Experimental Research on Seismic Behaviour of Railway Bridge Pier

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Abstract. The shear failure of railway bridge piers has become the main feature of modern bridges. In order to study the shear resistance of railway bridge piers, three models were designed in this paper, including two piers model with a ratio of 1:5 based on Chenglan Railway bridge prototype piers and a test research model. Through the pseudo-static test study on the shear resistance of piers, the failure process of the specimen was given. It was indicated that that A1 and A2 specimen were typical bending failure and possessed enough ductility. And A3 specimen was typical flexure-shear failure. Before loading to yield displacement, stirrup provided little shear strength. After loading to yield displacement, the shear strength provided by stirrup increased gradually with the development of cracks. When the stirrup yielded, its restraint to the core concrete was weaken rapidly, which resulted in the rapid destruction of the bridge pier.

1. Introduction

The earthquake damage of the bridge structure mainly includes the crash of the superstructure, the damage of the supporting connector, the destroyed of the pier and the abutment, the failure of the foundation etc.¹. The pier is the most vulnerable member during the earthquake. There are three kinds of typical failure modes of piers: flexure failure, shear failure and flexure-shear failure². The flexure failure belongs to the ductile failure, which is manifested by the crushing and spalling of concrete, bare and buckling of the steel bar, and even breaking. There is a large plastic deformation when it is broken. It usually occurs in piers with large shear span ratio or sufficient restriction hoops. Shear failure belongs to the brittle failure, which is mainly manifested as a small amount of spalling of concrete, hoops are broken, and forming obvious shearing inclined cracks. There is small plastic deformation and a sharp drop in strength and stiffness when damage occurs. The ductility and energy dissipation capacity are very poor. It often occurs in piers with small shear span ratio or insufficient restriction hoops. Flexure-shear failure is a failure form between flexure and shear failure. Its ductility and energy dissipation capacity are poor, which has certain brittle characteristics. For pier with shear failure and flexure-shear failure, its deformability and energy dissipation capacity are poor, and it is difficult to repair after damage.

With the development of the research on the ground motion and the structural dynamic characteristics, the seismic design method has changed from the strength theory to the ductility seismic theory. It was found that using the plastic deformation of the structure under seismic action to consume seismic energy can better against the seismic action, and it is easy to repair after the event. However, in the ductile seismic design of piers, sufficient shear strength must be obtained in the ductile stage to ensure that brittle shear failure will not occur under strong earthquakes³. Therefore, two actual piers of
Chenglan Railway Bridge with a ratio of 1:5 were selected as prototype piers. A test research model was designed for studying the shear performance of pier and there are three models in total. And these models were used to conduct pseudo-static test.

2. Design Parameters of Trial Piers
Respectively, A1, A2 and A3 are the test models of the three piers. A1 and A2 are the prototype test models of Chenglan Railway Bridge piers, and A3 is the test model to study the shear performance. During the test, on the one hand, the rationality of the design of the prototype bridge pier is evaluated, on the other hand, the shear failure mechanism of the plastic hinge area is studied, and the influence of design parameters on the shear capability of the pier is analyzed. The specific model parameters of the three piers are shown in Table 1.

### Table 1. Model parameter.

| Model number | Section shape | Section size(mm) | Effective height | Longitudinal reinforcement ratio | Stirrup ratio | Axial pressure (kN) | Axial load ratio | Shear span ratio |
|--------------|---------------|------------------|-----------------|-------------------------------|---------------|-------------------|-----------------|-----------------|
| A1           | Rectangle     | 710×600          | 2200            | 0.47%                         | 0.16%         | 120               | 0.70%           | 3.7             |
| A2           | Rectangle     | 846×446          | 1200            | 0.21%                         | 0.13%         | 240               | 1.59%           | 2.7             |
| A3           | Rectangle     | 720×420          | 630             | 0.93%                         | 0.12%         | 120               | 0.99%           | 1.5             |

3. Test Scheme

3.1. Layout of Strain Gauge
The length of plastic hinge area at the bottom of pier is calculated and predicted at first. The strain gauge with longitudinal reinforcement tries to cover the height of possible plastic hinge region along the height direction of the specimen, and 1~2 times the height range of the section is taken. The strain gauge with longitudinal reinforcement is arranged symmetrically on both sides of main reinforcements and perpendicular to the loading direction, five main bars are arranged on each side. The strain gauge with hoops is arranged on both sides and parallel to the loading direction and in a continuous manner along the direction of height. The range of layout is consistent with the strain gauge of the main reinforcement.

For catching the strain variation regularity of concrete before cracking, three strain gauges are arranged on both sides of the pier along the plastic hinge area, and the direction perpendicular to the loading direction. Three groups of strain rosette are arranged on one side of the specimen which parallel to the loading direction. The static strain testing system was used to collect the strain values of steel bars and concrete at each peak of load.

