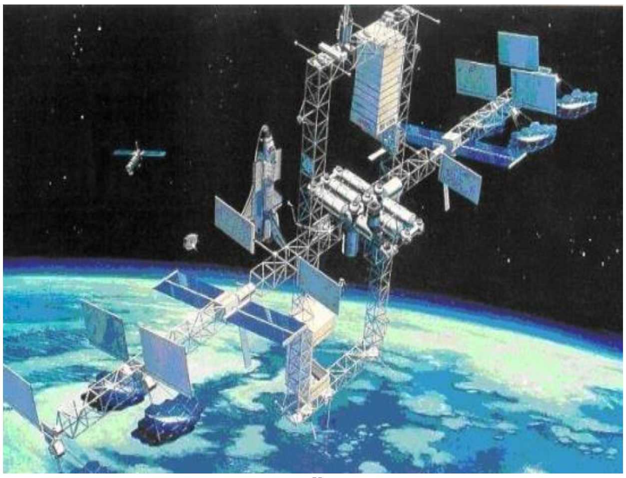

FIGURE 1 Satellite CFRP truss

FIGURE 2 Airship CFRP skeleton

In the composite truss structure, CFRP composites pipe components is the basic composition, and the stability of axial compression bearing capacity is the key to affect the whole structure stability. However, at present the study on stable of long tube CFRP are rare, and the research on bigger slenderness CFRP axis compression member is more rare. But the stability of the long tube from other materials research methods mainly can be divided into the following kinds:

Theoretical derivation:

The earliest Study of aluminum bending member overall stability is researched by Hill and Clark [1, 2], the stable theory research is Mainly done in solid rectangular section, box and i-section section aluminum alloy extrusion profiles component. And the related formula of axial force and bending moment was put forward.

Experimental study:

Aluminum alloy axial compression member is researched by Shen Zuyan, Guo Xiaonong [3], Qian Ruojun, Li Ming [4], etc. Cross section forms include circular pipe and "H" type of section, the test results show that members are bent instability. And for glass fiber reinforced composites (GFRP) pipe compression members, Qian Peng, Ye Lieping [5,6] get the basic parameters of the mechanical properties of GFRP pipe through short pipe compression test firstly,

***Corresponding author** e-mail: nb2003ccc@163.com

then select 4 different slenderness ratio of 12 GFRP long pipe to do experiment to study its stability.

Numerical analysis:

Compared to these two materials, Steel constitutive relationship has been relatively mature, Shi Yongjiu, Wang Yuanqing et al. [7, 8] using ANSYS finite element software, calculate overall stability capacity of High-strength steel welded box-section axial compression column, accurately simulate residual stress and geometric components of the initial defect. The results are in good agreement with the experimental results.

The above method has the following disadvantages: if the material model is simple, Stability capacity of members can be obtained accurately both the theoretical analysis and simulation; if the material model is complex (FRP composite material), results are obtained through the test method, and can only get a small amount of results.

Different angle of winding short CFRP pipe was analysed, then choose a better layer, and establish effective stress strain model, get its nominal yield strength according to Ramberg-Osgood equation; then through different slenderness ratio CFRP components axial compression, derived relationship Stability factor between the slenderness ratio, Finally, large number of parameters was analysed to discuss the law for components of the initial defect affecting its stability capacity.

2 Numerical simulation for short winding CFRP pipe axial compression

2.1 HASHIN PROGRESSIVE FAILURE CRITERIA

CFRP composite laminated structure mainly has 5 kinds of common failure criteria: yhe maximum stress theory, the maximum strain theory, Tsai-Hill criteria, Hoffman criteria, Tsai-Wu criteria. Failure criterion is single directional plate fiber by using a variety of the strength of the composite material under different load conditions; these theories do not consider the injury accumulation before the damage completely. The Hashin failure criterion [9] is a material consideration cumulative injury, damage evolution to achieve the criteria.

