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Study on Design Method of SRC Abnormal Exterior Joint of Large-scale Thermal Power Plant Frame-bent Structure

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Abstract

Due to the demand of manufacture technology, the main factory building forms intricate frame-bent structure, many abnormal joints with strong beam-weak column and changed beam and changed column. The bearing mechanism of abnormal joints is very complex, and design of those joints becomes the hard point in the design of large-scale thermal power plant. In order to improve seismic behavior of the thermal power plant frame-bent structure, the research group put forward SRC frame-RC dispersive short-pier shear walls mixed structure, and carried out SRC frame-dent structure sub-space model test. Based on the sub-space model test, the paper chose four typical SRC abnormal exterior joints to take the experimental research. Through the pseudo-static test of the joints, this paper mainly analyses the force-transmission path and bearing mechanism of the SRC abnormal exterior joints, and studies on the main factors which affect the shear capacity of joint. Besides, it puts forward some detailing requirements. Those may be references for practical design.

Keywords: Steel reinforced concrete (SRC) abnormal exterior joint, Bearing mechanism, Force-transmission path, Detailing requirements

1. Introduction

Large-scale thermal power plant is one of the important lifeline projects, and the safety of the main building structure is directly related to the normal supply of the power. Therefore, the main building structure of power plant must have sufficient capacity to resist earthquakes. The joint is a key component in the overall structure which connects the beams with columns, and is the transmission hub of the components of the entire structure. So that safe and reliable joints are the premise for the normal work of the structure. In view of the complex production process and the larger load of the main plant in the thermal power plant, we can use SRC frame-bent with distributed RC shear walls mixed structure as the main plant structure. Thus, the structure of the main plant includes the abnormal joints with complex structure and bearing performance.

At present, the research work on joint is mainly directed against conventional joints. For SRC abnormal joints, there are

some approaches that are based on the concept and experience. So that it lacks a large number of trial bases. Moreover, SRC abnormal joints are imposed by the integrated forces of bending, shear and pressure. At the same time, there are its own abnormal characteristics which give it more complex bearing performance. In this paper, the main research object is SRC abnormal exterior joints. Firstly, it is necessary to clarify force-transferring path and to study on its bearing mechanism and the influencing factors of its shear strength. Then, to put forward some reasonable and practical structural measures to ensure the work of joints is safe and reliable. Thus, it can provide a reference for designing this kind of joints.

2. The overview of test

SRC abnormal exterior joint refers to the joint with high beam, varying column cross-section and some short-pier shear walls laid in the part of the bottom house. Such joints are widely used in industrial and high-rise buildings. To ensure shear failure of the abnormal joints doesn't happen before the structure reach the ultimate capacity state, we need to fully understand bearing and deformation behaviors of the joints. Therefore, our research group carries out the test study on bearing and deformation behavior of SRC abnormal exterior joints under the influence of the low-cycle repeated load.

2.1 Specimen design

The prototype of experimental study model is a certain thermal power plant SRC main power house. It is a twelve-bay, three-span SRC mixed construction system. The test study is based on the studies of seismic behavior of 1000MW generator set main plant three-bay, three-span SRC frame-bent subspace model containing the house with steam engine, the room with deaerators and coal bunker. We select four typical abnormal exterior joints (SJ-1, SJ-2, SJ-3 and SJ-4) to carry out experimental studies.

In accordance with the relative information of joint test (Tang, Jiuru, 1989, P. 370-the last page), the test is designed. Combined with the actual situation in the structure of main plant and laboratory conditions, model scale is 1:5. In view of the production of test specimens, the dimensions of test specimens can be adjusted. However, the principle of adjustment is to try not to change geometric properties and bearing characteristics of the prototype structure.

The design parameters of the specimens are: beam size, cross-section size of column, axial compression ratio, short-pier shear wall etc. Steel reinforcements and profile steel of samples are calculated in compliance with the scale principles and existing relevant norms. Steel bars anchoring and the selection and arrangement of steel need to meet the detailing requirements of the existing norms (Water Resources and Electric Power Press, 1993, P. the whole book; China Building Industry Press, 2002, P. the whole book). Structure types of SRC abnormal exterior joints are shown in Tab.1, the parameters are shown in Tab.2, and arrangements of steel bars are shown in Fig.1.

2.2 Experiment loading and test

2.2.1 Test loading scheme

Experimental study of seismic behavior of SRC abnormal exterior joint adopts pseudo-static loading manner, the joint test is carried out in the structure and seismic laboratory of Xi'an University of Architecture and Technology.

The whole process of the test is manipulated and controlled by MTS electro-hydraulic test servo system, axial load acted on the upper end of column is imposed by 100 tons vertical reaction force loading system, the horizontal low-cycle repeated load is imposed by the electro-hydraulic servo actuator whose displacement range is ±150 mm. Load-bearing test-bed system is one-way reaction wall which is 12.5 m high, 18m wide, and 2.5 m thick, the bending and shearing capability of its foundation base can meet the test requirements. Test data is recorded by the MTS system computer and TDS-602 static data acquisition instrument, the number of data acquisition channels are about 100~200. After the experiment, we will sort out the test data and make the comprehensive analysis of the test results. The test device is shown in Fig.2.

