THE STUDY ON SEMIRIGID JOINTS OF CFST FRAME

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ABSTRACT: Since the 70th and 80th of the 20th century, in fields of steel structure and composite structure, the study on semirigid joints had obtained a lot of achievements, including the study of computing method and a great deal of connection database that were set up through experiments. However, in the field of CFST (concrete-filled steel-tube), semirigid research obviously lagged behind. At present, more than twenty types of beam-to-CFST column joints have been applied in practice, and these joints are assumed as pinned or rigid in frame analysis. We need to attach importance to the rationality and the effect on frame analysis of these assumptions.

This paper focused on the study of restraining stiffness of stiffening ring joint and continuous web plate joint in CFST frame. Firstly, the solid models of CFST joints were created and analyzed by using ANSYS. Secondly, 11 one-third scale specimens of joints were made to process static experiments, and then to verify the applicability of the finite element models with the experiment results. Finally, basing on the models, some factors, such as the dimensions of beam and column, were changed to confirm the influence on semirigid and $M-\theta_r$ models of the joints were created.

In the course of analysis, this program avoided carrying on a large number of tests. The analysis on each influencing factor was being finished by the finite element model. The $M-\theta_r$ curve model can be suitable for frame analysis.

Keywords: concrete-filled steel-tube, semirigid joints

1. INTRODUCTION

Since the 20th century, two approaches in semirigid research were discussed mainly. Firstly, in the filed of the computing technology, some kinds of simple and accurate expressions to reflect various kinds of $M-\theta_r$ relations of connections were discussed. To educe the expression of stiffness from mechanics is the general method. For example, Liu et al. [1] proposed J= f (E, I, G, I_P, μ, L, D, b, h) for double-beam joint, Xu [2] defined connection's rigidity parameter α . Owing some assumptions and simplifications were introduced in creating the models, the method had its limitation. Secondly, a large number of tests were being used to verify static and dynamic performance of semirigid joints frame. Since 1970's, Chen and Lui [3] and other scholars made a large amount of works in steel semirigid joints. Since 1980, several connection databases for structure analysis were developed. Certainly, utilizing a large number of data to simulate parameter model belongs to the category of numerical calculation. The parameter in the function of the model has no clear mechanics meaning. In addition, finite element method was used. Many structural analysis programs were utilized. That only suitable constitutive model of material and suitable element type can simulate material and behavior of structure factually. How to appraise and analyze the result of finite element method is still a problem too.

However, in the field of CFST, semirigid research obviously lagged behind. Presently, more than twenty joints have been applied in practice, and these joints are assumed as pinned or rigid in frame analysis. We need to attach importance to the rationality and the effect on frame analysis of these assumptions.

This paper focused on the study of restraining stiffness of stiffening ring joint and continuous web plate joint of CFST frame. The stiffening ring joint came from the code DL/TB 5085—1999 of

China. The continuous web plate joint came from the code CECS 28:90 of China, and also referred to other documents (Elremaily and Azizinamini [4]). These two joints have been used in many structures. In this subject, we gain the information of restraining stiffness of joints as follows: (1) A finite element model of joint were made by using ANSYS [4]. (2) The accuracy of the analytical models was verified by comparing to the test data. (3) The influence factors were analyzed by using the verified models. In this way, we can acquire the needed $M-\theta_r$ models instead of doing large quantity tests.

