Experimental Study on Joint Properties of Steel Secondary Beam Connected with Concrete Main Beam Using an Embedded Part

Xiaohong Sun¹, Xiaoxiao Feng²*, Shutong Yang², Shenglin Li¹ and Yanqiang Wang¹

¹ Shandong Electric Power Engineering Consulting Institute Corp., LTD, Jinan 250000, China
² Department of Civil Engineering in College of Engineering, Ocean University of China, Qingdao 266100, China
Email: fengxiaoxiao@stu.ouc.edu.cn

Abstract. In this paper, a joint of I-shaped steel secondary beam connected with concrete main beam using an embedded part was simplified from a practical engineering by adopting the scale 1:3. Six specimens were tested. The effects of different concrete main beam heights (245 mm and 295 mm), concrete floor slab, rigidity of steel secondary beam and height difference between the secondary beam and main beam tops on the mechanical performance and failure mode of specimens were analyzed. Results show that flexural failure is often found in the steel secondary beam. But the failure mode is changed to joint failure in the main beam if the rigidity of steel beam is increased locally at the mid-span region. Moreover, setting floor slab and increasing rigidity of steel secondary beam can all improve the load-carrying capacity of the joint. The safety of joint can be obtained by strengthening the stirrups adjacent to the embedded part and longitudinal steel bars under the part.

Keywords. Steel secondary beam, experimental study, concrete main beam, embedded part.

1. Introduction
Steel-concrete composite structures are usually used in each floor of the main power house of large capacity thermal power plant [1-2]. The structures can sufficiently reflect the excellent characteristics of steel and concrete. Compared with concrete structures, they can greatly reduce the dead weight of the structure, shorten construction period and save cost. Nowadays, most of the studies are aimed at the steel-concrete composite structures [3-5]. The construction procedures of each member of the steel-concrete composite floor and commonly used construction methods in the United States are summarized in the literature [6], and some common construction problems for relevant practitioners are consequently avoided. Di et al. [7] performed an experimental study on two types of connections between steel columns and concrete foundation and found that the traditional anchor-bolt connection has poor ductility and belongs to brittle fracture when the bolt is damaged. Kyung [8] improved the traditional T-shaped steel main beam-concrete filled square steel tube column joint. Thus, the fracture of stiffening rib between steel beam and concrete-filled steel tube column under cyclic load can be avoided., Moreover, Sheikh proposed a design model for steel beam-concrete column joints in the 1980s [9].

* Corresponding author.
However, there are relatively few studies on the connection form of steel secondary beam to concrete main beam. Yang [10] proposed a new joint structure by cutting off the upper flange of the steel beam before inserted into the concrete main beam, and welding two steel plates. Results show that the welded flange in the core zone yields and the joint ductility is good when the transverse area ratio of the welded steel plate to the upper flange of the secondary beam is 0.35 ~ 0.5. The present study embedded a part in the concrete main beam and connected the I-shaped steel secondary beam via the embedded part with high-strength bolts with reference to a practical thermal power plant. Six types of specimens were tested under monotonic static loading. The results would then provide some reference for practical engineering application.

2. Experimental Programme

According to a practical I-steel secondary beam-concrete main beam joint using an embedded part, six joint specimens with 1:3 scale were designed, named SCJ-1 ~ SCJ-6. The overall structure for test is shown in figure 1, which mainly includes two concrete main beams, one steel secondary beam, and one concrete floor if available. The two ends of each main beam are fixed in cast-in-place concrete piers. In order to simulate the restraint effect of the column on the main beam in practice and prevent the main beam from rotating, two fixed steel beams are arranged parallel on both sides of the secondary steel beam, and connected with the concrete main beam with high-strength screw as shown in figure 1. The present test is mainly aimed at the influence of concrete floor slab, height of main beam, height difference between main and secondary beam tops and strengthening of steel secondary beams on the mechanical properties and failure modes of joint specimens. The specific design parameters are shown in table 1.