In order to truly reflect the bearing state of joint in the actual engineering structure, joint test horizontal load is imposed on the upper end of column (Lu, Ying, 2007, P. the whole book) to consider the P-Δ effect which can not be ignored under the larger axial pressure. According to the axial compression ratio designed, we use constant pressure devices to exert vertical load, and keep the axial pressure constant during the test process. The test adopts force-displacement hybrid control loading system (see Fig.3), before joint samples are yielding, we use load control loading. After joints are yielding, we adopt displacement control cyclic loading until the joints are destroyed.

Test loading process is divided into three steps: first of all, a small preload was imposed to test whether the connection of the equipments and instrumentations are correct, and whether they are work normally; second, according to the formula of 'SRC Composite Structures Technical Specification' (JGJ138-2001) to estimate the bearing capacity of the joints, and to exert stepwise load. Each step load is 30kN imposed in three steps (10 k N per step). When the load is close to the estimated cracking strength (Bai, Guoliang, Zhu, Jianing and Li, Hongxing, 2003, 19, P.12-16), the load step is reduced to half (5 k N per step). Each load step makes once cycle. After per cycle load, we suspend loading.

After the deformation of the joint fully develops, we start to observe the development situation of cracks; finally, after the joint is yielding, we adopt displacement control cyclic loading. We regard the yielding of steel web as a symbol of the joint yielding, and regarded the corresponding maximum displacement at the end of the column as the yielding displacement Δ_1. At first, we imposed load for three times based on the yielding displacement, then imposed cycle load based on 1/3~1/4 yield displacement (according to the damage state course of the joints during experiment courses to control), each displacement is applied for three times until the load get to 80% of ultimate load, and then the test is over.

2.2.2 Test measurement contents

During test process, the horizontal load P is imposed by the load sensor belonged to the actuator at the end of column. Horizontal displacement Δ is measured by the displacement meter with appropriate measurement range at the corresponding position, thus, a P-Δ curve, that is, load-displacement hysteretic curve can be received; the displacement meters with appropriate measurement range are laid at the end of beams and columns, the root of beams and columns, and the top of columns, etc. to measure the displacement of every measuring point, and the P-Δ_i curves are get; the dial indicators are installed in joints core area at a certain angle to measure shear deformation, and to study the shear properties of the joint core area (location of instrumentation is shown in Fig.2). The strain gauge pasted on the measuring points which are on the longitudinal reinforcement, steel, stirrups and external concrete of the beams and columns are used to measure the strain, and used to analyze the joint bearing performance (the case of pasting strain gauges is shown in Fig.4). During the course of the experiment, the development situations of cracks in various loading stages are observed and recorded, and the destruction and deformation situations of joints are shot by the camera and recorded.

2.3 Material properties

The longitudinal stress reinforcement of joints uses HRB335 grade steel, the stirrups use HPB235 grade steel, the profile steel uses Q235 grade ordinary hot-rolled steel. Materials properties tests are carried out in the constructional material testing laboratory in our school as required. And their performance indicators are shown in Tab.3 and Tab.4.

The concrete of the joints is C35 grade commercial ready-mixed concrete. The joint models adopt vertical pouring. And they are supported with wood patterns. The test specimens are maintained in the outdoor natural surroundings. And the test starts after the strength of the joint meets requirements. When the test samples are poured, a group of test cube blocks are set aside, they are maintained in the same conditions as the joint specimens, the mechanical properties of concrete are tested by concrete blocks, and its performance indicators are shown in Tab.5.

Based on the formula- $f_{cu,k} = \mu_{fcu} \times \left(1 - 1.645\delta_{fcu}\right)$ (China Building Industry Press, 2002, P. the whole book) for calculating the standard strength of concrete the actual standard strength of concrete is calculated to be $f_{cu,k} = 27.57\text{Mpa}$, and the corresponding ultimate strain is 875 $\mu\varepsilon$. It is slightly higher than the normative value.

Wherein:

δ_{fcu} - According to the norms, the coefficient of C35 concrete is 0.13;

μ_{fcu} -Average compressive strength of test cube block.

3. Analysis of test results

3.1 Analysis of force-transmission path

Although the dimensions, reinforcement, axial force, load imposed on every stage of the four test exterior joints are different, the history and patterns of their destruction are similar. They all have gone through initial cracking, thorough cracking, ultimate and failure four stages (Li, Hongxing, Bai, Guoliang and Zhu, Jianing, 2006, 38, P.168-176). The damage situations of the joints are shown in Fig.5. Through the analysis about the state of cracking, deformation and failure during the entire loading process of the joints, we research the force-transmission path.

Before the initial cracking of concrete in the core area, joints work in the elastic state. By the time, the strain of stirrups is very small, the concrete and steel can work together well and both of them bear the shear. In the initial loading term, the beam cracks first. The beam-end tension steel is conveyed into joint core area by the beam steel flange and beam steel reinforcements, and the beam-end pressure is conveyed by the beam steel and concrete. The column steel flange and stiffening rib in the core area bind the concrete intensively, which make the shear capacity of the SRC abnormal joints increase to some extent. As the load increases, the strain gradually reaches the tensile strength of the concrete and the concrete cracks. So the cohesive force between the concrete and steel is gradually reduced. With increasing deformation of concrete, the shear shared by steel and concrete is gradually shared by the steel by itself, so the strain of steel quickly increases and the deformation of joints also develop fast. Going on loading, the strain of steel and the deformation of joints further increase, the steel webs in the core area of joints tend to yield. Because the yielding of the steel is an expansion process from the local to circumference, the shear shared by the steel can continue to increase until

the whole steel yields. Imposed on the repeated loads, the steel gradually yields; the shear shared by the concrete of the core area is increasing. Many crossed cracks come forth in the core area. The cracks divide the core area into many irregular small lozenge-shaped blocks.