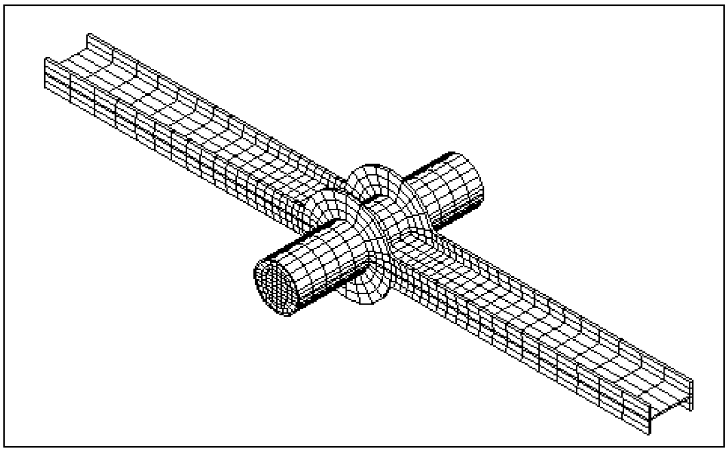
2. FEM ANALYSIS

The FEM software ANSYS [4] is applied in analysis.

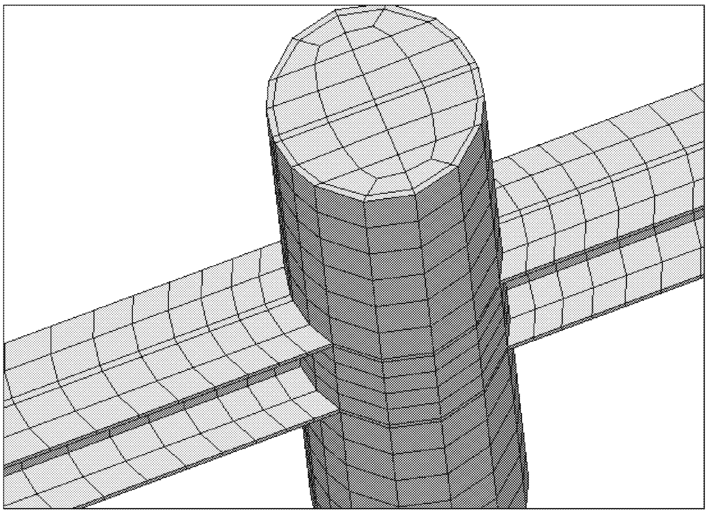
2.1 The Creation of Finite Element Model

Through analysis, a kinematic hardening model was used to simulate steel components and Drucker—Prager yield rule was used to describe the core concrete of CFST. As shown in Table 2, the material parameters of steel were from the experiment of material. Poisson's ratio of steel was 0.283. The compression strength of concrete was 50 MPa，and Poisson's ratio was 0.2 in elastic range. The elastic modulus was taken as 3.455×10^4 MPa that was calculated from the code GB 50010-2002 of China. The cohesion value （c）was 5.117 MPa. The angle of internal friction (ϕ) was 56.03.

Two kinds of finite element models of joints were shown in Fig.1. Solid element was adopted for steel tube, beam and concrete. Steel tube and concrete interface adopted surface-to-surface touch element. The inner surface of steel tube is target surface with 3-D Target Segment TARGE170, and the exterior surface of concrete is contact surface, with 3-D surface-to-surface CONTA174 (173). The contact and target surfaces constitute a "Contact Pair".



(a) Stiffening ring joint



(b) Continuous web plate joint

Figure 1. The Finite Element Models of the Joints

Considering the real condition when the specimens were loaded, the axial freedom of all nodes on the end surface of column was limited.

While solving equation, direct solution was adopted. There were many measures to enhance convergence property in the course of non-linear solving as follow: (1) Using Newton-Laphson Iteration to control the non-linear iterative error in some range permitted. ⑵ Determining convergence criterion based on force, using square root of quadratic sum of all degree of freedom unbalanced forces to check convergence and controlling the admissible error less than 2%. (3) Controlling iterative loop less than 25 times. (4) Determining size of load increment in sub-step by procedure and deciding to increase or reduce time step (sub-step) during solving.

2.2 The Result of ANSYS Analysis

The result of ANSYS [4] analysis includes strain at each direction, stress at each direction, equivalent stress and total deformation. Through particular analysis, the details under loading were understood, and the information contributed to comprehend the mechanics behavior of joints. Analysis result from ANSYS [4] offers guidance for design and measure of joint test.

