The Influence of Joint Details and Axial Force Ratios on Failure Mechanisms of SCFT Column-beam Connections

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Abstract
Three types of joint detailing are suggested in Chinese specifications to reinforce CFT column-steel beam connections, including internal diaphragms (ID), external diaphragms (ED) and through diaphragms (TD). Previous research has mainly focused on a single type of connection detail; very little comparative research has been conducted on the differences of these details in influencing the behavior of the connections. Full-scale experimental research and finite element analyses (Abaqus) are conducted to study the effect of joint details and axial force ratios on the failure mechanisms of CFT column-steel beam connections. Force transfer mechanisms and shear deformations of the joint are further investigated using advanced computational models. The results show that the connections with reinforcement details suggested by Chinese specifications provide satisfactory seismic performance. ED connections exhibit the highest shear strength and lowest ductility. ID connections provide the highest ductility and lower shear strength. TD connections exhibit similar performances as ID connections. The comparison of these connections shows that connection type, diaphragm thickness and tube thickness have a significant influence on the joint confinement and may lead to different failure mechanisms of the connections. A high axial force ratio may also cause an undesirable column yielding mechanism if the reinforcement of the joint is inadequate.

Keywords: CFT connection; failure mechanism; diaphragm; axial force ratio; FE analysis

1. Introduction
Concrete filled steel tube (CFT) columns have become commonplace in high-rise building design throughout the world in recent years because of their excellent seismic performance (Morino S. et al., 2003, Ricles J.M. et al., 2004, Rong B., 2007). In CFT columns the concrete increases the local buckling strength of the steel tube, and the steel tube provides confinement to the concrete. This synergistic behavior results in structures with high strength and stiffness, capable of resisting large lateral cyclic deformations. However, this synergistic composite action between the steel tube and the concrete cannot be fully achieved without proper reinforcement of the connections. Three major reinforcing details for CFT column-steel beam connections are suggested in Chinese specifications (CECS, 2004), including internal diaphragms (ID), external diaphragms (ED) and through diaphragms (TD) connections.

The principle of a "strong joint-weak element and strong column-weak beam" is recommended for structural design in China because beam yielding results in better ductility, higher safety margins and easier repair after damage compared to column yielding or joint yielding. Structural designers simply need to verify if the relevant codified equations are satisfied in their element design. The equations consider the geometries of the elements (beam, column and joint), material properties and axial force ratios.

Previous research has mainly focused on the seismic performances of a particular connection detail on small scale specimens (Morino S. et al., 1993, Lu X. et al., 2000, Elremaily A. et al., 2001, Nishiyama I. et al., 2004, Han L.-H. et al., 2007, LEE S.-H. et al., 2010). Very little research on CFT column systems have considered the relation between the codified equations and connection behavior, the effects of reinforcing details on failure mechanisms, the key factors governing the structural failure, and the coupled effects of these factors. Therefore a comparison of these connection details is needed to clarify their differences in reinforcing the joint and possibly leading to different failure mechanisms of the connections. In addition, CFT column sections are becoming larger and larger.
in real practice (Fan H. et al., 2009), so full-scale experiments are necessary to better predict the seismic behavior of these connections. Experiments and finite element analyses using Abaqus were conducted for full-scale CFT column-steel beam connections with various diaphragms to investigate the effect of different connection details and axial force ratios on failure mechanisms of the connections.

2. Experimental Research
2.1 Test Setup

Nine full-scale CFT column-steel beam connections are tested (Fig.1.) under constant axial force and cyclic lateral displacement at the top of the column. The bottom of the column is pinned to the ground, and both beam-ends are supported vertically (Z direction) so that the beam can move freely in the horizontal direction (X direction). The connection specimen consists of a CFST column (□-400X400X14) and an I-shaped built-up steel beam (I-500X250X8X10). The slenderness of the beam flange and web is close to the slenderness limit for plastic design in the Chinese code. The column height is 3000mm and the total beam length is 4200mm. Diaphragms and beams are connected to the steel tube column with full penetration welding at the ED and ID connections. Columns are divided into three sections and welded to the beams at the TD connections. Parameters studied include connection reinforcement types (ED/ID/TD connection), thickness of the diaphragms (10mm/14mm), thickness of the steel tube at the joint area (14mm/18mm), beam details (regular/dog bone beam), and axial force ratios (0.11/0.34/0.68) as shown in Table 1. All of these specimens are designed to meet the principle of a "strong joint-weak element; strong column-weak beam" by referring to the equations for RC structures and steel structures. Capacity design concept is used to induce intended failure mode. Material properties of the steel and the concrete are tested and the results are shown in Tables 2. and 3. Displacement control is adopted in the test, so that the story drift angle of the connection is equal to 1/1000, 1/800, 1/500, 1/400, 1/300, 1/200, 1/100, 1/50, 1/30 and 1/20 in each loading level respectively. Two cycles are conducted for the first two loading levels, and three cycles are performed for all other loading levels.