The basic principle of this theory includes fiber tensile fracture, compression buckling under transverse tensile and shear fracture when matrix under transverse compression and shear failure such as crushing, mainly includes the following forms:

Fiber tension ($\hat{\sigma}_{11} \ge 0$):

$$F_f^t = \left(\frac{\hat{\sigma}_{11}}{X^T}\right)^2 + \alpha\left(\frac{\hat{\tau}_{12}}{S^L}\right)^2 . \quad (1)$$

Fiber compression ($\hat{\sigma}_{11} \le 0$):

$$F_f^c = \left(\frac{\hat{\sigma}_{11}}{X^C}\right)^2 . \quad (2)$$

Matrix tension ($\hat{\sigma}_{22} \ge 0$):

$$F_m^t = \left(\frac{\hat{\sigma}_{22}}{Y^T}\right)^2 + \left(\frac{\hat{\tau}_{12}}{S^L}\right)^2 . \quad (3)$$

Matrix compression ($\hat{\sigma}_{22} \le 0$):

$$F_m^c = \left(\frac{\hat{\sigma}_{22}}{2S^T}\right)^2 + \left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right]\frac{\hat{\sigma}_{22}}{Y^C} + \left(\frac{\hat{\tau}_{12}}{S^L}\right)^2 , \quad (4)$$

X^T is axial tensile strength. X^C is axial compressive strength. Y^C is transverse compression strength. Y^T is transverse tension strength. S^L is axial shear strength. S^T is transverse shear strength. α is the coefficient of shear stress for fiber tensile failure $\hat{\sigma}_{11}$, $\hat{\sigma}_{22}$, $\hat{\tau}_{12}$ are the component effective stress $\hat{\sigma}$. $\hat{\sigma}$, which assess the initial damage equation:

$$\hat{\sigma} = M\sigma , \quad (5)$$

where σ is the nominal stress, M is the damage factor:

$$M = \begin{bmatrix} \frac{1}{(1-d_f)} & 0 & 0 \\ 0 & \frac{1}{(1-d_m)} & 0 \\ 0 & 0 & \frac{1}{(1-d_s)} \end{bmatrix} \times d , \quad (6)$$

d_f, d_m, d_s for the internal damage variable of shear characterization of fiber, matrix. They are derived from the previously mentioned four damage model related damage variable d_f^t, d_f^c, d_m^t, d_m^c:

$$d_f = \begin{cases} d_f^t\_if\_\hat{\sigma}_{11} > 0 \\ d_f^c\_if\_\hat{\sigma} < 0 \end{cases} , \quad (7)$$

$$d_m = \begin{cases} d_m^t\_if\_\hat{\sigma}_{22} > 0 \\ d_m^c\_if\_\hat{\sigma}_{22} < 0 \end{cases} , \quad (8)$$

$$d_s = 1 - (1-d_f^t)(1-d_f^c)(1-d_m^t)(1-d_m^c) . \quad (9)$$

Before the injury occurred, M is unit matrix, so $\hat{\sigma} = \sigma$. Once the injury began, it evolved at least one kind of mode above, injury began to occur, $\hat{\sigma}$ represents the real bearing capacity.

2.2 NUMERICAL SIMULATION OF SHORT PIPE AXIAL COMPRESSION BASED ON LAYERED SHELL ELEMENT

2.2.1 Layer Angle

Fiber is called the longitudinal direction, expressed with an "*x*", in vertical direction (sometimes have woven fiber, fiber content less) called lateral, expressed with "*y*", Thickness direction with "*z*", *tk is* the thickness of single layer. θk is angle between Fiber and principal axis direction (as shown in Figures 3-5).

Size	L=150mm, D=50mm
thickness	4mm
Number of layer	8
Element type	S4R
Element number	2400
Boundary conditions	One end fixed, one end free
Load	2mm displacement
Diameter-thick ratio	12.5