3. THE STATIC EXPERIMENT OF JOINT

3.1 The Design of Experiment

Joints are taken from middle joint of a layer of one high frame structure. The height of column is 3m and the length of beam is 6m generally. Considering the experimental conditions, one-third scale specimen was chosen. The sections of steel tube and beam are shown in Table 1. Steel tube was filled with C50 concrete. The frame is characterized by having inflection points near the midpoints of the beams and columns, so the length of each side's column is 1m, and the length of both sides' beam is 1m too.

In the test, although one-third scale specimen was adopted, the size of steel tube and steel beam, and the strength grade of concrete are used in practice. So the question of size effect can be disregarded. Universal rule and calculation theory that were verified in the test can be popularized.

Table 2 shows the relevant data that was from the steel mechanics test. The compressive strength of the concrete in tube was 56.2 MPa according to the code GBJ 81-85 of China.

Table 1. Size of Specimens

Number	Section of column	Section of beam	type of Joint	Width of stiffening ring (mm)	Thickness of stiffening ring(mm)	Quantity
A1	Φ159*5	I16	Stiffening ring	10	80	3
A2		HN175x90x5x8		8	80	2
A3		HN198x99x4.5x7		8	80	2
B1		HN175x90x5x8	Continuous web plate	--	--	2
B2		HN198x99x4.5x7		--	--	2

Table 2. Parameter of Steel Material

Material	Yield stress (MPa)	Modulus of elasticity (MPa)	Ultimate strength(MPa)
159*5	275.0	1.96×10^{5}	--
I16	308.45	2.055×10^{5}	398.68
H175	324.96	2.075×10^{5}	482.46
H198	300.00	2.048×10^{5}	440.14

3.2 Test Series

In order to simulate the inflection point, a hinge was adopted at the bottom of the column. While assembling the specimens and preloading, the position and direction of the loading must be restricted to avoid unanticipated stress condition.

With the expressions of 4.1.2-2 and 3 from CECS 28:90 of China, the carrying capacity of CFST column can be gained. Considering the ability of loading device also, 500kN was introduced. Under 500kN, steel tube and concrete support stress alone, tightening hoop load is inexistence [1]. Two loading systems are shown in Fig.2. A constant axial load was applied on the column. This load was applied first until it reached 500kN which can control the column to work in normal employing condition. Equal vertical loads were applied at two beam ends in the same direction and increased monotonically in 5kN until 45-50kN.

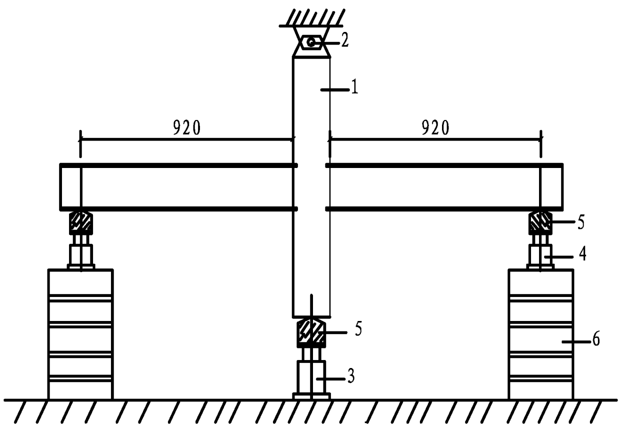


Figure 2. The Schematic of Test Setup
1. Specimen 2. Hinged support 3. 100t hydraulic jack
4. 10t hydraulic jack 5. Pressure sensor 6. Steel bracket

The whole deformation and the part deformation, including the surface strain of beam and column, the displacement of beam ends, and the relative rotation of beam to column are measured. IMP data collection system was used to collect strain data, and displacement sensor was used to measure displacement and rotation.

