Experiment on Seismic Behavior of Neotype Column-slab High Piers

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Abstract. The low-cyclic reversed loading test was carried out for a scale model of a neotype column-slab high pier. The test was designed to investigate its failure modes, hysteretic characteristics, ductility, energy dissipation, residual deformation stiffness degradation. Test results indicate that the neotype column-slab high pier has strong and stable bearing capacity, good ductility and energy dissipation capacity, small residual deformation. The destruction process of the structure components is that bending cracking of the wing slab bottom firstly, shear cracking at the junction of the web plates with the corner columns, then bending cracking at the roots of the corner columns. Cracking and energy dissipation of the slabs decrease the stiffness of the structure, which effectively protects the corner columns. The study contributes to the literature for developing future design guidelines, for the purpose of providing experimental and theoretical background of the neotype column-slab high pier.

1. Introduction
With the advantage of integrity and superior economic performance, the traditional round end pier and rectangular hollow pier are widely employed in tall bridge pier design. Because of the stiffness controlling, large section size and masonry make the pier cost always occupy a high ratio to the total project cost [1-2]. It is still in elastic state under the rare earthquakes so that the bridge foundations endure force too largely and are difficult to design. At present a kind of lattice pier with multi-columns, that double columns are jointed by beams, is introduced abroad. The stiffness of the beam is relatively weak, so it is easy to form the plastic hinge at a optimal pacing site under the rare earthquake. It depends on the the beam deformation to consume the earthquake energy in order to protect the main body and ensure the safety of the foundation [3].

Li xiaojun [4] and others put forward a neotype column-slab high pier (four-column pier) by using the research results and successful application of other countries for reference. Four columns of the pier are connected by slabs and a small amount of beams. The slabs and beams can provide high stiffness to the pier during the normal service stage and frequent seismic, and ensure safety of the bridge. Due to the fact that the columns are stronger compared to the slabs, the slabs are first broken in strong earthquake, which eads to the structure stiffness degrade rapidly, the fundamental period prolongs and the earthquake damage to the main structure is reduced. But the rectangular hollow pier is not allowed to crack, so it does not have the advantage on the seismic performance.

The low-cyclic reversed loading test [5] was carried out for a scale model of a neotype column-slab high pier with the background of a actual project data. The test was designed to investigate its failure modes, hysteretic property, ductility, energy dissipation, residual deformation and stiffness degradation. The study contributes to the literature for developing future design guidelines [6].
2. Test Conditions

2.1. Specimen Fabrication
As the background of a continuous rigid frame bridge with long-span and high-piers, the main pier of the bridge had the height of 112m, the anti-earthquake degree was 7, and its category was I. The lower 80m of the main pier was shrunk at the rate of 1:20 to design a column-slab specimen with variable cross-section, four columns and the total height of 4.875m. Because of the only 70mm thickness of the slabs, it was difficult to cast concrete.

2.0m above the base was designed into neotype column-slab cross section(Zone A). Intermediate 1.775m was hollow rectangular cross section(Zone B),and 0.6m at the specimen top was filled rectangular cross section for loading(Zone C).It was variable width from 1.5m to 1.168m in zone A along the loading direction, while keeping in 1.168m invariably in zone B and C. The width perpendicular to the loading direction was 1.2m constantly. The reinforcement ratio was referring to the prototype and Code for design on reinforced and prestressed concrete structure of railway bridge and culvert[7]. The strength grade of concrete used in trials was C40 reinforced with HRB335 steel bars. Stirrup and steel bar in slabs was HRB235. The compressive strength of the standard cubic test blocks of concrete was 46.5Mpa. Mechanical properties of steel is listed in Table 1.

Table 1. Mechanical properties of steel

| Diameter (mm) | Standard  | Yield strength $f_y$/N·mm$^{-2}$ | Ultimate strength $f_u$/N·mm$^{-2}$ | Yield strain $\varepsilon_y$/×10$^{-6}$ | Modulus of elasticity $E$/N·mm$^{-2}$ |
|---------------|-----------|----------------------------------|-----------------------------------|-------------------------------------|-----------------------------------|
| 12            | HRB335    | 406.9                            | 523.7                             | 2413                                | 1.614×10$^5$                      |
| 10            | HPB235    | 411.2                            | 463.1                             | 2371                                | 1.842×10$^5$                      |
| 8             | HPB235    | 351.2                            | 408.0                             | 1913                                | 1.803×10$^5$                      |
| 6             | HPB235    | 342.5                            | 396.3                             | 1681                                | 1.791×10$^5$                      |

2.2. Loading Equipment and Testing Contents
In this pseudo-static experiment, the specimen was subjected to vertical axial pressure and transverse horizontal force. The axial compression ratio was 0.15. The specimen was too tall(4.875m) to applied the axial load by hydraulic jack, which replaced by axial prestresses. Four bunch of prestressing tendons were arranged on the top of the specimen. The horizontal force was applied by the electro-hydraulic servo loading system. The low cycle loading device is showed in Fig.2.

In order to test the loading device and measuring instruments, the horizontal load, which was 20% of the estimated crack load , was applied twice before formal loading. Referring to Specificating of testing methods for earthquake resistant building, force and displacement hybrid control was adopted as the loading mode(see Fig.3) , which means force control before the specimen yielding and displacement control after the specimen yielding. The load was applied to the specimen damage or load dropping to 85% of the maximum load while the specimen entered the limit state , and each grade load was cycled once.
Test contents mainly included: the specimen displacement measured by using high precision displacement transducers, which were arranged in the top and bottom of the specimen, the column longitudinal reinforcement strain, the concrete strain of the columns and slabs. In order to achieve continuous measurement and automatic acquisition, the displacement transducers and strain gauge accessed to the 3815 data acquisition equipment at the same time. The columns and slabs cracking, crack width and distribution were also the key points concerned during the test.

