RESEARCH ON RESTORING FORCE CHARACTERISTICS OF HONEYCOMBED STEEL BEAM AND WELDED COMPOUND-RING-HOOP COLUMN COMPOSITE JOINTS

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ABSTRACT: Eight specimens of honeycombed steel beam and welded compound-ring-hoop column composite joints, designed in 4 different types of connection, were tested under cyclic horizontal loads. The restoring force model including a general skeleton curve and hysteretic rule is formed. Two different destruction forms “weak beam-strong column-strong joint” and “strong beam-strong column-weak joint”, occurred as the result of the different connection methods. Meanwhile the relevant hysteretic loops changed into well-developed spindle-shape or converse S-shape with the augmentation of displacement. Certain pinch and the development of the ductility of the structure are shown in the curves for different transverse reinforcement ratio in joint core zone and joint stiffness, and the effect on ductility is advantaged. The tri-line load-displacement restoring model and hysteretic rule based on connection and transverse reinforcement ratio are proposed as well as the formulas for calculating the rigidity of either loading or unloading. The regularity of rigidity degeneration of both loading and unloading condition according with exponential law is also concluded in the article. The restoring force model not only reflects the hysteretic character properly but also is conveniently applied to engineering analysis, which is already verified by comparing with the test.

KEYWORDS: restoring force model, skeleton curve, hysteretic loop, rigidity degeneration, composite joint

1. INTRODUCTION

The design of the joints is one of the most important issues in the anti-seismic design of the construction, for the joints not only transmit the forces from beams to columns but also assure all the pieces of the frame work as a whole. As the composite construction has rapidly developed since the 1980s, the seismic resistance of the composite joint has become one of the significant research subjects. The honeycombed steel beam and welded compound ring hoop columns composite construction has the advantage of less consumption of concrete and steel, high bearing capacity and light weight and so on. The concrete strengthened by compound welding ring stirrups has the similar characteristics with the steel-tube concrete. But the seismic performance of the honeycomb steel beam-welded compound ring hoop columns joints hasn’t been studied as fully as the steel tube column-steel beam joins [1]. For this reason, a series of pseudo-static tests were done to study the seismic performance of this kind of composite joints with different connections. On the basis of the low-circle reversed tests, integrating theory analysis with practice, the skeleton curves of the test were drawn from the load-displacement hysteretic curves referring to the tests before. A general restoring force model was obtained so as to study the seismic performance of the composite joints furthermore.

2. EXPERIMENTAL PROGRAM

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8 cross joints were designed for the test. The specimens were divided in to 4 groups according to the connection with 2 specimens in every group to avoid the error in constructing. The connection of the joints was designed in three types: steel-through connection, flush end-plate connection and extending end-plate connection. The honeycomb steel beam was made of the steel I beam, the size of which is 260mm×160mm×24mm×10mm, the span length of the pass-through steel beam is 2700mm, the bolted connection beam is 1200mm.The steel is grade Q345 with nominal yielding strength f_y=345*MPa*; the bolts are high strength friction-grip bolts (grade 10.9), the length of which is 320mm.The details of the connection are shown in Table 1.

Table 1 Details of specimens

Connection type	end-plate's dimension (mm)	Number of bolts	Bolt diameter	stirrups ratio in zone
Steel-through	—	—	—	0
Steel-through	—	—	—	0
Extended	400×250×260	8	20	3.79
Extended	400×250×260	8	20	3.79
Flush	145×230×35	6	20	3.79
Flush	145×230×35	6	20	3.84
Steel-through		—	—	3.84
Steel-through		—	—	—

Table 2 Property of concrete

Specimen number	f_{cu} /N·mm^{-2}
RCSJ1-1	53.0
RCSJ1-2	57.1
RCSJ2-1	59.2
RCSJ2-2	59.7
RCSJ3-1	57.4
RCSJ3-2	58.8
RCSJ4-1	40.56(53.0)
RCSJ4-2	39.95(57.1)

Tag: The figure in bracket is the characteristic value of cubic concrete compressive strength.