![Figure 1. Schematics of structure in the test.](image_url)

| Nos. of specimens | Main beam height (mm) | Top difference between main and secondary beam (mm) | Sizes of concrete slab (mm) (length/width/height) | Strengthening of steel secondary beam or not |
|-------------------|-----------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------|
| SCJ-1             | 245                   | 0                                             | 3600/800/50                                   | Yes                                       |
| SCJ-2             | 245                   | 0                                             | N/A                                           | Yes                                       |
| SCJ-3             | 295                   | 50                                            | 3600/800/50                                   | Yes                                       |
| SCJ-4             | 295                   | 50                                            | N/A                                           | Yes                                       |
| SCJ-5             | 295                   | 50                                            | 3600/800/50                                   | No                                        |
| SCJ-6             | 295                   | 50                                            | N/A                                           | No                                        |

The concrete strength used in the main beam is C40, the cover thickness is 20 mm, and the steel secondary beam is HM194×150×6×9 I-shaped steel with the standard value of yielding strength 235 MPa. The width and thickness of concrete floor slab are 800 mm and 50 mm, respectively. In the specimens with no difference between the tops of the main and secondary beams, the concrete slab covers both the steel secondary beam top and part of the concrete main beam top. The embedded parts in the specimens SCJ-1 and SCJ-2 are HM150×150×7×10 I-type steel, while the embedded parts in the specimens SCJ-3~SCJ-6 were HM194×150×6×9 I-type steel. All the parts have the standard values of yielding strength 235 MPa and the insertion depths are 100 mm. The embedded parts are
connected to the steel secondary beam by two Class 8.8 high-strength bolts with diameters 25 mm. The stirrup spacing in the core area of the main beam joint is arranged at 250 mm intervals so that the embedded parts can be conveniently inserted in the main beam. The details are shown in figure 2. In the specimens SCJ-3 ~ SCJ-6, steel plates with 1000 mm×180 mm×10 mm were welded between upper and lower flanges on both sides of secondary steel beams in the mid-span regions as shown in figure 3 to increase the local stiffness.

Moreover, the devices used in the test include several concrete counterweight blocks, one hydraulic jack, one balance steel beam, etc. The test setup is shown in figure 4. When the test begins, the loading is applied directly on the steel secondary beam at the mid-span or the floor slab on the secondary beam via the hydraulic jack and the concrete counterweight blocks are used as a reaction frame. According to the Standard for Test Methods for Concrete Structures (GB/T50152-2012), the specimen is pre-loaded before formal loading, and then loaded in a graded manner, with each grade of 10 kN. When one grade of loading is applied, the load is kept for 10 minutes and the crack development in the specimen is observed. The test is finished when the specimen is completely damaged.
The displacements and strains are measured using displacement gauges and strain gauges, respectively. The measuring point on the steel bar is polished using a grinding machine, and then the strain gauge is pasted, coated with epoxy resin and wrapped with gauze. Strain gauges were used to measure the strains at the upper longitudinal reinforcements, lower longitudinal reinforcements and stirrups in the core area of concrete main beam joints, and the lower flange of steel secondary beam at the mid-span. Displacement gauges are used to measure the relative slippage of the upper and lower flanges of steel secondary beam to the concrete main beam, and the deflection of secondary beam at the mid-span. The arrangement of displacement meter and strain gauge is shown in figure 5.

![Figure 5. Arrangement of displacement and strain gauges.](image)

### 3. Analysis of Test Results

#### 3.1. Failure Modes

There are generally two failure modes observed in the test. If the steel secondary beam are not strengthened, such as specimens SCJ-5 and SCJ-6, the failure occurs in the secondary beam with yielding of the lower flange. Taking the specimen SCJ-5 as an example as shown in figure 6, the mid-span displacement of the steel secondary beam increases slowly, and the load-displacement curve shows a straight line with a relatively large slope in the early stage of loading. When the load is increased to 40 kN (about 38% of the load-carrying capacity), a fine crack appears in the concrete floor slab adjacent to the slab-main beam joint, the slope of load-displacement curve decreases slightly, and the structural rigidity is reduced. When the load is increased to 90 kN (about 84% of the load-carrying capacity), the cracks in the surface of slab propagate continuously and even through the floor slab. The steel secondary beam begins to yield and the mid-span displacement increases rapidly. When the load is increased to the maximum, the crack propagation in the slab surface is arrested. But the mid-span displacement of steel secondary beam is so large that the specimen can not be loaded further. The test is then stopped.