The connection of beam to column transfers a group of generalized force including axial force, shear, moment, and torsion. The influence of torsion can be neglected in plane problem. For most connections simultaneity, axial deformation and shearing deformation are very small. Therefore, only rotational deformation is considered generally. The relative rotation may be defined as be shown in Figure 3. Figure 4 shows the location of displacement meters.

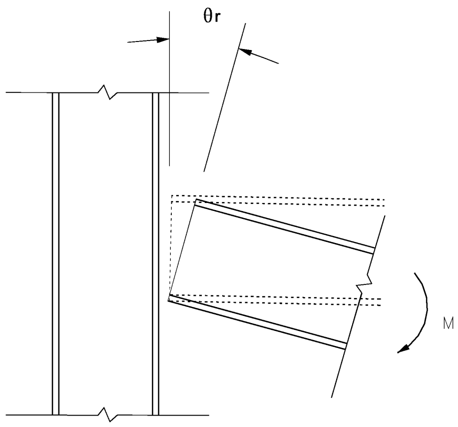


Figure 3. Relative Rotation of Beam to Column

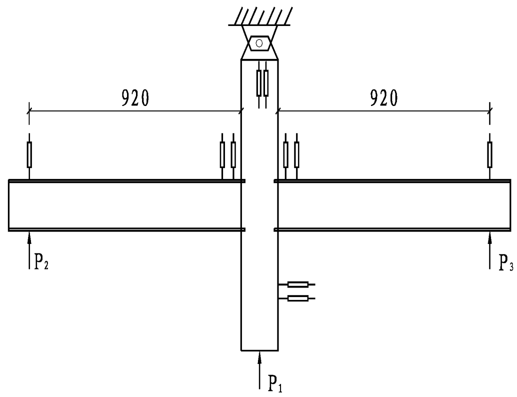


Figure 4. The Location of Displacement Meters

3.3 Analysis of Experimental Result

The specimens were observed carefully in the whole process of experiment. When column was loaded, there was not obvious deformation. When beam was loaded, two ends of beam had obviously deformation. While getting to 45~50kN, yield deformation can be founded obviously, and in the later stage, the beam leaned. But some dangerous deformations such as fracture of the welding line, protruding and concaved deformation of the steel tube wall in the joint area did not appear. The thorough comprehension of behavior of joints can be obtained by experiments. Greater details of the two kinds of joints are narrated in Yuan [6] and Chen et al. [7].

Deflection of the beam was shown in Figure 5, the result of mechanics was different from the result of experiment. The higher the load, the more difference between the result of mechanics and experiment (19~43%) appears. The analysis showed that to calculate continuous web plate joint as fixed joint was unreasonable.

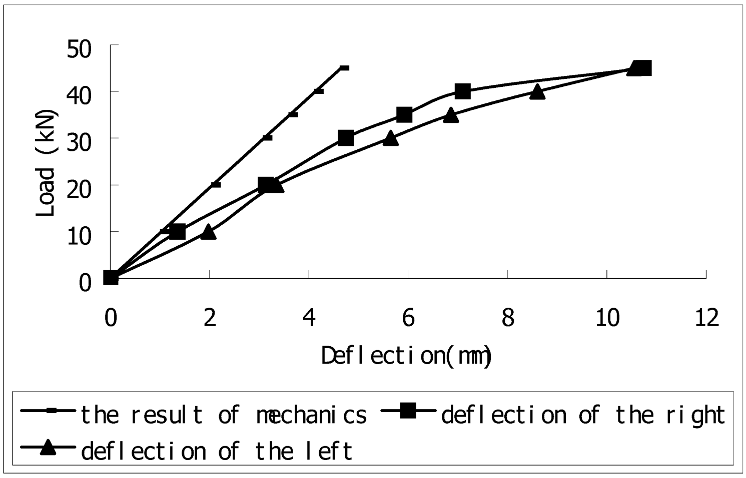


Figure 5. Deflection of the Beam End

The $M-\theta_r$ curve of the stiffening ring joint is shown in Figure 6. There are many differences between experiment and FEM analysis because of the loading rate of two beam ends and the accurate of measuring devices, but the trend of $M-\theta_r$ curve is similar.