The dimension of the cross section of the concrete column is 300mm×250mm, the effective height is 1800mm, and the concrete grade is C50. The actual material properties of the concrete are shown in Table2. The nominal elastic strength of the bolts is 206000MPa. The longitudinal bar is HRB400.The ratio per unit volume of longitudinal bars is 2.62%. The specimens used the HRB335 welded compound stirrups, the diameter of which is 10mm. The spacing of stirrups is 80mm. (There are no stirrups in the core zone of the specimens in group one.)The cross section of the column is shown in Fig.1. The specimens in the same group are totally with same parameters. The connection of the joints is shown in the Fig.2: (a)the specimen 1-1 (1-2) with the connection of steel-through; (b)the specimen 2-1 (2-2)with the connection of bolted extended end-plate; (c)the specimen 3-1(3-2)with the connection of bolted flush end-plate; (d)the specimens 4-1 (4-2) were obtained by reinforcing the damaged pieces of 1-1 and 1-2 with concrete and 6 couples of welded ring stirrups in the core zone.

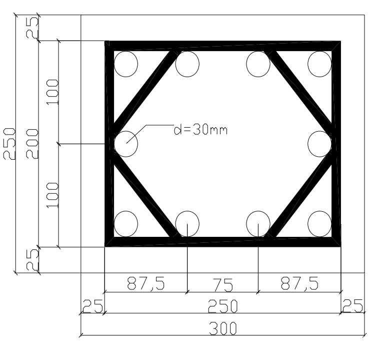


Figure 1 The cross section of column

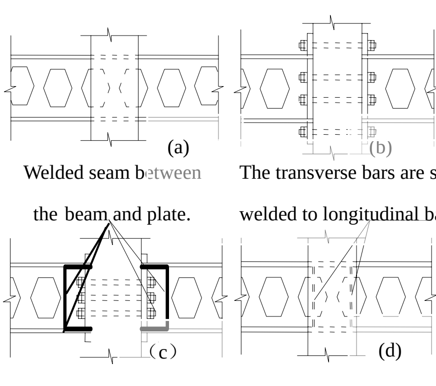
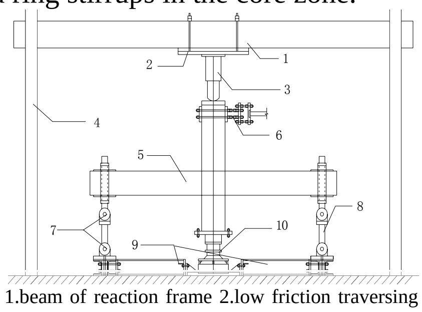


Figure 2 The beam-column joints



1.beam of reaction frame 2.low friction traversing crane 3.vertical lifting jack 4. reaction frame 5. specimen 6.load end (connecting with actuator and control system) 7.mechanical bearing 8.tension rod 9.fixing ground beam 10.fixing spheric hinge

Figure 3 The test equipment

In order to reflect the real performances of the beam-column joint under the seismic loading and get the P - Δ relation, the load was applied on the upper-side of column. The test equipment is shown in the Fig.3. A lifting jack with a full-scale load 800KN was applied to exert the vertical load on the top of the column. There was a glide car between the lifting jack and the reaction beam to assure the column can move synchronously along with the displacement loaded. The cyclic horizontal loads are applied to the top of column by MTS. The test procedure is controlled by displacement of column top. Preloading 1/6 vertical force before the test to assure the specimen was under the axial pressure by observing the strain of longitudinal bars of the same cross-section generally identical. A constant vertical load was applied to the column end to assure the equipment all worked well. The cyclic loading procedure was a displacement control method according to the current specification for seismic testing [2]. The whole test was monitored by the hysteretic curve of horizontal displacement at the column end. Before the specimen yields, loading cycled once per load deflection. After yielding appears, the load deflection increased one yielding-deflection per time and the loading cycled three times per loading deflection. The test didn't finish until the bearing capacity declined to 85% of the peak bearing capacity.

3. EVALUATION OF THE TEST RESULTS

The four groups of specimens failed as follows: the bonding-slipping failure between the steel beam and the concrete, shear failure in the core zone of the joints, the fracture of the high-strength bolts at the welded point, and the hinge-damage at the steel girder. The yield load, maximum load, ultimate bearing capacity and so on were all shown in the Table 3.