Affected on the repeated loads, the crossed cracks of the concrete widen unceasingly, and the stress and strain of the stirrups soon increase. On this stage, its mode of force-transmission is basically the same as the last stage. Due to the larger deformation of concrete, the binding from steel and stirrups to the concrete strengthens and the strength of the concrete increases. As the displacement increases, the concrete are gradually crushed, squeezed out, and gradually withdraw from the work, while the binding effect weakens. Then the shear capacity of the joints begins to attenuate, until the joints reach the failure state. Through the analysis of the destruct ional joint specimen, it is found that the steel web does not warp in the whole process. It shows that steel and concrete of the core area are still bound each other until the joint is destroyed.

3.2 Analysis of bearing mechanism

At present, the common bearing mechanisms include diagonal compression strut mechanism, truss mechanism, shear friction mechanism and binding mechanism and so on. These models are commonly used to analyze the bearing of the conventional joints. Among of them, diagonal compression strut mechanism, truss mechanism and binding mechanism also apply to the abnormal joints.

In the initial loading term, the steel and the concrete in the core area bear the best part of load. At this time, the diagonal compression strut model is used to analyze the bearing performance of the joint. However, the diagonal compression strut is different from the conventional joint. On the initial loading stage, the column steel flange of the SRC abnormal joint can bear pressure together with the steel reinforcements of beam. So that the steel flange can be equivalent to the beam steel bars. The steel web can be equivalent to the concrete of core area, so it can be one of the factors which affect the bearing performance of the diagonal compression strut. Thus, the strength of the diagonal compression strut model is higher than the RC joints.

For the solid-web SRC joint, in such a case that the steel and the concrete bear the best part of load, in addition to shearing resistance, the stirrups can bind the concrete out of the steel, which can strengthen the cohesive force between the concrete and steel, and prevent the yielding of the column vertical steel reinforcements. Therefore, a certain amount of stirrups are needed to be set, particularly the relatively weak scopes of the abnormal joints, such as the part of the variable column cross-section. Stirrups must be closed, and its layout has two methods: cutting across the beam steel web and welding on beam steel.

Because of the changing cross-section of columns, so the axial force has bias that the working characteristic of the diagonal compression strut is not symmetrical when the load reverses. Hence, the width and the inclination angle of the diagonal compression strut in the joint core area are different under the repeated load (see Fig.6). When the column-end is pulled, the diagonal compression strut is located at the intersection zone of beam and the large column, and it slopes to the column outside at a smaller inclination angle. This moment, the diagonal compression strut is wider than that under the reverse load; when the column-end is pushed, the diagonal compression strut is located at the intersection zone of beam and the small column, and it tends to the column inside at a larger inclination angle. At the same time, the diagonal compression strut is smaller than that in the above case, that is, it forms the minor core area. On the effect of the eccentric axial force, the width and the inclination angle of the diagonal compression strut make the scale of compression zone different. Therefore, the outside and inside capacity and damage degree are different. As a result of bearing asymmetry, we can take some measures to ensure that the bearing of the joints is balance and reliable, such as the asymmetric layout of column longitudinal steel reinforcements, the asymmetric shape steel layout and so on.

After the core area of the joint cracks, the force shared by the steel reinforcements and steel gradually increases, but the force shared by the concrete tends to be smooth and steady, and the test specimens come into the stage on which the cracks evenly develop. With the cracking of concrete, the stress of the stirrups and steel web continuously increases. By this time, it is reasonable to use steel truss model to simulate the work of the joints.

The steel flanges and horizontal stiffening ribs of columns form the rigid frame. The diagonal compression strut composed by the concrete and steel web could be regarded as the baroclinic web member of the rigid frame. Column steel web may be regarded as the diagonal tension member of the rigid frame. Those above-mentioned constitute the quintic hyperstatic steel truss shown in Fig.7. The bending moment, axial force and shear transferred from the beam-end and column-end can be equivalent to affect on the steel truss in the joint core area. At the same time, the stirrups of the core area provide the restraining action on it, which can enhance the strength of its own.

The rigid frame of the abnormal joint isn't rectangle but right-angled trapezoid (shown in Fig.8). Under the positive displacement, the strength of the diagonal compression strut is quite high due to the large steel web area in the direction of the main tensile stress, and the main tensile strain is also small. According to the softening theory of the concrete, it is also conducive to maintain the compression strength of the concrete in the direction of the diagonal compression strut;

under the negative displacement, the inclination angle of the diagonal compression strut is smaller than that in the above case, and it will bear further more horizontal force. Therefore, the first crack of the abnormal joints in the core area may occur under the negative displacement, and the bearing capacity under the positive displacement is higher than that under the reverse displacement. The conclusion is in line with the test phenomenon all right.