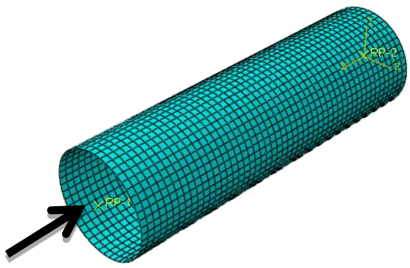

FIGURE 3 Model grid partition map

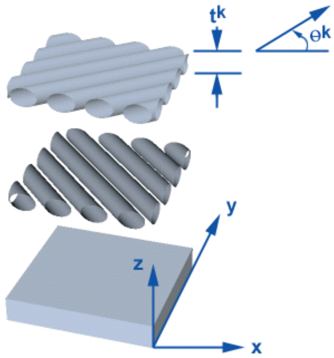

FIGURE 4 Fiber layer directions

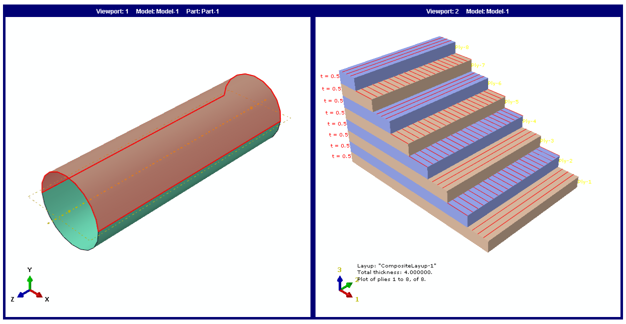

FIGURE 5 90/0/90/0/90/0/90/0 layer angle

2.2.2 The calculation results

Through to the mechanical properties of layer angle analysis of CFRP pipe, the strength of 90/0/90/0/90/0/90/0 orthogonal layer is high, but it belongs to brittle failure, if accompanied by plus or minus 45° layer can achieve very good effect (Figure 6).

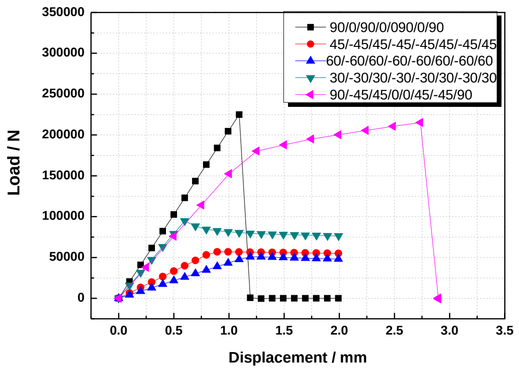

FIGURE 6 Load - displacement curve for each layer angle

2.3 THE EQUIVALENT STRESS AND STRAIN CURVE

According to the load-displacement curve, we found that 90/-45/45/0/0/45/-45/90 angle is the best. Select the layer mode as the research object, using the homogenization thought the macro components of load-displacement curve into material such as microscopic stress-strain curve, the following equation:

$$\sigma = \frac{F}{A} = \frac{F}{\frac{\pi}{4}(D^2 - d^2)}, \tag{10}$$

$$\varepsilon = \frac{\Delta l}{l}. \tag{11}$$

The equivalent of the stress-strain curve as follows:

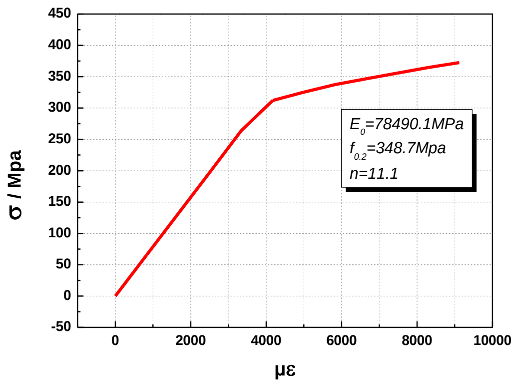

FIGURE 7 Equivalent stress - strain curve

Stress-strain curve of CFRP has no obvious yield platform, Ramberg - Osgood [10] formula was used to describe that:

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{f_{0.2}}\right)^n, \tag{12}$$

E is material elastic modulus. f0.2 is nominal yield strength. *n* is used to describe the strain hardening material, Its value can be calculated according to 0.1% and 0.2% nominal yield strength.

$$n = \frac{\ln(2)}{\ln(f_{0.2} / f_{0.1})}. \tag{13}$$

The equivalent material parameters such as Table 1.