3. Test Results Analysis

3.1. Failure Phenomena of the Specimen

In the zone A, S and N-slab were the equi-width wing slabs, which were perpendicular to the horizontal force and mainly bore bending. E and W-slab were the variable width web slabs, which were parallel to the horizontal force and mainly bore shearing. During the initial load, the specimen was in elastic state without cracking. At the point of the displacement level was 3mm, the bottoms of S and N-slab were cracking in tension, and the column bottoms also had a little tension crack, while the specimen was yielding. When the displacement level was 5mm, shear diagonal cracks appeared at the junction site of the E and W-slab with columns, and the specimen reached to the peak load. As the load...
increased, tension cracks of S and N-slab extended and expanded upward, which dominated by horizontal cracks accompanied with vertical cracks, and both formed map cracking, while there were only horizontal tension cracks on the columns (see Fig.4). The shear diagonal cracks of the E and W-slab extended and expanded to the middle and upper web slabs. The worst damage was in the corner of the junction site of the E and W-slab with columns (see Fig.5). The final failure mode was that, the S, N-slab damage belonged to the tensile and compressive failure, the E and W-slab damage were shear fracture, and bend cracks produced on the columns surface. The cracks on the columns, the wing and web slabs were interconnected. Steel bars didn’t yield before the specimen reached ultimate state. As a result, the slabs had a good protective function for the columns. With the continues increase of the load, some of the longitudinal bars in the columns yielded. The specimen yielding referred in this paper was symbolised by the obvious inflection point on the test hysteretic curve. Visible microcrack was observed in the test process but disappeared after the test was over.

**Figure 4.** Cracking of S, N-slab

**Figure 5.** Cracking of E, W-slab

### 3.2. Hysteresis Loop

In the test process, the horizontal displacement of the specimen top under each load was measured. Fig.6 shows the load-displacement hysteresis curve[8-9], which is comprehensive embodiment of structure anti-seismic property, and is also as the main basis for anti-seismic elastoplastic response analysis of structures. In the initial loading stage, the hysteresis curve almost loops in a straight line and the area of hysteretic loop was small, which illustrates that the specimen was small damage, low energy dissipation and elastic characteristics. In the medium and later loading stage, as the damage degree of the slabs increased, the area of hysteresis loops was developing rapidly, which indicated that more and more energy dissipation happened. The slope of the curve reduced with the increase of cycles, which shows that the structure stiffness was degenerating. The hysteretic loops are plump, and don’t have any obvious pinch phenomenon. When larger cracks emerged on the columns, the lateral load descends abruptly. After lateral unloading, the specimen had residual deformation, and the value became larger and larger along with the continuously increasing of repeated loading and unloading.

### 3.3. Skeleton Curve

The specimen skeleton curve of the load-displacement hysteresis curve is shown in Fig.7.

The curve is S-shaped with the obvious yield point and strength drop point, which shows that the specimen experienced three stages under the low cycle reciprocating loads: the elastic stage, while load and displacement was in a linear relationship and the initial stiffness had unclear change; the strengthening stage, while the shape of the curve was quadratic curve, the slope was reducing and the stiffness was descending; the failure stage, while the curve was decreasing slowly.

### 3.4. Ductility and Energy Dissipation

The displacement ductility factor(μ) is used to measure the structure ductility performance[10-11]. The displacement ductility factor (μ) is the ratio of ultimate displacement(Δu) to yield displacement(Δy), which is shown as formula (1).

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\mu = \frac{\Delta_u}{\Delta_y}
\]  

(1)
Figure 6. Load-displacement hysteretic loops

The displacement, corresponding to the bearing capacity that descends to 85 percent of the peak load, is regarded as the ultimate displacement. In Fig.7, it’s a long distance from the yield displacement to the ultimate displacement. The ductility factor of the specimen is 3.1. The results show that the specimen has good ductility.

Energy dissipation is the capacity of structure to absorb or consume energy by deforming or partial damage under earthquake[12-13]. The area of each hysteretic loop reflects the ability of structure absorbing seismic energy. Energy dissipation coefficient $E$ is used to evaluate the specimen energy dissipation capacity[14], which is the ratio of the total energy of a hysteretic loop to the elastic energy of the structure. The $E$ of the specimen in yield displacement, peak load and limit displacement are 0.45, 1.71, 2.59, respectively. During the loading process, slab cracking firstly consumed most of energy, which reduced the whole stiffness of the structure so that protected the columns.

4. Conclusion

(1) The damage of this neotype column-slab high pier is initiated from wing slab cracking in tension, then the specimen is soon led to the yielding state. When bending-shear cracks generate at the junction of web slabs with columns, the specimen reaches to peak load. The specimen enters the limit state while the cracks on the columns, the wing slabs and web slabs are interconnected and the unrecoverably cracks generate on the corner columns. Slab cracking has a good protective function for the columns.

(2) The load-displacement hysteresis curve is plump and has no obvious pinch phenomenon. The skeleton curve is S-shaped, and the specimen experiences elastic, strengthening and failure three stages. The results show that the neotype column-slab high pier has good ductility.

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