Through the above analysis, it can be speculated that the steel stiffening ribs of the SRC abnormal joints form the above-mentioned the steel truss model. Assuming that we fit multi-channel stiffening ribs, it will form a multi-layer steel truss or a multi-level hyperstatic model. Thus, the shear strength of the joint can increase, and the seismic capacity can be enhanced. This is an assumption and needs the further experimental and theory research to prove. Multi-layer steel truss model is shown in Fig.9.

Compared with the diagonal compression strut shear failure model of the conventional joint, the internal structure of the SRC abnormal joints is more complex, and its bearing is also more complicated. In the initial loading term, the diagonal compression strut model is established by using the baroclinic field theory of the core area concrete, and its surrounding steel and stirrups can provide an effective constraint on it. On the whole, the binding diagonal compression strut-steel truss model (Wang, Peixin, 2008, P. the whole paper) is applied to analyze the bearing mechanism of the conventional joint; while for the SRC abnormal joint, its applicability has yet to be proved by more experimental and theory analysis, and then it can be spread the application.

3.3 Analysis of shear strength influencing factors

As the weak link of the structure, the joint is the key force-transmission junction. In the structural design, the bearing capacity of joints must be greater than that of the various components that are connected with it, that is to say, when the other components fail, the joints can also transmit internal force reliably under the combined effect of the earthquake and vertical load. There are a lot of factors influencing the shear capacity of SRC abnormal joints, such as profile steel, horizontal stirrups, column longitudinal steel reinforcements, orthogonal beams, the grade of concrete, the axial pressure, short-pier shear walls, construction techniques, etc. In this paper, we mainly analyze that profile steel, horizontal stirrups, the axial pressure and short-pier shear walls affect the shear strength of the joints.

1) Profile steel

Regarded as an important factor, the profile steel bears part of the outer load, and moreover, steel web is one of the main factors resisting shear. The steel flange-frame binds the concrete of the core area, so that the initial cracking strength and the ultimate strength of those joints are higher than the RC joints. The initial cracking strength of the joint SJ-3 with SRC-beam is about 20% higher than the joint RC SJ-2 with RC-beam (shown in Tab.6).

2) Horizontal stirrups

the horizontal stirrups is one of the factors resisting shear of the SRC joints, but its shearing resistance impact is fully exerted after the steel web yields, and its impact is weaker than the profile steel. Through experimental analysis, it is known that the rate of joint stirrups has almost no impact on the initial cracking strength of the joints. With the cracking of concrete, the truss model gradually forms, and the force shared by the stirrups increases. The stirrups can not only effectively bind the deformation of concrete and compression yielding of column longitudinal steel reinforcements to improve the strength of concrete, but also bear a part of shear. So that it delays the destruction of the joints and improved the ductility of the joints. Therefore, the minimum stirrup ratio of SRC joint should be determined with double criteria of the ductility and strength. When the joint fails, the stirrups of the core area don't yield simultaneously. The figure 10 shows the change of stress distribution of stirrups along core height with the load increasing. Taking into account the asymmetry of bearing, the stirrup resistance item in the bearing capacity formula should be reduced by multiplying a reduction factor. At present, the factor usually gets 0.8, which is safe for the test joint design.

3) Axial pressure

Because of the binding of the profile steel and stirrups, the axial pressure makes the concrete of the core area in the three dimension stress state (shown in Fig.11), which inhibits the cracking of concrete. After the cracking of concrete, the axial pressure also makes the larger mechanical friction formed between the concrete blocks, so that a moderate axial compression ratio can enhance the shear strength of the joints.

However, if the axial pressure exceeds the critical value, the concrete will be crushed, and the shear strength will reduce. The axial compression ratio critical value of the SRC abnormal joint is higher than the RC abnormal joint. That is to say SRC structure can withstand much more axial pressure than that of RC structure.

Due to the changing cross section of columns, the eccentric axial force forms, which will cause the stress of the joint area to superimpose, and the destruction of the eccentric side is serious. The stiffness, ductility and energy dissipation performance of the overall joint will decrease with the increase of eccentric bending moment. Under eccentric axial force, the distribution of cracks of the entire joint is non uniform, and the main cracks occur in the eccentric side of the axial force. The greater the axial force is, the greater the eccentric moment is, and the more seriously the joint damages.

Therefore, it is should be further studied whether the beneficial effect of the axial pressure to shear capacity of SRC abnormal joint would be considered.

4) Short-pier shear wall

As can be seen from Tab.6, the skeleton curve peak of the joint SJ-1 with the vertical wall is higher than that of the joint SJ-2 without walls, the joint strength increases by about 20%; the skeleton curve peak of the joint SJ-4 with the two-way walls is higher than that of the other joints, and its strength is about 50% higher than the joints without the walls. Through the above comparative analysis, it can be seen that the vertical wall can also enhance the bearing capacity of the joint, but the effect is not obvious compared with the wall in the loading direction. As can be seen from the backbone curve of joints (see Fig.12), the strength and stiffness degradation of the joint SJ-4 is more gentle, especially in the declining stage, it shows the good ductility. All in all, the short-pier shear wall can improve the strength and stiffness and improve the seismic performance of the joint, such as ductility, energy dissipation performance and so on.