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Table 1. Connection Specimen Details

| Reinforcement type       | Connection specimens | Steel tube at the joint | Diaphragm details                  | Axial force ratio | Axial force (kN) |
|-------------------------|----------------------|-------------------------|------------------------------------|------------------|------------------|
| External diaphragm      | JD11                 | 400x14                  | Width 150mm; thickness 10mm        | 0.11             | 1482             |
|                         | JD12                 | 400x14                  |                                     | 0.34             | 4445             |
|                         | JD13                 | 400x14                  |                                     | 0.68             | 8890             |
|                         | JD22                 | 400x14                  | Thickness: 10mm; hole diameter: 250mm | 0.34             | 4445             |
| Internal diaphragm      | JD22-B (dog bone beam) | 400x14                  |                                     | 0.34             | 4445             |
|                         | JD22-D               | 400x14                  | Thickness: 14mm; hole diameter: 250mm | 0.34             | 4445             |
|                         | JD22-T1              | 400x18                  | Thickness: 10mm; hole diameter: 250mm | 0.34             | 4445             |
|                         | JD-23                | 400x14                  |                                     | 0.68             | 8890             |
| Through diaphragm       | JD-32                | 400x14                  | Width 500mm; hole diameter: 250mm   | 0.34             | 4445             |
2.2 Test Results
2.2.1 Failure Modes

Typical failure modes of the connections are shown in Fig. 2. ED connections JD11, JD12, and JD13 initially yielded in the beam flanges close to the external diaphragms, and the yielding then extended to the external diaphragms. Finally, the beam webs began to buckle locally, leading to large local buckling in the flanges at the transition between the beam and the diaphragm. The web buckling decreased the capacity of the overall specimen to carry loads. Therefore, the resistance of the specimen decreased rapidly after the story drift angle reached 1/50. The loading was stopped at the story drift angle of 1/20, when the strength decreased to less than 85% of the maximum value.

ID connections showed various failure modes depending on the connection details. Specimens JD22, JD22-B, JD22-D, and JD22-T1 yielded initially in the beams, while JD23 yielded in the column. Specimens JD22 and JD22-D initially yielded in the beam flanges, followed by severe local buckling of the beam flanges at the transition zone, local buckling of the beam webs and finally by fracture of the beam flange. The failure modes of JD22-B and JD22-T1 are similar to that of JD22. However, the beam flanges of JD22-B and JD22-T1 did not crack even though the overall specimen shear strength decreased to less than 70% of its maximum value. This shows that both thicker steel tubes at the joint and dog bone beam details improve the brittle failure mode of internal diaphragm connections. In addition, JD22-B's yielding and buckling occurred within the dog bone section. The column of the JD23 connection yielded under the high axial force (0.68 P/P_c), and this was followed by local buckling of the tube forming an "elephant foot" around the column, and then by weld fractures of the steel tube at the "elephant foot" and crushing of the infilled concrete. The fracture of TD connection JD32 occurred at a story drift angle of 1/50, at the location where the beam flange and the through diaphragm meet. This crack grew rapidly with the increase of the displacements, resulting in a serious decrease in shear strength.

Comparison of JD12, JD22 and JD32 shows the influence of the connection type on failure modes: ED connections exhibited ductile behavior at locations away from the joint (where the beam flange meets the external diaphragm); ID connection exhibited brittle failure in the beam close to the joint; TD connection exhibited brittle failure at the beam diaphragm transition. These observations show that the diaphragm type has a significant influence on the failure mechanism (ductile/brittle) of the connection and the location of the yielding.

The axial force ratio of JD23 is the same as JD13 but their failure modes vary. This is because the external diaphragms provide a strong reinforcement to the steel tube and confinement to the concrete in the joint. The column retains its strength even under a very high axial force ratio. The confinement provided by internal diaphragms to the joint is weaker, so the

Table 2. Material Properties of the Steel

| Steel thickness (mm) | fy (MPa) | ft (MPa) | Es (GPa) | Elongation (%) |
|----------------------|---------|---------|---------|---------------|
| 8                    | 333.88  | 525.57  | 206     | 29.0          |
| 10                   | 354.62  | 553.83  | 211     | 29.5          |
| 14                   | 324.41  | 498.49  | 206     | 29.3          |
| 18                   | 336.80  | 512.68  | 218     | 33.6          |

Table 3. Material Properties of the Concrete

| Concrete | fc (MPa) | fc' (MPa) | ft (MPa) | Ec (GPa) |
|----------|----------|-----------|----------|---------|
| C40      | 47.8     | 45.0      | 2.35     | 32.6    |

Fig. 2. Typical Failure Modes of the Connections
steel tube buckles and the inner concrete crushes. This observation shows that the level of confinement provided by the diaphragms has a significant effect on the failure mode of the connections.