If the steel secondary beam is strengthened, such as specimens SCJ-1, SCJ-2, SCJ-3 and SCJ-4, the failure mode is changed to bending-shearing failure of concrete main beam near the embedded part as shown in figure 7(a). Taking the specimen SCJ-3 as an example, when the load is increased to 35 kN (about 29% of the load-carrying capacity), there is a fine crack in the concrete floor slab adjacent to the slab-main beam joint as shown in figure 7(b). The crack width increases with the increasing of loading. When the applied load is increased to 105 kN (about 86% of the load-carrying capacity), two cracks appear in the main beam, distribute symmetrically in two sides of the joint adjacent to the upper flange of embedded part, and propagate in an inclined direction towards the beam bottom. As the load increases, more inclined cracks are found in the main beam. When the load is increased to 122 kN, i.e., the maximum value, the crack in the slab surface propagates through the slab, and serious peeling of concrete surface layer is observed around the embedded part. The anchorage action on the embedded part by the concrete fails. The test has to be stopped.
3.2. Load-Displacement Curve

Figure 8 summaries the load-displacement (mid-span displacement of steel secondary beam) curves. The load-carrying capacity of joint is provided by both the bending and shearing resistance. When the load of the specimens having concrete floor slab is increased to about 30 kN, the slope of the load-displacement curve decreased significantly due to the crack initiation in the slab adjacent to the slab-main beam joint. When the applied loads are the same, the mid-span displacements of steel secondary beams having concrete floor slab are smaller than the ones without concrete floor slab. It means that the application of reinforced concrete floor slab can effectively improve the structural load-carrying capacity and rigidity. Moreover, the maximum applied load of SCJ-1 is 12.7% larger than that of SCJ-3. It is mainly because the tops of main and secondary beams in SCJ-1 are at the same height so that the reinforced concrete floor slab can cover both tops of the two beams. Strengthening provided by the floor slab improves the load-carrying capacity significantly.

The maximum applied loads of SCJ-3 and SCJ-4 are 11.7% and 8.4% larger than those of SCJ-5 and SCJ-6, respectively. It again demonstrates that the improvement of local rigidity of steel secondary beam can increase the structural load-carrying capacity. For specimens SCJ-3 and SCJ-4, however, the failure occurs in concrete main beam in the joint region with significant bending-shearing inclined cracks. Thus, it belongs to brittle failure and should be avoided in practical engineering. Therefore, the spacing of stirrups in the two sides of embedded part should be shortened to delay the crack propagation in the main beam. For SCJ-5 and SCJ-6, the failure mode is yielding of lower flange in the steel beam and no crack is observed in the main beam. Therefore, it belongs to ductile failure and is adopted in practical engineering.

3.3. Load-Strain Curves

Figure 9 shows the load-strain curve of longitudinal steel bars under the embedded parts. At the early stage of loading, the strain of specimen SCJ-2 is larger under the same load, and the strain growth rate is also faster. It is mainly because of the relatively low stiffness of the main beam with height 245 mm. When the structure is completely damaged, the strains in the longitudinal steel bars under the embedded parts of SCJ-5 and SCJ-6 are lower than those of other specimens because the failure mode of the two specimens is yielding of steel secondary beam at the mid-span.
The load-strain curves of lower flanges of the steel secondary beams at the mid-span are shown in figure 10. At the early stage of loading, the strain increases with the increasing of the applied load. Besides, the load-strain curves are almost linear for the specimens with locally strengthened steel secondary beams at the mid-span regions. If the steel beams are not strengthened, there are linear portions in the load-strain curves at the early stage of loading. But the strains increase faster as the loads are further increased. When the load is improved to 85% of the maximum value, the lower flange of the steel beam yields and the strain increases rapidly until failure.