3.2. Sensor Placement
The displacement of pier crown under horizontal load mainly includes bending deformation, shear deformation and slip deformation of longitudinal reinforcement. In order to investigate the deformation components of the bridge pier in the loading process, displacement sensors were placed in some positions to record the deformation of the pier at different positions in the loading process.

In this test, 1) MTS actuator sensor was used to record the lateral force of pier crown. The lateral displacement of pier crown is modified by the measured value of displacement sensor at effective height as the actual side displacement of pier crown, while the recorded value of displacement sensor on the base is used for aided-accuracy. 2) In the plastic hinge region on both sides of the pier, the recorded value of the linear differential displacement sensor along the height of the pier is used to calculate the slippage component of the longitudinal reinforcement and curvature characteristics of the section. 3) Three groups of linear differential displacement sensors arranged on the side that parallel to the loading direction are used to calculate the shear deformation component of the pier. The actuator and sensor layout diagram are shown in Figure 1.

3.3. Loading System
Variable displacement loading is adopted in this test. A small displacement grade is used at the preliminary stage of loading, and the step loading is carried out with an increment of 1mm until the...
pier yields (In this test, the longitudinal strain strain value at 5 cm from the bottom of the pier is 2000 \( \varepsilon \) for the first time.) In order to observe the development and damage changes of the pier before yielding crack. After the pier yields, the yield displacement is the increment of each stage, and the cycle of each stage is three times. According to the code for seismic design of railway engineering \[6\], when the loading displacement of the bridge pier at a certain level is first circulated, the lateral force drops below 80% of the maximum resistance on the same side, which is defined as the failure of the bridge pier and the termination of the test. The test load waveform \[7\] is as shown in Figure 2.

![Figure 1. Test setup and instrumentation of pier specimens.](image1)

![Figure 2. Load pattern.](image2)

### 4. The Experiment Results and Analysis

#### 4.1. Summary of Test Results

According to the measured data in the test, the parameters of specimen seismic performance are summarized as shown in Table 2.

#### 4.2. Description of Test Phenomenon

According to Table 2, the failure types of the test pier are mainly divided into flexure failure and flexure-shear failure. A1 and A2 piers are flexure failure, and A3 piers are flexure-shear failure. When the actuator is pushed forward, the direction is positive, and when pulled back, it is negative.

| Model number | Damage direction | Equivalent yield displacement | Ultimate displacement | Ultimate shear strength (kN) | Displacement ductility ratio | Failure mode |
|--------------|------------------|------------------------------|-----------------------|----------------------------|-----------------------------|--------------|
| A1           | negative         | 7.21                         | 70.18                 | 139.01                    | 9.74                        | Flexure      |
| A2           | positive         | 3.04                         | 35.75                 | 147.58                    | 11.76                       | Flexure      |
| A3           | negative         | 5.46                         | 24.60                 | 382.33                    | 4.51                        | Flexure-shear |

**4.2.1. Flexure Failure.** At the initial stage of loading, transverse cracks of the pier with flexure failure appear at the bottom of the pier front (plane A and C) and extend to the two sides. With the continuous loading, the cracks at the bottom of the pier are constantly widened, other pre-existing cracks develop slightly, and fewer new cracks are generated. In the process of further loading, transverse cracks at the bottom of the pier continue to widen, and other cracks widen slightly. The concrete at the bottom of the pier begins to spall gradually, and part of the reinforcement is bare. In the final stage of loading, the cracks at the bottom of the pier are rapidly developed, the steel bars are cracked, the bearing capacity is obviously decreased, and the specimens are destroyed. The destruction features of this kind of specimen are: there are few cracks in the pier body, and the width is small. The crack at the bottom of the pier develops rapidly and the crack width is large, and the final failure is the longitudinal reinforcement fracture. The prototype pier is the failure mode. **Figure 3** and **Figure 5** show the ultimate failure cracks of bridge piers A1 and A2.
The hysteretic curves of flexure failure types are plump and show good ductility. The hysteretic curves and skeleton curves of A1 and A2 piers are shown in Figure 4 and Figure 6 respectively.