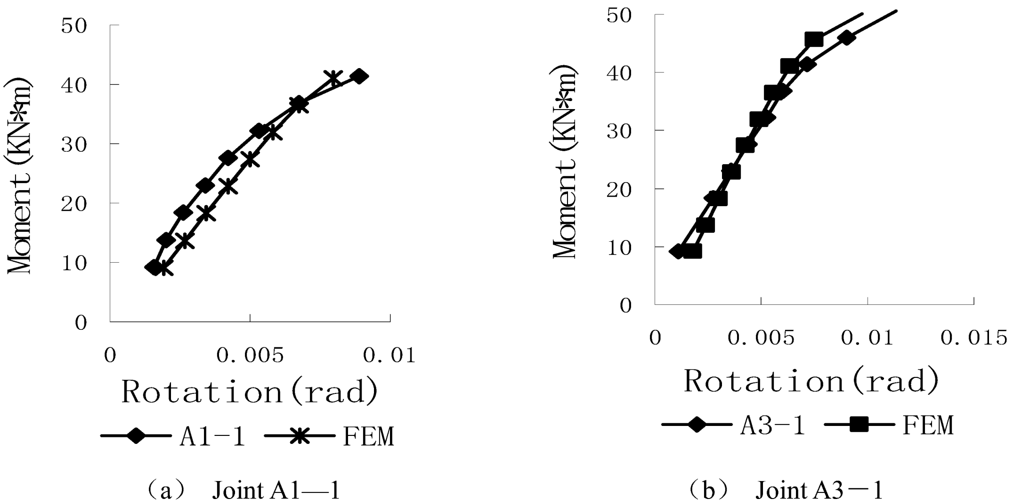


Figure 6. $M-\theta_r$ Curve

3.4 Checking the FEM Analysis

In order to verify the FEM analysis, the results from the experiments are compared to the FEM analytical data. A good agreement between the experimental and FEM analytical of load-deflection relationships are observed from Figure 7, Table 3, and Figure 8.

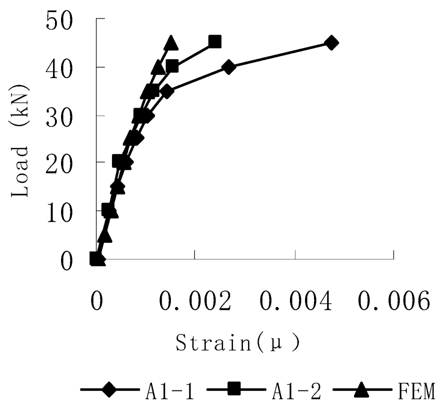


Figure 7. Load-strain Curve of Beam's Flange to Stiffening Ring of Joint A1.

Table 3. A Comparison of Vertical Strain on the Ektexine of Column

Vertical strain	FEM analytical result		Calculational result	Experimental result	
	Ektexine of column	concrete		Joint B1-1	Joint B2-2
μ	478.28	461.0	471.70	440.8	484.35

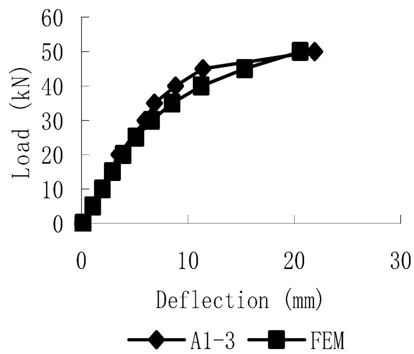


Figure 8. Load-deflection Curve of Beam End

4. THE ANALYSIS OF INFLUENCING FACTORS

For formed type joint, influencing factors on semirigid joints include geometrical and mechanical properties. Different joint must account for the contribution of the different components. In this paper, geometrical factors were mainly considered.