4. Conclusions and suggestions

1) In SRC frame-tent structure, the longitudinal steel reinforcements and stirrups are needed to form steel skeleton which can not only bear part of the load, but also bind the deformation of the internal concrete, while the concrete also ensure the stability of the steel. The stirrups should adopt intensive layout in the parts that is prone to damage, but the construction must be convenient and viable. In the layout of the steel reinforcements, if the steel web needs to be cut through, the steel cross-section loss rate should not exceed 25% of its web area (Metallurgical Industry Press, 1998, P. the whole book).

2) As the loading and bearing of the test abnormal exterior joint are asymmetrical, the column longitudinal steel reinforcements laid in the inside and outside of the joint may be asymmetric. The more longitudinal steel reinforcements of joint column are laid in the lateral of the joint where it is prone to damage, which must meet the requirement of steel reinforcement spacing. Or the steel flange or web can be thickened to enhance the weak side, or steel plate is welded on the weak side, and so on. Putting forward those measures is to ensure that the bearing of SRC abnormal exterior joint is balanced and harmonious.

3) Through the analysis of joint force-transmission path, we can see that the bearing of this kind of joint is very complex. So that it needs the more experiments to research on it.

4) Through the analysis of bearing mechanism, we can speculate that if we set multi-channel stiffening ribs in the joint core area, it will form a multi-layer steel truss or a multi-level hyperstatic model. Thus, the shear strength of the joint can increase, and the seismic capacity can be enhanced. However, the above content is an assumption and needs the further experimental and theoretical research to prove it.

5) Through the analysis of the shear bearing capacity influencing factors of the SRC abnormal exterior joint, we preliminary know about the bearing characteristics of it and the influencing degree of each component. It is a basis for the further research on the shear bearing capacity calculation of this kind of joints. Besides, we know the short-pier shear wall can improve the strength and stiffness and improve the seismic performance of the joint, such as ductility, energy dissipation performance and so on.

6) In the world, we can see the advantage of this kind of joints. However, for SRC abnormal joints, there are steel, steel reinforcements of columns and beams, the horizontal stirrups, some additional steel members and concrete, etc. in the joint core area, so its structure is very complicated. Besides, the type of the joint in the SRC power plant main building structure is much, such as beam-column joint, beam-wall-column joint and so on. The joint forms with good seismic performance which are received based on the test analysis must meet the feasibility of the construction. We should sort out a set of systemic standard collective drawing of SRC joint to guide design and construction. It is a long-term work and needs further in-depth experiment study and detailed theoretical analysis.

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Table 1. SRC abnormal exterior joints test structure type

Joint number	column	beam	Remarks
SJ-1	SRC-column	RC-beam (700 mm high)	To set up vertical walls
SJ-2	SRC-column	RC-beam (700 mm high)	-
SJ-3	SRC-column	SRC-beam (500 mm high)	-
SJ-4	SRC-column	RC-beam (700 mm high)	To set up two-way wall
The other details are seen in Table2 and Figure1.			

Table 2. SRC abnormal exterior joints test design parameters

Test specimen number			SJ-1	SJ-2	SJ-3	SJ-4
column	upper column	b × h (mm)	250×240	250×240	250×240	250×240
		profile steel	H140×90×4×6	H140×90×4×6	H140×90×4×6	H140×90×4×6
			(2.65%)	(2.65%)	(2.65%)	(2.65%)
		steel (ρ_s) reinforcement	6$\underline{\Phi}$12	6$\underline{\Phi}$12	6$\underline{\Phi}$12	6$\underline{\Phi}$12
			(1.13%)	(1.13%)	(1.13%)	(1.13%)
		stirrups (ρ_{sv})	ϕ8@100	ϕ8@100	ϕ8@100	ϕ6@100
			(0.40%)	(0.40%)	(0.40%)	(0.23%)
		volumetric percentage of stirrups (ρ_v)	(0.94%)	(0.94%)	(0.94%)	(0.53%)
	below column	b×h(mm)	250×280	250×280	250×280	250×280
		profile steel	H180×90×4×6	H180×90×4×6	H180×90×4×6	H180×90×4×6
			(2.50%)	(2.50%)	(2.50%)	(2.50%)
		Steel (ρ_s) reinforcement	6$\underline{\Phi}$12	6$\underline{\Phi}$12	6$\underline{\Phi}$12	6$\underline{\Phi}$12
			(0.97%)	(0.97%)	(0.97%)	(0.97%)
		stirrups (ρ_s)	ϕ8@100	ϕ8@100	ϕ8@100	ϕ6@100
			(0.40%)	(0.40%)	(0.40%)	(0.23%)
		volumetric percentage of stirrups (ρ_v)	(0.86%)	(0.86%)	(0.86%)	(0.48%)
the core area of joints		stirrup (ρ_s)	ϕ6@120	ϕ6@120	ϕ6@125	ϕ6@100
			(0.20%)	(0.20%)	(0.20%)	(0.23%)
		volumetric percentage of stirrups (ρ_v)	(0.40%)	(0.40%)	(0.40%)	(0.48%)
beam	b×h(mm)		200×700	200×700	200×500	200×700
	steel (ρ_s) reinforcement	upper Steel (ρ_s) reinforcement	4$\underline{\Phi}$20	4$\underline{\Phi}$20	2$\underline{\Phi}$16	4$\underline{\Phi}$20
			(0.95%)	(0.95%)	(0.43%)	(0.95%)
		below steel (ρ_s) reinforcement	4$\underline{\Phi}$20	4$\underline{\Phi}$20	2$\underline{\Phi}$16	4$\underline{\Phi}$20
			(0.95%)	(0.95%)	(0.43%)	(0.95%)
	profile steel				H400×60×5×6 (4.43%)	
	stirrups (ρ_s)		ϕ10@100	ϕ10@100	ϕ8@100	ϕ10@100
			(0.79%)	(0.79%)	(0.51%)	(0.79%)
shear wall	b× h_w (mm)		longitudinal wall	-	-	longitudinal wall / transverse wall
			80×220			80×220 / 80×450
	vertical distributed steel reinforcements (ρ_s)		16ϕ5	-	-	16ϕ5 / 12ϕ5
			(2.01%)			(2.01%) / (0.71%)
	horizontal distributed steel reinforcements (ρ_s)		ϕ4@60	-	-	ϕ4@60 / ϕ4@60
			(0.53%)			(0.53%) / (0.53%)
axial compression ratio			0.25	0.15	0.15	0.25
grade of concrete			C35	C35	C35	C35