TABLE 1 Material parameters

Material	E0 (MPa)	f0.1 (MPa)	f0.2 (MPa)	fu (MPa)	n
CFRP	78490.1	327.5	348.7	372.4	11.1

3 Research on winding CFRP long pipe stable performance

Calculating ideas of long pipe stable are as follows. The real component is modeled using finite element software. First linear modal analysis was done, a first-order modal L/1000 was extracted as the initial defect component to be applied to the original member. Then the arc method was used to do nonlinear finite element calculation considering the effect of large deformation (Figures 8-10).

FIGURE 8 Modal analysis

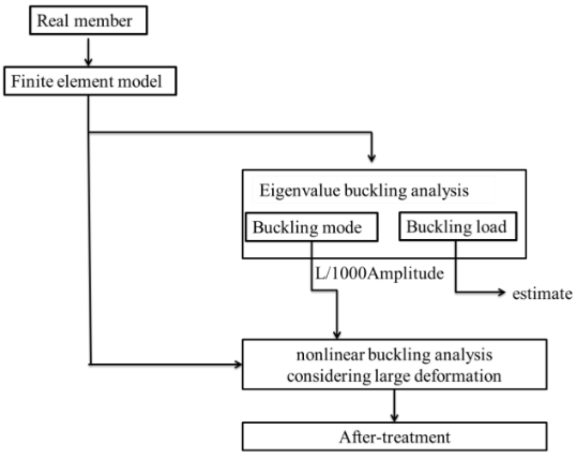

FIGURE 9 Calculation process

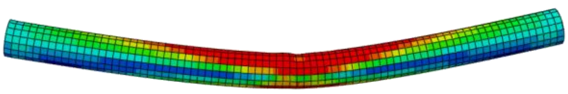

FIGURE 10 Nonlinear finite element calculation

3.1 LOAD - DISPLACEMENT ANALYSIS

In order to avoid local buckling, select section for Φ70×10 pipe [11], and calculate the pipe of slenderness ratio of 40, 60, 80, 100, 120, get the whole process of load – displacement curve (as shown in Figure 11) and load – mid-span deflection curve (as shown in Figure 12).

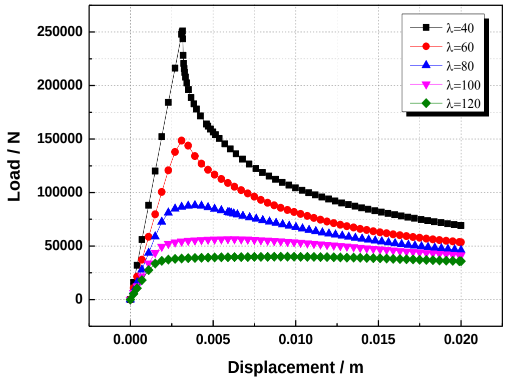

FIGURE 11 Load 3 – displacement curve

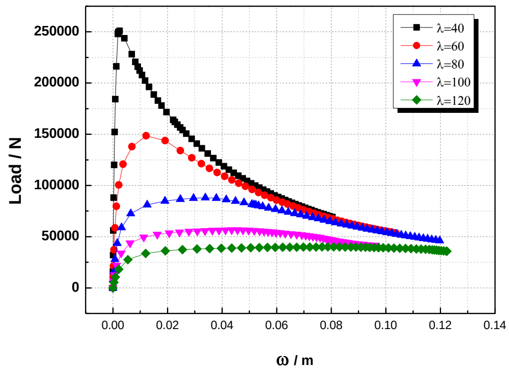

FIGURE 12 Load - deflection curve

As shown in Figure 11 along with the increase of slenderness ratio, compression stability bearing capacity of pipe falling; Slenderness ratio λ of 40 and 60, the shape of load – displacement curve is sharp, brittle failure mode, Mainly because CFRP is brittle material When λ is 80, 100, 120, the shape corners disappear into a smooth gradient inflection point, it shows overall instability of the structure.

As shown in Figure 12, for slenderness smaller components, load - mid span deflection curves presents "tip" is brittle failure, less deformation span; for slenderness relatively large components, load - mid span deflection curve is smooth, elastic deformation, the larger the amount of deformation span.