4.1 Stiffening Ring Joint

Influencing factors that were shown in Figures 9-14 included width of stiffening ring, diameter and thickness of steel tube, height of beam, width of beam, thickness of flange and thickness of web plate. The thickness of web plate was ignored because of its little influence.

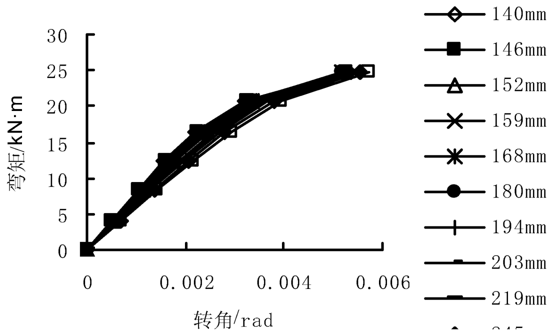


Figure 9. Moment-rotation Curve on Various Diameter of Steel Tubes

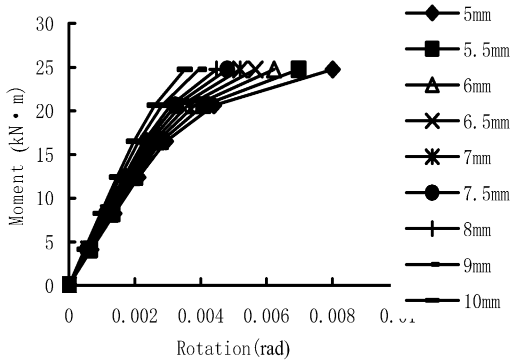


Figure 10. Moment-rotation Curve on Various Thickness of Steel Tubes

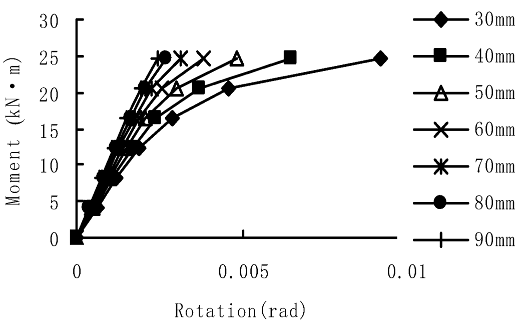


Figure 11. Moment-rotation Curve on Various Width of Stiffening Rings

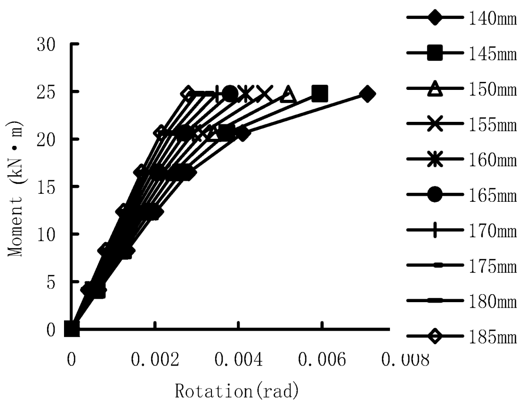


Figure 12. Moment-rotation Curve on Various Height of Beams

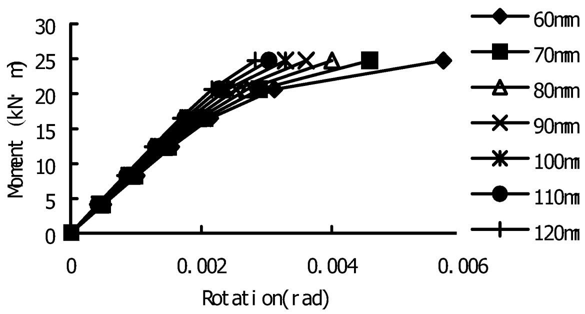


Figure 13. Moment-rotation Curve on Various Width of Beams

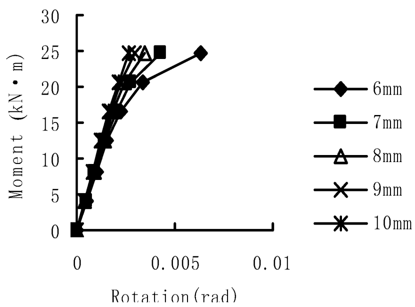


Figure 14. Moment-rotation Curve on Various Thickness of Flanges