**Figure 10.** Load-strain curves of lower flange of steel secondary beam at the mid-span region.

### 3.4. Discussion

It is found from the test that the failure modes and load-carrying capacity of the specimens are different if the rigidity of steel secondary beam at the mid-span is different. If the failure occurs in the concrete main beam in the joint regions, the load-displacement curve has a larger slope at the initial stage of loading, the strains of longitudinal steel bars under the embedded parts are relatively large but the steel secondary beam does not yield at the mid-span. The load-carrying capacity is then higher than that of specimens with failure mode of steel beam yielding. When the failure mode is changed to yielding of steel secondary beam, the rigidity of specimen is lower and the load-carrying capacity is reduced. The strains of longitudinal steel bars under the embedded part increase with the increasing of loading, but the increment is relatively low. Moreover, there are generally four stages during the loading process for the specimens with two failure modes, namely, elastic stage, cracking stage, yielding stage and ultimate stage. Table 2 summaries the cracking load $P_{cr}$ and the corresponding mid-span displacement $\Delta_{cr}$, the yielding load $P_{y}$ and the corresponding mid-span displacement $\Delta_{y}$, and the maximum load $P_{max}$ and the corresponding mid-span displacement $\Delta_{u}$. The characteristics in the four stages are further discussed as follows.

| Nos. of specimens | $P_{cr}$ (kN) | $\Delta_{cr}$ (mm) | $P_{y}$ (kN) | $\Delta_{y}$ (mm) | $P_{max}$ (kN) | $\Delta_{u}$ (mm) |
|-------------------|--------------|------------------|-------------|----------------|---------------|--------------|
| SCJ-1             | 30           | 3.6              | 111         | 23             | 135           | 45           |
| SCJ-2             | 35           | 5.6              | 100         | 20             | 120           | 38           |
| SCJ-3             | 30           | 5.4              | 90          | 18             | 106           | 30           |

At the elastic stage, both concrete beams and steel secondary beams are in the elastic state. The shape of load-displacement curve is almost linear. The strains of the steel secondary beam’s lower flange at the mid-span and the longitudinal steel bars under the embedded part are very small.

At the end of the elastic stage, longitudinal tensile cracks appear in the slab-main beam joint. The concrete part subjected to tension in the cross-section of floor slab gradually disappears. The crack in the slab develops continuously with the increasing of applied load, and the slope of load-displacement curve is slightly reduced.
At the yielding stage, if the steel secondary beam is strengthened locally at the mid-span region, the cracks in the main beam at the two sides of embedded part appear from the upper region of the embedded part and propagate in an inclined direction towards the beam bottom. As the crack width increases, the longitudinal steel bars and stirrups near the embedded part yield, and the load then increases slowly. If the steel secondary beam is not strengthened, the displacement at the mid-span of steel beam increases rapidly and the load increases slowly. The lower flange of steel beam at the mid-span yields. But the stirrups near the embedded part and longitudinal steel bars in the main beam do not exceed the yield limit. No crack is observed in the main beam.

When the ultimate state is reached, the maximum crack width is 2~4 mm in the main beam if the steel secondary beam is strengthened locally at the mid-span region. The crack in the floor slab propagates through the whole slab. The displacement at the mid-span of secondary beam and strains in the longitudinal steel bars increase rapidly with the slow increment of the applied load until the $P_{\text{max}}$ is reached. If the steel secondary beam is not strengthened, the stress state in the lower flange of steel beam at the mid-span enters hardening stage after yielding stage. The displacement increases significantly until the specimen can not carry the load further, and the test is then stopped.