Table 3. Steel bar materials performance

steel-bars diameter	detailed parameters	F_s(kN)	F_y(kN)	f_s(Mpa)	f_y(Mpa)	E_s(Mpa)	$\varepsilon_y(\mu\varepsilon)$	$\varepsilon_s(\mu\varepsilon)$
3.5	3.6	7.25	-	712.629	-	2.1×10^5	-	339 3
6	6.4	16.3	-	506.942	-		-	241 4
8	8.1	23	-	446.569	-		-	212 7
10	9.9	34.5	-	448.414	-		-	213 5
12	11.75	66	44.25	608.974	408.289	2.0×10^5	204 1	304 5
16	15.4	121	82.5	649.942	443.142		221 6	325 0
18	16.9	138	90.5	615.511	403.651		201 8	307 8
20	19.1	171	113.5	597.117	396.332		198 2	298 6

Table 4. Profile steel materials performance

steel type	width	thickness	F_y (kN)	F_s (kN)	f_y (Mpa)	f_s (Mpa)	E_s (Mpa)	ε_y ($\mu\varepsilon$)	ε_s ($\mu\varepsilon$)	$\overline{\varepsilon}_y$ ($\mu\varepsilon$)	$\overline{\varepsilon}_s$ ($\mu\varepsilon$)
4	49.9	3.6	60	81	334.001	450.902	2.06×10^5	162 1	218 9	165 9	224 3
4	50.5	3.6	63.5	86	349.285	473.047		169 6	229 6		
5	50.8	4.4	71	104	317.645	465.283		154 2	225 9	155 0	226 4
5	49.6	4.4	70	102	320.748	467.375		155 7	226 9		
6	50.3	5.7	88	125	306.930	435.981		149 0	211 6	154 1	203 8
6	53	5.7	99	122	327.706	403.840		159 1	196 0		

Table 5. Concrete materials performance

Test specimen number	actual dimension (cm^3)	area of cross section (mm^2)	actual bearing load (N)	actual strength (Mpa)	modulus of elasticity (Mpa)	ε_u ($\mu\varepsilon$)
1	15×15×15	225 00	820 000	36.444	3.15×10^4	115 7
2	15×15×15	225 00	690 000	30.667		974
3	15×15×15	225 00	900 000	40.000		127 0
4	15×15×15	225 00	685 000	30.444		966
5	15×15×15	225 00	805 000	35.778		113 6
6	15×15×15	225 00	835 000	37.111		117 8

Table 6. SRC abnormal exterior joints test loads

Joint	test cracking load (kN)		test ultimate load (kN)		cracking load /ultimate load (%)		axial compression ratio
	Push	Pull	Push	Pull	Push	Pull	
SJ-1	70	-60	105	-106	67	57	0.25
SJ-2	50	-60	80	-92	63	65	0.15
SJ-3	60	-60	80	-80	75	75	0.15
SJ-4	120	-80	203	-122	59	66	0.25