At first, the dimensions of beam and column were changed. According to the FEM analysis, the height of beam is the major factor, then the width of the flange. Other factors make litter influence. Greater details were provided in reference (Yuan [6]). Secondly, as shown in Figure 15 and Table 4, the proportion of rigidity per unit length of beam to column does not make direct influence to $M-\theta_r$ relation. Finally, the axial compressive force ratio was considered. As shown in Figure 16, the rotation increased obviously when the moment increased under higher axial compressive force ratio.

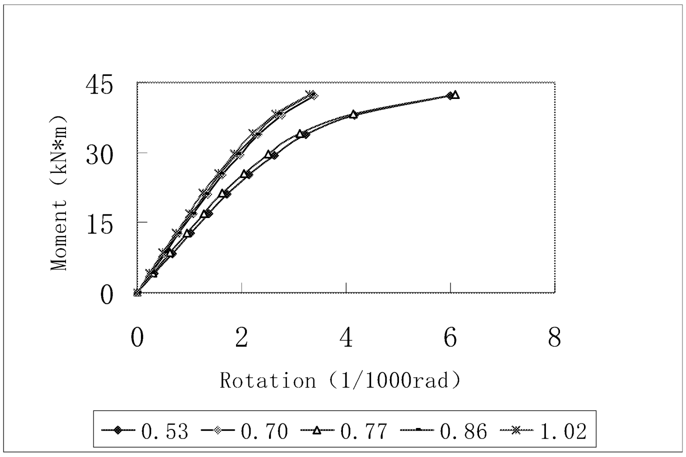


Figure 15. $M-\theta_r$ Curve on Various Proportion of Rigidity Per Unit Length of Beam to Column

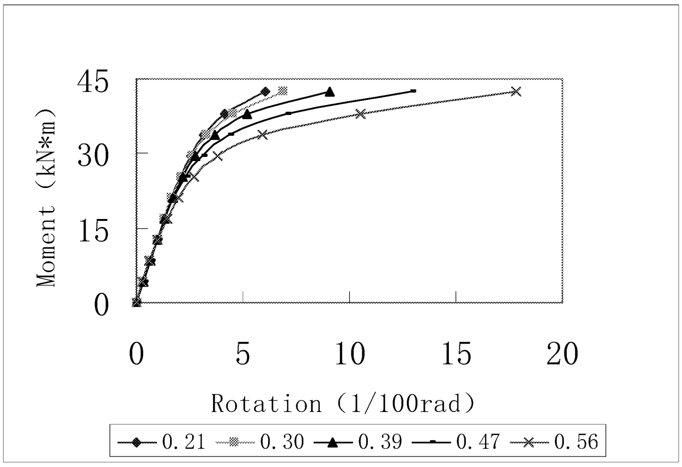


Figure 16. $M-\theta_r$ Curve on Various Axial Compressive Force Ratio

Table 4. The Relationship between Proportion of Rigidity Per Unit Length of Beam to Column and Rotation

proportion of rigidity	Type of beam	Type of column	Rotation when moment is 38.3kN*m （1/1000rad）
0.53	HN175	φ168*5	4.16
0.70	HN198	φ168*5	2.77
0.77	HN175	φ152*5	4.13
0.86	HN198	φ159*5	2.70
1.02	HN198	φ152*5	2.65