Table 3 The load and displacement at characteristic point

Specimen	P_y	Δ_y	P_m	Δ_m	P_u	Δ_u	u
RCS1-1	80.2	12.0	88.6	22.6	71.4	35	2.92
RCS1-2	76.9	11.8	87.9	17.8	74.7	35.8	3.03
RCS2-1	114.3	21.9	141.3	44.7	90	120.6	5.51
RCS2-2	137.5	23.1	170.5	57.5	90	156	6.75
RCS3-1	—	—	—	—	—	—	—
RCS3-2	—	—	—	—	—	—	—
RCS4-1	82.9	13.9	93	29.8	75	45	3.33
RCS4-2	82.2	15.9	91	27.3	75	45	2.83

P_y , P_m , P_u is the yeild load, maximum load and ultimate load. Δ_y , Δ_m , Δ_u is the displacemet related 。

It can be seen from the hysteretic curves in the Fig.4, the reaction of the composite joints under low cycle load can be devided into following four stages. (1) In the first two loading-circle, the displacement of the specimen is limited and the *P-D* relation is almost linear. And then the *P-D* curve changed to ascend non-linear, which is because the stiffness of the specimen decented as the concrete cracked. For the steel-through connection, after a few of loading circles, the inflection point appearing on the loadig curve reflected the phenomenon of rheostriction. The rheostriction became more and more obvious along with the increasing of loading displacement. All of the loading curves point to one point. And the relations of the load or displacement between this point and the maximum load point are different as the connections differ. (2) Every specimen had almost the same unloading rigidity with loading rigidity in the initial several cycle. As the test proceeded, the unloading rigidity descented obviously prensented in the hysteretic curve as the rate of the slope reduced along with the loading procesure. The permanent deformation accumulated as the cycle index increased. The curves reflected that there was a certain degree slip especially for the specimens in the first group when unloading to zero. (3) When loading reverse direction the peak load descended because of the effect of bonding-slip. (4) From the Fig.4 we can see that all the hysteretic curves are quiet full except the specimens in group three. The bearing capacity of the specimens in group one didn’t displayed fully since the specimens were bonding-slip damaged. The specimens in group two have good hysteretic characteristic until the bearing capacity descended to as much as 85% of the maximum load and good energy-dissipation as well. Most of the longitudinal bars and stirrups yielded analysing from the test results, so that the joints performance has fully displayed. For the specimens in group four the hinge occurred at beam end,and the specimens also had good engry-dissipation ability.

4. RESTORING FORCE MODEL

Restoring force model consists of skeleton curve and hysteretic law. Skeleton curve provides the boundary points for all the states. The main characteristics such as cracking, yielding and failure should be reflected in the skeleton curve. The hysteretic law reflects the member’s characteristics of non-linear, such as strength decay, stiffness degeneration and bonding-slipping and so on. Generally, reliable theoretical formulas should be developed to determine the characteristics point in the skeleton curve when establishing the restoring force model. The hysteretic law is generally determined by the low cycle reverse load test.

Comparing the skeleton curves in the Fig.5, the test results can be concluded as follows: (1)The load-displacement stage of all the specimens from loading to failure can be divided into four typical stages: linear stage, non-linear ascending to yield, strengthened stage after yielding, and descent stage after the maximum load. (2)The specimens in group four was connected in the same way with those in group one, while the concrete stress in the core zone was lower. But the bearing capacity of the former was tested to be higher than the latter, which proves that the ultimate load increases along with the increasing of the ratio of stirrups, and so does the ductility as the skeleton curves appears more smoothly after the peak load. (3)The bolted-end plate connection specimens all belong to the “strong beam-strong column-weak joint” specimens. With the same ratio of stirrups, the specimens connected by bolted-extending end-plate damaged in a higher bearing capacity and had a good ductility. It’s hard to judge the ductility of the flush end-plate connection specimens for the butt welded bolts ruptured at the welded seam. But compared with the former the maximum load under the same displacement descended. (4)The two damaged type of specimens, the “strong beam-strong column-weak joint” and “strong joint-strong column-weak beam”, can both meet the requirement for the bearing capacity and ductility under seismic load. The “strong joint-strong column-weak beam “specimen has a relatively lower bearing capacity, while the enveloped area of the hysteretic loop is bigger, which means a better energy dissipation.