3.2 STABLE FACTOR – SLENDERNESS RATIO CURVE

The Figure 11 shows the extraction the stability bearing capacity of the whole process load - displacement curve and the stability bearing capacity of the corresponding displacement are listed in the table below.

TABLE 2 List of stable bearing capacity - slenderness ratio

Slenderness ratio λ	**Stable bearing capacity (*N*)**	**The stability bearing capacity of displacement (*mm*)**
40	250842	2.8
60	148483	3.1
80	88027	3.9
100	56520	5.9
120	39975	9.5

In order to facilitate the comparison of component stability bearing capacity of different sizes, stable factor is introduced; stable factor φ can be calculated through the following equation:

$$\varphi = \frac{F_u}{F_{0.2}}, \tag{14}$$

where F_u for buckling load, $F_{0.2}$ for the product of nominal stress and the cross section (Figure 13).

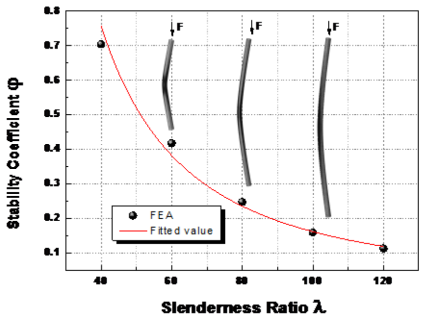

FIGURE 13 $\bar{\lambda}-\varphi$ curve

According to $\lambda-\varphi$ curve, stability coefficient decreases with the increase of slenderness ratio, by fitting curve can be ensure stable factor of slenderness ratio of 50 at 0.5.

3.3 INFLUENCE OF INITIAL DEFECTS

In order to investigate the initial defects of different cross section and the influence of different elastic modulus components, regularization slenderness ratio could be calculated to achieve it, specific methods are as follows:

$$\bar{\lambda} = \sqrt{\frac{F_{0.2}}{F_E}}, \tag{15}$$

$$F_{0.2} = Af_{0.2}, \tag{16}$$

$$F_E = \frac{\pi^2 E_0 I}{L_e^2}, \tag{17}$$

where A is term cross-sectional area, $f_{0.2}$ is nominal buckling strength, E_0 is initial elastic modulus, I is moment of inertia, L_e is calculated length, $F_{0.2}$ is load yield, F_E is Euler critical force (Figure 14).

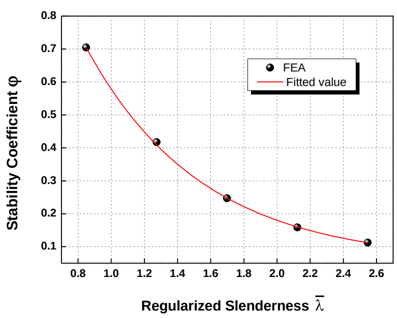

FIGURE 14 $\bar{\lambda}-\varphi$ curve

In this paper, the overall magnitude of bending the initial defect was analysed, includes 6 kinds of conditions, L_e/500, L_e/800, L_e/1000, L_e/1500, L_e/2000, L_e/3000, the results as shown below (Figure 15):

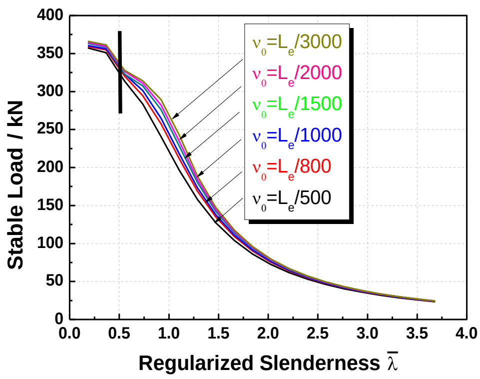

FIGURE 15 Sensitivity analysis of initial defect

The calculation results show that, the length of the smaller member ($\bar{\lambda} < 0.5$) is the intensity of damage, others are overall instability. in the whole range, buckling load of member decreases with the increase of the amplitude of the initial defect, initial defect has the larger the effect on member of the regularization slenderness ratio ($0.5 \le \bar{\lambda} \le 2.0$), when slenderness ratio ($\bar{\lambda} = 1$), Buckling load is most sensitive to changes in the initial defect, has Little effect even negligible when $\bar{\lambda} > 2.0$.