5. $M-\theta_r$ MODEL

According to the analytical theory of semirigid steel frame by Chen and Lui [3] who introduced Colson-Louveau [8] and Kishi-Chen [9] models and the analysis of influencing factors, a power function is used as the $M-\theta_r$ model of the two joints in equation (1). In Colson-Louveau [8] and Kishi-Chen [9] models, M_u is the ultimate moment of connection and it is obtained by analytical method generally. Considering the failure may happen in beam for stiffening ring joint and continuous web plate joint, assume M_u be ultimate moment of beam.

$$\theta_r = \frac{M}{C_1 K[1-(M/M_u)^{C_2}]} \tag{1}$$

Where M(N·mm） is the beam moment of joint, θ_r (rad) is the relative rotation of beam to column, C_1 and C_2 are fitting parameters of curve, K is a standard constant. For stiffening ring joint, C_1 equals 167.96, C_2 equals 18.38, K is determined by the equation (2).

$$K = d^{-0.18} t_s^{0.58} b_j^{0.80} h^{1.30} b^{0.71} t^{0.90} \tag{2}$$

Where d(mm） is the diameter of column, t_s(mm） is the thickness of steel tube, b_j(mm） is the width of stiffening ring, h(mm）is the height of beam, b(mm） is the width of beam, t(mm）is the thickness of the beam flange.

For continuous web plate joint, C_1 equals 612.91, C_2 equals 15.54, K is determined by the equation (3).

$$K = d^{-0.76} t_s^{0.16} h^{2.58} b^{0.12} t_w^{0.48} t^{0.04} \tag{3}$$

Where d(mm） is the diameter of column, t_s(mm） is the thickness of steel tube, h(mm） is the height of beam, b(mm） is the width of beam, t_w(mm)is the thickness of the web plate, t(mm) is the thickness of the beam flange.

6. CONCLUSION

(1) The research of semirigid joints of CFST column promotes the application of the structure of CFST. The discussion has already been carried on analysis of frame (Chen [10]).

(2) An alternative means to gain the information of restraining stiffness of joint is applied in this paper. This means can be applied in research of other type joints.

(3) Stiffening ring joint and continuous web plate joint have some semirigid characteristic. Through analyzing, the $M - \theta_r$ models of joint are created finally.

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REFERENCE

[1] Liu, Zhibin, Zhong, Shantong, "Rigidity of Joint of RC Double-beam and CFST Column", Journal of Harbin University of C.E. & Architecture, 2001, (8).

[2] Xu, Jianxun, "Study of the Connection Mechanical Behavior and Its Affection on Steel Frame", Master Degree dissertation, Zhejiang University of Technology, 2002.

[3] Chen, W.F. and Lui, E.M., "Stability Design of Steel Frames", CRC press, 1991.

[4] ANSYS, general purpose software, Ansys Software Pvt.

[5] Elremaily, A. and Azizinamini, A, "Design Provisons for Connections Between Steel Beams and Concrete Filled Tube Columns", Journal of Constructional Steel Research，2001, pp. 971-995.

[6] Yuan, Jixiong, "The Study on the Restraining Stiffness of Continuous Web Plate Joint of Steel Beam to CFT Column", Master dissertation, Department of Civil Engineering, ShanTou University, 2004.

[7] Chen, Juan, Wang, Zhan, Yuan, Jixiong, "The Study on the Stiffness of Joint of Steel Beam to CFT Column with Stiffening ring", Journal of Building Structures, 2004, 25(4).

[8] Colson, A. and Louveau, "Connections Incidence on the Inelastic Behaviour of Steel Structureal, Euromech Colloquium, 174, 1983.

[9] Kishi, N. and Chen, W.F., "Data Base of Steel Beam-to-column Connections", Structural Engineering Report No. CE-STR-86-26, School of Civil Engineering, West Layafette, IN.

[10] Chen, Xi, "The Study on the Stiffness of Joint of Steel Beam to CFT Column in Frame Structure and the Effect on the Behavior of Frame Structure", Master dissertation, Department of Civil Engineering, ShanTou University, 2005.