The non dimensional skeleton curves were developed from the Fig.5 (a) by the relative value of P/P_yandD/D_y. The yield point was determined [3] as the longitudinal bar close to the bringe of the column or the flange of the steel beam yield firstly. And the development of the skeleton curves, which were shown in Fig.6, was also considered at the same time. The non dimensional skeleton curves of different specimens have the similar change tendency. A general trilinear non dimensional skeleton curve was developed through averaging the value in both the positive and negative direction. The simplified three sections are: the liner section before yield point, the strengthened section from yield load to maximum load, and the descending section after maximum load as shown in the Fig.7.

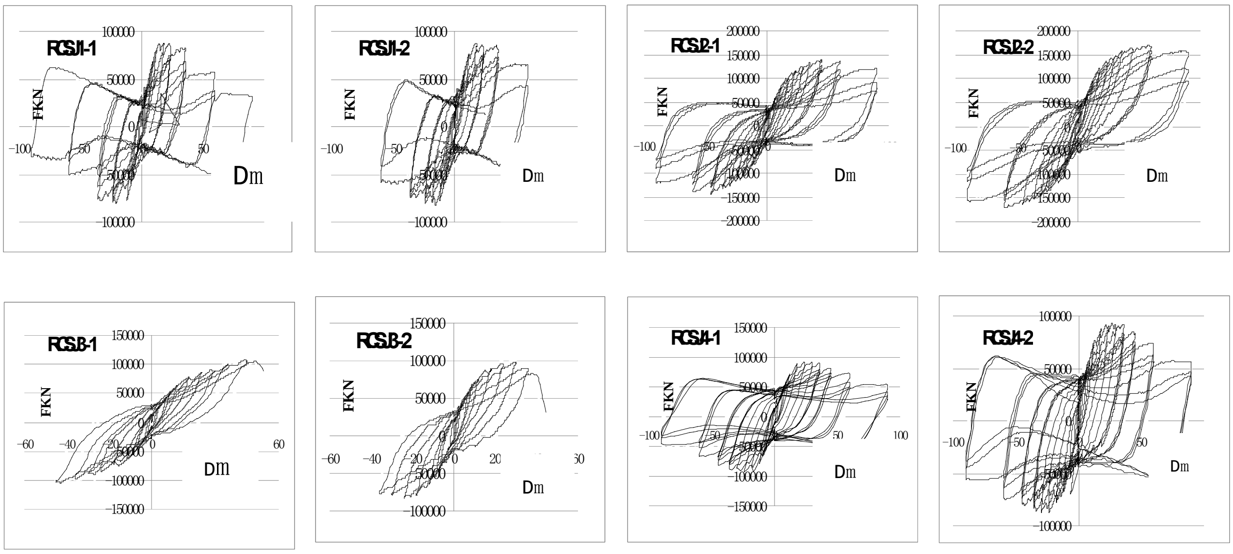


Figure 4 Hysteretic curves

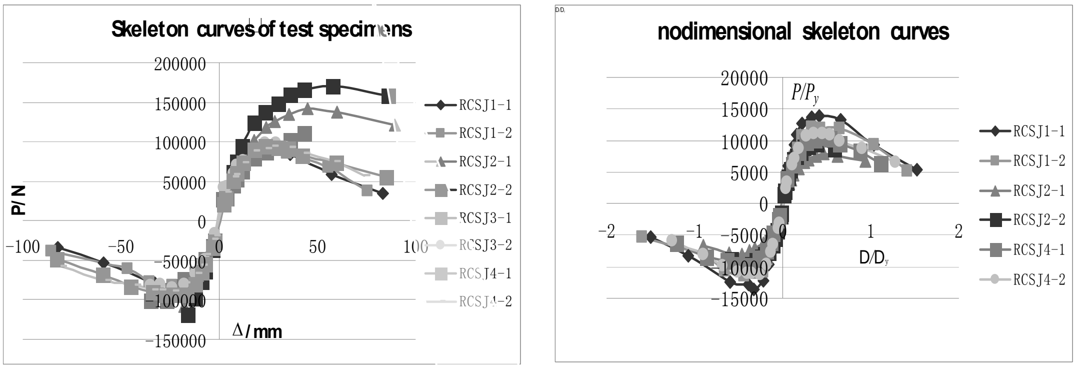
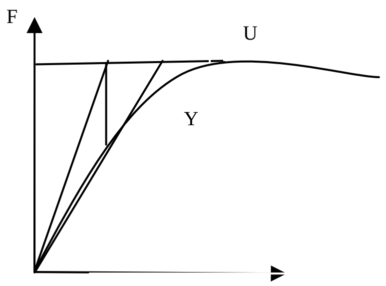