A comparison of JD22 and JD23 shows that the failure mode of the connection changes from beam failure (JD22) to column failure (JD23) with the increase of the axial force ratio.

2.2.2 Load-deformation Hysteresis Curves

Story shear force ($V_c$) versus story drift angle ($R_t$) relations for all specimens are shown in Fig.3. The story drift angle is defined as the ratio between the displacement at the top of the column to the height of the column. All the hysteresis curves show a pinching effect close to the origin of the coordinate; this is probably caused by initial gaps in the unloaded configuration between the bolts and nuts in the testing system which is difficult to eliminate in the test. The $V_c$-$R_t$ curves for JD11, JD12, JD22, JD22-B, and JD22-D are stable up to a story drift angle of 1/20. However, the strength of the JD13 and JD23 decreases rapidly after the 1/50 deformation level (approximately the maximum strength point) because of the high axial force ratio. JD32 also shows a serious strength decrease.

Fig.3. Story Shear Force-Story Drift Angle Curves of the Connections
in the second and third cycle at the 1/30 loading level; this is caused by fast crack growth initiated in the beam flange and through diaphragm transition. JD22-T1 was the first specimen tested, and the test was stopped before the story drift rotation reached 1/20 because of considerations concerning damage to the loading system. The available data for JD22-T1 shows stable strength up to the 1/30 loading level.

2.2.3 Load-deformation Envelope Curves

Fig. 4. shows the envelope curves used to characterize the effect of axial force ratio and joint details on the story shear force-story drift angle relations. High axial force decreases shear strength of the connection and intensifies the strength deterioration after the maximum strength. The ED connection (JD12) shows higher strength and more severe strength deterioration than ID (JD22) and TD (JD32) connections. The dog bone specimen (JD22-B) decreases the global strength of the connection but shows little initial stiffness reduction. Increasing both the thickness of the steel tube (JD22-T1) and diaphragm (JD22-D) in the joint area increases the global strength while intensifying the strength deterioration after the maximum strength point.

2.2.4 Shear Strength and Ductility

The shear strength and ductility of the connections are listed in Table 4.

The story drift angle ductility factor is used to characterize the ductility of the connections. The yield strength of the specimen is calculated with the method proposed by Han (Han L., 2004), in which the yield deformation is defined as the deformation at the intersection of the initial stiffness line and the tangent line at the maximum strength point of the load-deformation relationship curve.

The ED connection (JD12) provides the highest capacity and the lowest ductility, while the ID connection (JD22) provides a lower shear capacity but higher ductility than the ED connection. The TD connection (JD32) provides similar shear strength but lower ductility compared to the ID connection. Increasing the axial force ratio causes earlier yielding, and lower shear strength and ductility (compare JD11, JD12 and JD13). Increasing both the diaphragms thickness (JD22-D) and steel tube thickness (JD22-T1) in the joint increases the shear capacity while

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**Table 4. Main Test Results of Connection Specimens**

| Connection specimens | Direction | Yielding Strength (kN) | Story drift angle | Maximum Strength (kN) | Story drift angle | Ultimate Strength (kN) | Story drift angle | Ductility factor |
|----------------------|-----------|------------------------|------------------|-----------------------|------------------|------------------------|------------------|-----------------|
| JD11                 | +         | 429.8                 | -0.016           | 505.6                 | -0.019           | 429.8                 | -0.034           | 2.123           |
| JD12                 | +         | 402.0                 | -0.013           | 494.7                 | -0.018           | 420.5                 | -0.027           | 1.860           |
| JD13                 | +         | 450.0                 | -0.013           | 553.5                 | -0.019           | 455.2                 | -0.027           | 1.839           |
| JD22                 | +         | 283.0                 | -0.011           | 361.9                 | -0.020           | 307.6                 | -0.040           | 3.433           |
| JD22-B               | +         | 293.0                 | -0.014           | 379.9                 | -0.031           | 322.9                 | -0.038           | 2.586           |
| JD22-D               | +         | 313.0                 | -0.012           | 401.1                 | -0.020           | 340.9                 | -0.034           | 2.666           |
| JD22-T1              | +         | 313.0                 | -0.012           | 406.2                 | -0.024           | 345.3                 | -0.035           | 2.455           |
| JD23                 | +         | 311.0                 | -0.010           | 483.7                 | -0.017           | 411.1                 | -0.032           | 2.775           |
| JD32                 | +         | 316.0                 | -0.013           | 405.1                 | -0.020           | 344.3                 | -0.033           | 2.668           |