4. Conclusions

(1) In this paper, a new type of main beam-secondary beam joint using embedded part is proposed instead of anchor tendon plus H-shaped embedded steel. The proposed type of joint has good mechanical properties and is convenient for construction. Thus, the construction period can be shortened.

(2) The load-carrying capacity can be improved by setting reinforced concrete floor slab.

(3) There are generally two failure modes observed in the test. If the steel secondary beam is strengthened locally at the mid-span region, the failure occurs in the main beam near the embedded part with significant bending-shearing inclined cracks and the steel beam does not yield. It belongs to brittle failure. If the steel secondary beam is not strengthened, the failure is changed to yielding of lower flange in the steel beam at the mid-span region. No crack is observed in the concrete main beam. It belongs to ductile failure and can be adopted in practical engineering.

(4) When the concrete floor slab is set, the load-carrying capacity for the failure mode of yielding of steel secondary beam at the mid-span is 11.7% lower than that for joint failure mode. If no concrete floor slab is set, the maximum applied load for the former is 8.3% lower than that for the latter. Increasing the rigidity of steel secondary beam locally at the mid-span can effectively improve the structural load-carrying capacity. Moreover, it is recommended that the safety of joint should be ensured by shortening the stirrup spacing in the joint region and reinforcing the longitudinal steel bars under the embedded part.

Acknowledgement

The authors gratefully acknowledge funding from Shandong Electric Power Engineering Consulting Institute Corp. LTD.

References

[1] Huang X L, Shen T and He Y M 2016 Mechanical behaviors of embedded joint connections between steel timbers and concrete girders (in Chinese) J. Struc. Eng. 32 35–41 DOI: 10.15935/j.cnki. jggcs. 2016. 04. 006.

[2] Yu Q, Lu Z D, Yu J T, Zhao X Z and Dai J 2011 Experimental study on specimens of steel secondary beam embedded in reinforced concrete girder of frame structure Advanced Materials Research 243–249 1072–84 DOI: 10.4028/ www. scientific.net/ AMR. 243-249. 1072.

[3] Jia S S, Wang Y, Wang X J and Liu X L 2020 Seismic behavior and restoring forcemodem of connections between rectangular tubular columns and H-shaped beams using single direction bolts (in Chinese) J. Build. Struct. 41 168–179 DOI: 10. 14006/ j. jzjgxb. 2018.0365.
[4] Han L H, Hou C C and Xu W 2018 Seismic performance of concrete-encased column base for hexagonal concrete-filled steel tube: numerical study J. Constr. Steel. Res. 149 225–238 DOI: 10.1016/j.jcsr.2018.07.006.

[5] Xu W, Han L H and Li W 2016 Seismic performance of concrete-encased column base for hexagonal concrete-filled steel tube: experimental study J. Constr. Steel. Res. 121 352–369 DOI: 10.1016/j.jcsr.2016.02.003.

[6] ASCE 2002 Construction considerations for composite steel-and-concrete floor systems J. Struct. Eng 128 1099–1110 DOI: 10.1061/(asce)0733-9445(2002)128:9(1099).

[7] Di S L, Pecce M R and Fabbrocino 2007 Inelastic response of composite steel and concrete base column connections J. Constr. Steel. Res. 63 819–832 DOI: 10.1016/j.jcsr.2006.08.007.

[8] Kyung J S, Young J K and Young S O 2008 Seismic behavior of composite concrete-filled tube column-to-beam moment connections J. Constr. Steel. Res. 64 118–127 DOI: 10.1016/j.jcsr.2007.04.001.

[9] Sheikh M S, Gregory G D, Joseph A Y and James O 1989 Beam-column moment connection for composite frame J. Struct. Eng. 115 2858–75 DOI: 10.1061/(ASCE)0733-9445(1989)115:11(2858).

[10] Yang Q F, Qin W K and Zhou J B 2011 Experimental study on the joint connection of unilateral steel timbers inserted into the concrete girder J. Civil Eng. Manage 28 53–58.