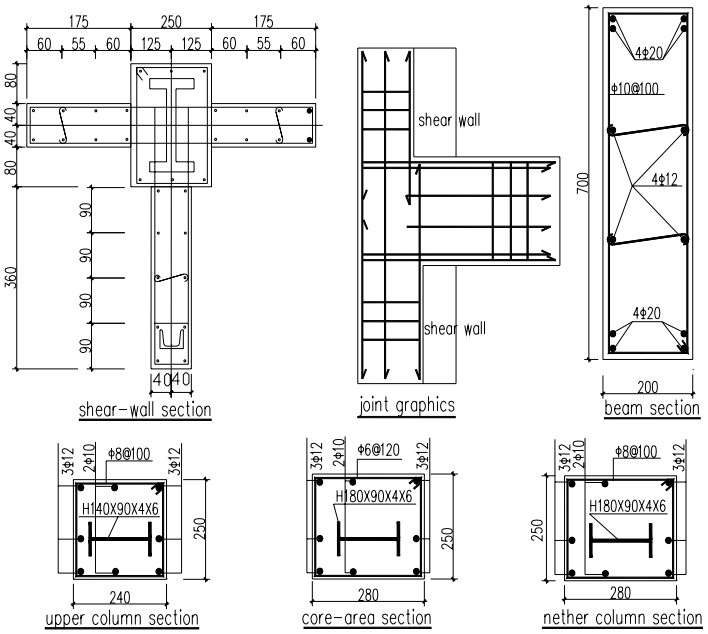


Figure 1. SRC abnormal exterior joints test working drawing

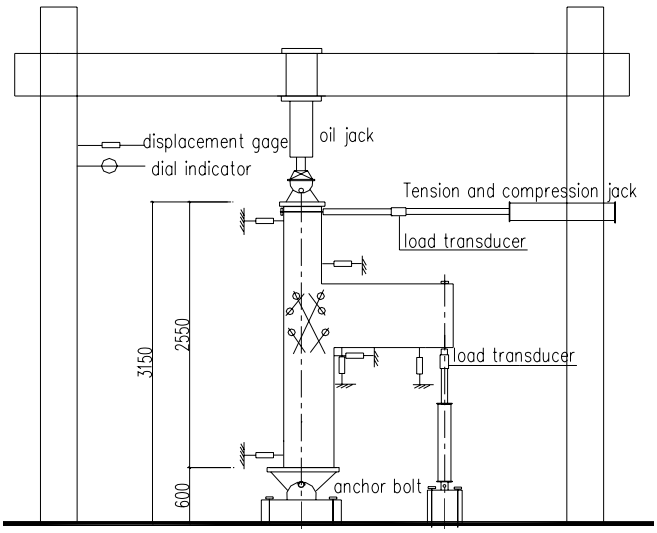


Figure 2. SRC abnormal exterior joints test setup drawing

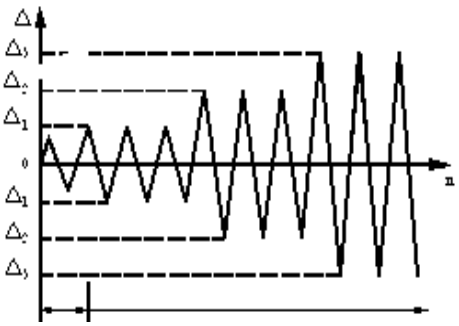


Figure 3. Test loading system of the test joint

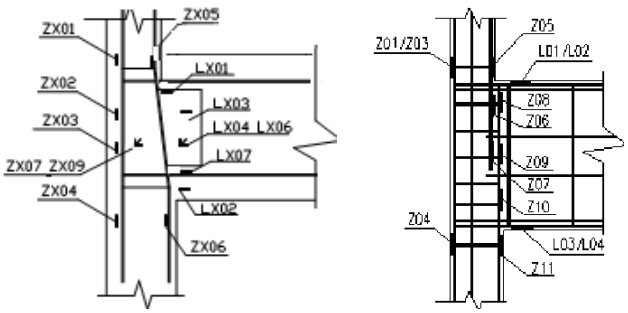
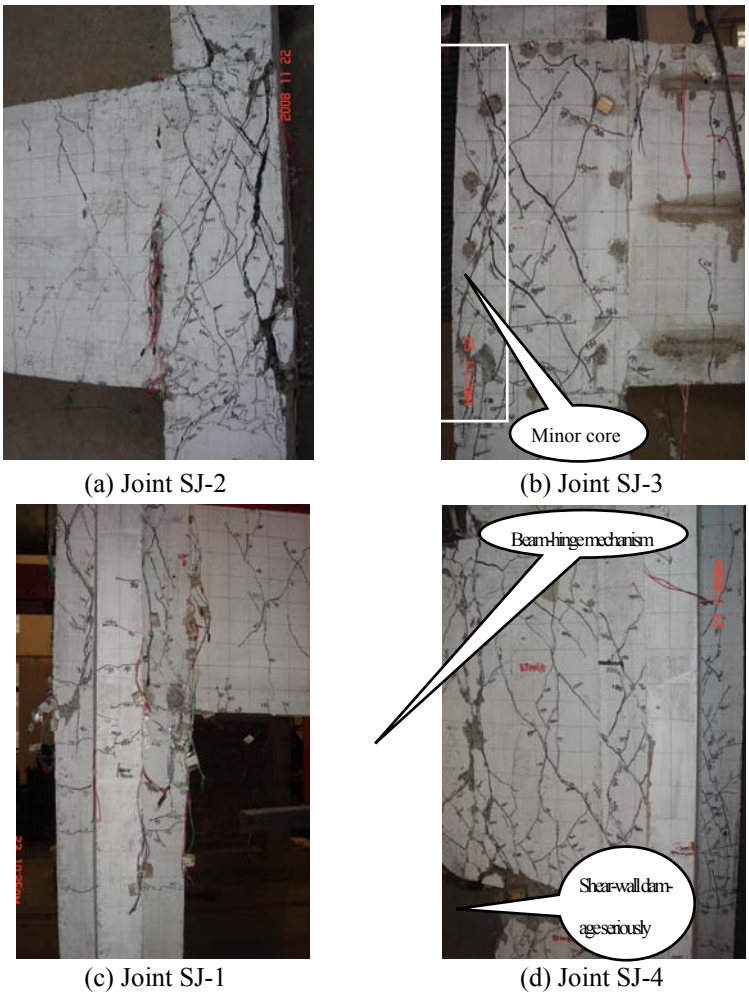