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Fig. 4. Influence Factors of Story Shear Force-Story Drift Angle Envelop Curves of the Connections
decreasing the ductility. The dog bone beam detail (JD22-B) tends to decrease both the ultimate strength and ductility.

The story drift angle at yield for the connections tested is between 0.01~0.0163 rad, which is 5.5~9.0 times that of the elastic limit of the story drift angle for RC structures (1/550), and 3.0~5.4 times that for steel structures (1/300). The ultimate story drift angle of the connections is between 0.0228~0.04 rad, which is 1.14~2 times that of the plastic limit of the story drift angle for RC and steel structures (1/50). All the connections tested exhibited excellent ductility.

3. Finite Element Analysis
3.1 FE Modeling
Computational models were created in Abaqus to further study the differences between these connections. A half model with symmetrical boundary conditions was used in order to save computational memory and time. Three-dimensional eight node brick elements with full integration and incompatible modes (C3D8I) were adopted for all the elements. A finer mesh was used in the joint area in order to capture the complex stress distribution at this location. A bilinear stress-strain relationship with a strain hardening of 1% was adopted for the steel. The constitutive model of the concrete suggested by Han (Han L., 2004) was adopted for the inner concrete, considering the confinement from the steel tube to the concrete. A "tie constraint" was used between the concrete and the steel tube because there was very limited slippage observed in the failed specimens.

3.2 FEA Results
Monotonic loading was used in finite element analysis to avoid convergence problems. The Abaqus model agrees well with the test results insofar as initial and unloading stiffnesses are concerned. The estimated shear strength is 60% and 80~95% of the test results for JD23 and all other connections, respectively. Higher shear strength from the test may be caused by a high strain hardening of the steel in the test, whereas strain hardening of 1% is adopted for steel in the model.

Table 5. Shear Deformations of the Joint

| Specimens | Simulated shear deformation at the steel tube web (γt) | Shear deformation from the experiment (γ) | Simulated shear deformation at the middle of the steel tube flange (γf) | η = γt/γf | η = γt/γf/2 |
|-----------|-----------------------------------------------------|----------------------------------------|---------------------------------------------------------------|-------------|----------------|
| JD11      | 0.0012                                              | 0.0024                                 | 3.7                                                           | 0.0024      | 0.96            |
| JD12      | 0.0009                                              | 0.0017                                 | 4.5                                                           | 0.0117      | ----            |
| JD13      | 0.0012                                              | 0.0014                                 | 3.8                                                           | 0.0014      | 1.72            |
| JD22      | 0.0021                                              | 0.0044                                 | 12.4                                                          | 0.0044      | 0.95            |
| JD22B     | 0.0016                                              | 0.0015                                 | 9.5                                                           | 0.0015      | 2.15            |
| JD22D     | 0.0025                                              | 0.0019                                 | 7.6                                                           | 0.0004      | ----            |
| JD22T1    | 0.0012                                              | 0.0019                                 | 12.3                                                          | 0.0019      | 1.29            |
| JD23      | 0.0040                                              | 0.0041                                 | 7.0                                                           | 0.0041      | 1.97            |
| JD32      | 0.0017                                              | 0.0026                                 | 14.0                                                          | 0.0026      | 1.33            |

3.2.1 Shear Deformations of the Joint
The LVDT gauges are placed on the surface of the steel tube webs in the test, so the shear deformations at the steel tube webs from the Abaqus simulations (γt) are compared to the tested results (γt) in Table 5. The experimental shear deformations of JD12 and JD22D are not deemed reliable because of instrumentation issues found during testing. The simulated shear deformations are 0.95~2.15 times the tested results with an average of 1.48 times; smaller shear deformations from the test may be due to the high strain hardening effect of the steel tube which provides higher confinement to the inner concrete than the model.

It is found from the Abaqus analysis that the steel tube flanges in the joint experience out-of-plane (Horizontal, X-direction) deformations and the largest deformation occurs at the middle of the steel tube flange. Shear deformations at the middle of the steel tube flanges (γf) of all specimens are listed in Table 5. The value of γf for ED connection is the largest and that of ID connections is the smallest. Increasing the thickness of the diaphragms or steel tube in the joint decreases the shear deformations. Higher axial force ratio tends to increase the shear deformations at this location.