Figure 5 Skeleton curves



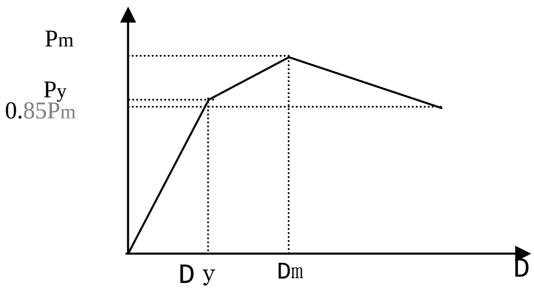


Figure 6 Determination of the yield stress

Figure 7 Trilinear skeleton curves

The characteristic points on the trilinear skeleton curve are the yeild point *Y*, the maximum point *M*, and the ultimate point *U*, And the ultimate load is about 85% of the maximum load. The test results are compared to the calculating results in the Table 4. The calculated value is relatively bigger than the test results, especially the displacement value, it should be due to neglecting the effect of the reinforcing bars at center-line of the cross-section.

(1)Calculation of the yeild point

Table 4 Calculation of the yield points

Specimen	$P_y^{'}$	$\Delta_y^{'}$	P_y	Δ_y
RCS1-1	77	19.5	80.2	12.0
RCS1-2	79.1	20.7	76.9	11.8
RCS2-1	154.6	28	114.3	21.9
RCS2-2	142.7	28.5	137.5	23.1
RCS3-1	114	28.2	—	—
RCS3-2	114.9	28.4	—	—
RCS4-1	90.1	22.2	82.9	13.9
RCS4-2	90.6	22	82.2	15.9

The little eccentric compression failure is suitable for the column damage in the test. Assume that the pressed reinforcing bars yield when the specimens damaged, and the concrete reached the compressive strength meantime. The cross section is of symmetric reinforcement, the cross-section strain accords with the plane sections hypothesis. The same material property is applied to the tension and compression strain of the longitudinal steel. The bilinearity model is applied to the stress strain relation of the longitudinal steel, while the curve-straight line shape is applied to the stress strain relation of the compressed concrete[4]. The enhanced coefficient of the stirrups to the concrete intensity is considered as k, $k=1+\lambda_v$, λ_v stands for the design value of the stirrups. The enhancement to the concrete intensity by the prestressed force when connected by the bolts should also be considered referring to the article [5].

$$f_{c,c} = 1.37\rho_v f_{ys} / f_c \tag{4.1}$$

$$f_c = f_{ck} / \gamma_c \tag{4.2}$$

where γ_c is the concrete strength factor taking value as 1.4. f_{ck} is the characteristic value of prismoid concrete compressive strength, which can be accessed by the characteristic value of cubic concrete compressive strength. The frame column is simplified as a cantilever structure, the curve flexion of which before yielding distributes as a straight line, the displacement of the top column can be calculated as follows:

$$\Delta_y = (1/3)\varphi_y H^2 \tag{4.3}$$

And then the horizon load of the top load is accessible according to the balance of the forces:

$$F_y = M - N\Delta_y / H \tag{4.4}$$

(2)Calculation of $F_{\max}$, $\Delta_{\max}$ at the peak load point.