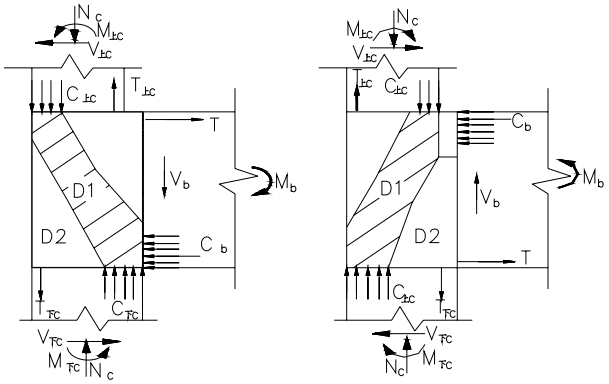
Figure 4. Arrangement of strain gauges in the test joint



(a) Joint SJ-2 (b) Joint SJ-3

(c) Joint SJ-1 (d) Joint SJ-4

Figure 5. Damage situations of the test joints



(a) Column-end is pulled (b) Column-end is pushed

Figure 6. The bearing analysis of SRC abnormal exterior joints

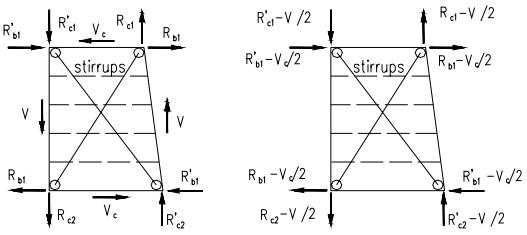


Figure 7. Steel truss model of test joints

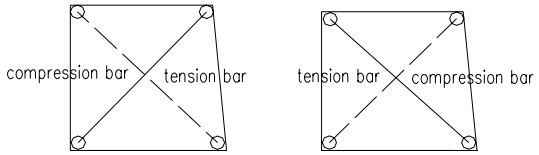
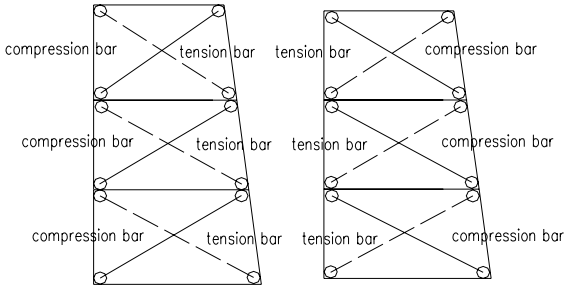


Figure 8. Tensile-compressive strut model of test joints



(a) Positive (push) displacement (b) Negative (pull) displacement

Figure 9. Multi-layer steel truss model of the joint

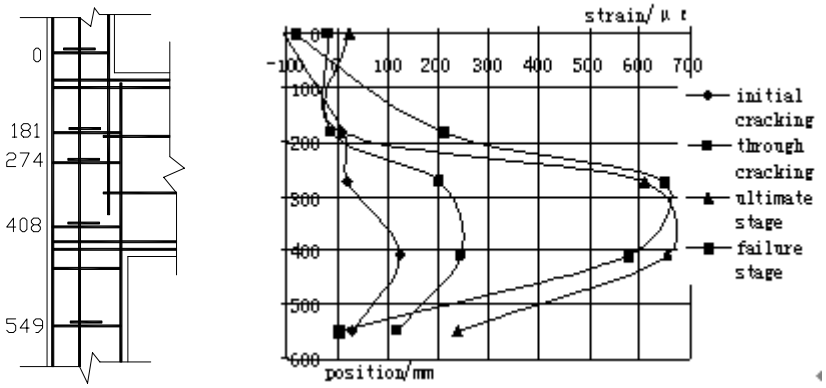


Figure 10. Strain analysis of stirrups in the joint core area

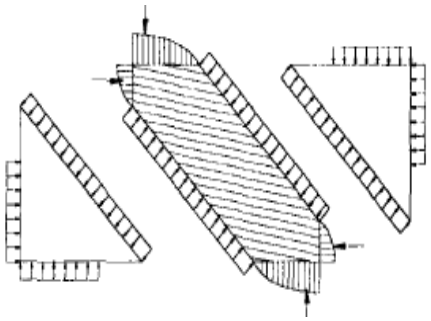


Figure 11. Surrounding concrete restricted diagonal struts

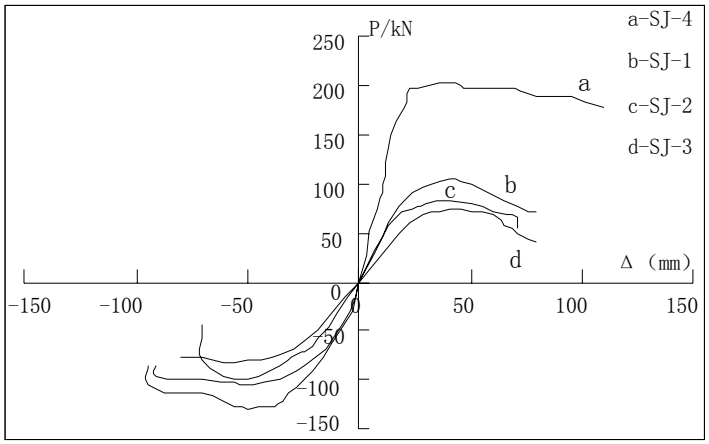


Figure 12. Backbone curve of test joints