4 Conclusion

1) The compression of short tube is analysed based on the progressive failure criteria (Hashin Criterion) to get the optimal layer angle 90/-45/45/0/0/45/-45/90, and equivalent relationship of stress and strain is obtained to define this layer material.

2) Before instability, CFRP winding pipe appears linear elastic characteristics, brittle characteristics when destroyed, and the length of the smaller member ($\bar{\lambda} < 0.5$) is the intensity of damage, length of middle and long pipe ($\bar{\lambda} > 0.5$) is overall bending instability.

3) According to the $\lambda-\varphi$ relationship curve, stability factor decreases with the increase of slenderness ratio.

4) Initial defect has the larger the effect on member of the regularization slenderness ratio ($0.5 \le \bar{\lambda} \le 2.0$), when slenderness ratio ($\bar{\lambda} = 1$), Buckling load is most sensitive to changes in the initial defect, has Little effect even negligible when $\bar{\lambda} > 2.0$.

Acknowledgments

The work described in this paper was jointly funded by the National Natural Science Foundation of China under Grant No. 51378150.

References

[1] Hill H N, Hartmann E C, Clark J W 1956 Design of aluminum alloy beam-columns *Transactions of the American Society of Civil Engineers* **121**(1) 19-21

[2] Clark J W 1955 Eccentrically loaded aluminum columns *Transactions of the American Society of Civil Engineers* **120**(1) 1116-1132

[3] Guo X-N, Shen Z-Y, Li Y-Q 2007 Theoretical and experimental research on aluminum alloy members under axial compression *Journal of Building Structures* **28**(6) 118-28 *(in Chinese)*

[4] Li M, Chen Y-J, Qian R-J 2000 Experimental research on the stability parameters of aluminum pipes under axially *Compression Load Spatial Structures* **6**(3) 59-64 *(in Chinese)*

[5] Qian P, Feng P Ye L-P 2007 Experimental study on GFRP pipes under axial compression *Journal of Tianjin University* **1**(1) 19-23 *(in Chinese)*

[6] Qian P, Feng P, Ye L-P 2008 Experimental study on GFRP pipes under axial compression *Frontiers of Architecture and Civil Engineering in China* **2**(1) 73-8

[7] Shi G, Wang Y-Q, Shi Y-J 2009 Behavior of high strength steel columns under axial compression *Journal of Building Structures* **30**(2) 92-7 *(in Chinese)*

[8] Shi G, Wang Y-Q, Shi Y 2009 Finite element analysis on overall bucking of ultra-high strength steel welded box section columns under axial compression **25**(2) 255-61 *(in Chinese)*

[9] Hashin Z, Rotem A 1973 A fatigue failure criterion for fiber reinforced materials *Journal of Composite Materials* **7** 448-64

[10] Ramberg W, Osgood W R 1943 Description of stress-strain curves by three parameters Washington D.C. *National Advisory Committee for Aeronautics* TN-902

[11] Hou W, Zhang X-H, Feng H-C 2010 Stability of axial compression members of Glass Fiber-Reinforced Plastic (GFRP) *Journal of Building Materials* **13**(4) 441-5 *(in Chinese)*

Authors

Bo Nan, born in April, 1984, Liaoning Province, Shenyang City, China

Current position, grades: Doctor at Harbin Institute of Technology.
University studies: Master's degree at Shenyang Jianzhu University in Shenyang City in 2010.
Scientific interests: space structure in civil engineering

Yue Wu, born in December, 1972, Heilongjiang Province, Harbin City, China

Current position, grades: professor at Harbin Institute of University.
University studies: Master's degree at Harbin Institute University in Harbin City in China in 1998. Doctor's degree at Harbin Institute University in Harbin City in China in 2003.
Scientific interests: space structure.