The maximum load and its corresponding displacement can be accessed by the formulas (4.5) and (4.6).

$$F_y / F_m = 0.87 \tag{4.5}$$

$$\Delta_y / \Delta_m = 0.25 \tag{4.6}$$

The un-loading stiffness K_u rigidity takes the slope of the straight line between the peak displacement point and the zero-load point. While the re-loading rigidity takes the slope of the straight line between the peak-load point and the zero-load point. According to the statics of the test results, both the un-loading rigidity and the re-loading rigidity degenerate as the loading displacement increased, and the ratio of the degeneration relate to the ratio of stirups. The foumulas for the rigidity of un-loading and re-loading were acceccessed through analysis of regression as formulas (4.7) and (4.8), where λ is the reinforcement characteristic design value. λ_ρ is the volume ratio of bolt. K_e is the initial rigidity of the specimen.

$$K_u = K_e \left(\Delta_y / \Delta_m\right)^{(4.725\lambda+0.099)(32.52\lambda_\rho-1)} \tag{4.7}$$

$$K_\gamma = K_e \left(\Delta_y / \Delta_m\right)^{(0.652\lambda-0.71)(10.25\lambda_\rho+1)} \tag{4.8}$$

(3) The route and strength aging degeneration when repetitive loading

Table 5 The degeneration ratio under different displacement

Specimens number	u =D/Dy				
	2	4	5	6	7
RCSJ1-1	0.8918	0.7265	0.6103	—	—
RCSJ1-2	0.8865	0.8289	0.5617	—	—
RCSJ2-1	0.8486	0.7898	0.6255	—	—
RCSJ2-2	—	0.8787	0.6045	—	—
RCSJ3-1	—	—	—	—	—
RCSJ3-2	—	—	—	—	—
RCSJ4-1	—	0.8304	0.8395	0.6953	0.6502
RCSJ4-2	—	0.8787	0.8516	0.7673	0.7613

After the peak-load point, the peak load of a certain cycle will fall down when repetitive loading under the same displacement. So there will be deviation between the real state and the rule [3, 6] that the curve points to the max-load of the circle before when reverse-loading after un-loading and reloading. The strength aging degeneration [7] should be considered in the restoring force model. The ratio of the strength aging degeneration is generally valued by the relative value of the peak load of the third circle and the first circle under the same displacement. The strength aging degeneration ratio of all the specimens is shown in the Table5. The strength degeneration ratio can be calculated as

$$\gamma = 1.2u^{-0.4} \tag{4.9}$$

Referring the hysteretic curves of the specimens, the hysteretic law was concluded as follows: (1)Before the yield point, loading and unloading tracked as the elastic section on the skeleton curves(0-1-0 in the Fig.8) (2)The loading route process along with the skeleton curves when the loading force is over the yielding load. (1-2,in Fig.8)The unloading rigidity can relatively be accessed by the formula (4.7). According to the different loading displacement and the ratio of stirrups.(2-3,in Fig.8) (3)Before the yielding load when reverse loading and reloading, the reverse loading route point to the yielding point from the unloading zero-load point. (3-4 in the Fig.8) the degenerating strength can be determined by the formula (4.9). (As the point of $2', 2'', 5'$)Point 2 is the peak loading of the circle before while the reloading route pointing to the point $2'$. The two points is with the same displacement while the load value of the point $2'$ is lower .The difference value of the two load value is called the degenerating strength. The loading and unloading force both point to the same point of the circle before.

5. CONCLUSIONS

In this study, four different connecting honeycomb steel beam-welded compound ring hoop column composite joints were tested under cyclic horizontal loads in order to investigate the influences on the connection bearing capacity, stiffness degeneration, strength aging degradation, skeleton curves and hysteretic curves. The restoring force model to reflect the hysteretic law was eventually established on the basis of the test results and the corresponding analysis and discussion; some conclusions were made as follows: (1)Comparing with the test results it's reasonable to considering the favorable effect of the prestressing force for the prestressed-high-strength bolt connection specimens. After the maximum load, the strength aging degradation is quicker for the loss of prestressing force. Proper ratio of stirrups can not only enhance the bearing capacity of the specimens but also prevent bonding-slipping prematurely, the ductility can be increased meanwhile. (2)Comparing the test results of specimens in group one and group four, dot welding the stirrups in the core zone with the longitudinal rods can improve the bearing capacity of the core zone of the specimens. (3)Formulas for rigidity and aging degeneration were concluded based on the test results, which can give reference in further study. (4)A collection of new specimens with different axial compression ratios should be tested in the future. And for the end-plate connection specimens, the effect of the bolts' cross section area as well as the thickness and area of the end-plate should also be studied furthermore.

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