The value of the shear deformation ratio η = γf/γt is further calculated in Table 5. This parameter was used to study the confinement difference of various connection types. It is obvious that the stronger confinement the connection provides, the smaller η will be. The analysis shows that external diaphragms provide more confinement to the connections than internal diaphragms, and thicker diaphragms or steel tubes in the joint provide higher confinement to the joint.

4. Force Transfer Mechanisms of the Joint
The force transfer mechanism of the joint is further studied to clarify the differences of connections with various diaphragm details. The tension (Ft) and compression force (Fc) in an ED connection is transferred from the beam flanges to the column through two paths: (1) one part is transferred to the
steel tube flange and the inner concrete; (2) the other part is transferred to the external diaphragm, and then to the steel tube web and the inner concrete. The forces from the beam flanges in an ID connection are transferred to the steel tube flanges first, and then are transferred to the inner concrete through: (1) friction between the diaphragm and concrete, and (2) the compression force at the inner hole. Connections with TD transfer the forces in some combinations of the paths specified for ID and ED connections described above.

Fig. 5. shows the forces transferred through external diaphragms of JD12 versus story drift angle relations. Tension force transferred through Diaph-1 is smaller than that transferred through Diaph-2. However, the compression force transferred through Diaph-1 is more than 4 times that transferred to Diaph-2. This analysis shows that concrete provides an efficient transferring path for compression while the external diaphragm provides an efficient transferring path for tension.

The effect of connection type on the total force transferred to the diaphragm versus diaphragm deformation relation is shown in Fig. 6. The total force transferred to the joint is in the following order: JD12 > JD32 > JD22. The deformation of JD12 is around 80% of that in JD22 and JD32. This comparison shows that external diaphragms provide a stronger confinement to the joint than internal diaphragms, and this leads to a smaller diaphragm deformation. Both the total forces transferred through the diaphragm and diaphragm deformations of JD22T1 are lower than those of JD22. This is probably because the thicker steel tube has a stronger stiffening effect on the inner concrete in the joint, resulting in a higher stiffness in transferring the forces in the concrete. Increasing the thickness of the diaphragm (JD22D) also increases the confinement of the joint, and this leads to smaller diaphragm deformations.

5. Conclusions

Seismic performance of full-scale CFT column-steel beam connections with various diaphragms was investigated experimentally and computationally to study the effect of joint details and axial force ratios on failure mechanisms of the connections.

The experimental research shows that:

1. All of the specimens exhibit excellent seismic performance, including high shear strength and ductility when compared to steel and RC structures. ED connections show the highest shear strength but lowest ductility among the three types of connections tested. ID connections have higher ductility and lower shear strength than ED connections. TD connections have similar shear strength but lower ductility compared to ID connections. Increasing the thickness of diaphragms and steel tube increases shear strength but decreases ductility. Increasing the axial force ratio tends to decrease both the shear strength and ductility of the connections.

2. Axial force ratio has a significant effect on yielding mechanism. Very high axial force ratio may lead to column failure even though the equations specified in the Chinese codes (CECS, 2004) are satisfied.

3. Different failure mechanisms of ED and ID connections under high axial force ratio indicates that the reinforcement details affect the failure mechanism of the connections; strong reinforcement of the connection is necessary to ensure the beam yielding mode, especially with a high axial force ratio.

Finite element analyses provide satisfactory simulations to the test results in light of the maximum story shear forces and joint shear deformations. The ratio of the shear deformation at the middle of the steel tube flanges (maximum joint shear deformation) to that at the steel tube web surface (minimum joint shear deformation) shows that external diaphragms provide stronger confinement to the connections than internal connections, and thicker diaphragms/steel tube in the joint tends to increase the confinement of the connections.

The analysis on force transferring mechanism shows that different connection types transfer the forces from the beam flange in different ways, and each connection type shows different force transfer mechanisms for tension and compression. The concrete in the joint is efficient in transferring compression forces, while diaphragms provide an efficient path for transferring
tension forces. Thicker steel tubes in the joint provide more confinement to the concrete, and this leads to smaller diaphragm deformations.

In a word, connection details including diaphragm types, diaphragm thickness and steel tube thickness in the joint provide different confinement to the joint which may cause different failure mechanisms of the connections. High axial force ratios may also cause undesirable column yielding mechanisms of the connections if the reinforcement of the joint is inadequate.

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