4.2.2. Flexure-shear Failure. At the initial loading stage of the flexure-shear failure type model, transverse cracks were generated in the front of the pier (plane A and C), then the cracks continued to develop and extend to the side (plane B and D) of the pier. With the continued loading, there are only a few penetrating transverse cracks on the front of the pier, and the inclined cracks on the side of the pier gradually increase and widen. In the later stage of loading, the number of transverse cracks in the front of the pier body tends to be stable, but the crack width continues to increase and the concrete gradually bulges. The side of the pier body forms-shaped main oblique crack with an obvious "X", and the concrete has an outer drum, peeling off, the main steel bar buckling, the hoop outer drum, the bearing capacity of the pier is greatly reduced, and the specimen is destroyed. The destruction features of this kind of model are as follows: a large number of oblique cracks appear on the side when the transverse crack appears on the front of the pier body, and, the concrete in the plastic hinge area is crushed and peeled with hoops are bulging outside when the failure occurs. Figure 7 shows the ultimate failure cracks of bridge piers A3. The hysteretic curve of the flexure-shear failure type is obviously pinched, with poor ductility and a fusiform shape. The hysteretic curves and skeleton curves of A3 pier are shown in Figure 8.

4.3. Analysis of Shear Failure Mechanism
In this paper, the shear failure mechanism is obtained by analysing the shear behaviour of hoop and concrete. In the process of cyclic loading, there are two main roles of stirrup. One is to bear the shear force and improve the shear behaviour of the structure. The other is formed reinforcement cage with
the longitudinal reinforcement. It can not only effectively prevent the buckling of longitudinal reinforcement, but also effectively restrain the core concrete, so as to improve the mechanical behaviour of concrete. 

**Figure 9** and **Figure 10** show the change law of stirrup strain with loading grade for B and D of specimen A3 (typical shear failure) under forward and reverse loading respectively. According to the data in the figure and the failure phenomenon analysis of shear failure, the strain value of stirrup is relatively small or even negative before the longitudinal reinforcement yield. In other words, stirrups provide less shear capacity, or even coordinate with concrete compression. Now the shear capacity of piers is mainly provided by concrete. When the longitudinal reinforcement yields, with the displacement increasing continuously, the oblique crack develops rapidly, and the strain value of the stirrup which through the oblique crack increases rapidly and reaches the yield. While the restraint effect of core concrete decreases rapidly due to the sudden increase of stirrup strain, which leads to brittle shear failure of the specimen.

![Figure 9. Stirrup steel tension strains for A3 (positive loading).](image)

![Figure 10. Stirrup steel tension strains for A3 (negative loading).](image)

In the test, the total shear force on the pier is divided into two parts. One part is the shear bearing capacity provided by stirrup, which can be calculated from the data of strain gauge. The other part is the shear capacity of concrete, including the shear capacity provided by concrete, axial pressure and longitudinal reinforcement. The total shear force can be readout by the horizontal actuator, so the shear capacity of concrete can also be calculated. **Figure 11** shows the total shear of A3 and the change law of shear bearing capacity with displacement ductility ratio of each part. The same rule can be obtained for other specimens.

![Figure 11. The variation of stirrups and concrete shear contribution for A3.](image)

The epigraph vividly illustrates the change mechanism of shear capacity of pier specimens under repeated loading. Before the longitudinal bars yield, the inclined cracks are less developed, the stirrups hardly bear the shear force, or even coordinate with concrete compression, and the concrete bears
almost the shear force. When the longitudinal bars yield, the cracks develop rapidly. When the inclined crack which intersecting with stirrup is formed, the shear contribution provided by stirrup increases gradually, while the area of compression zone of core concrete decreases gradually due to the generation and development of cracks. Repeated shear slip makes the aggregate occlusion and frictional resistance at the crack reduce continuously, and with the gradual crush of concrete, the bolt removal effect of longitudinal reinforcement also decreases. All these make the shear contribution of concrete decrease gradually. Once the stirrup yields, the restraint on the core concrete is greatly weakened, and the shear contribution of concrete begins to decrease obviously. Meanwhile, the stirrup has reached the shear bearing capacity, which can no longer make up for the lack of shear bearing capacity of concrete. As a result, the bearing capacity of specimens decreases rapidly, and the failure of specimens presents brittle feature.

5. Conclusion
Based on the research background of "The seismic comprehensive test of Chenglan railway pier", this paper described the pseudo-static test scheme of reinforced concrete pier in detail, and then the results of the experiment were analyzed and summarized.

(1) According to the analysis of the pseudo-static test results of the Chenglan railway prototype piers (A1 and A2), it was indicated that both piers were typical bending failure, with sufficient ductility reserve. When the pier body cracked, the crack at the bottom of the pier developed rapidly and the crack width was large, and the final failure was the longitudinal reinforcement fracture.

(2) According to the analysis of A3 specimen, it was indicated that pier was typical flexure-shear failure. A large number of oblique cracks appeared on the side when the transverse crack appeared on the front of the pier body, and the concrete in the plastic hinge area produced crush and peel as well as bulging outside of hoops when the failure occurred.

(3) The mechanism of shear failure under cycling loading is as follows: Before loading to yield displacement, shear strength was provided by stirrup little, which was mainly provided by concrete. After loading to yield displacement, the shear strength provided by stirrup increased gradually with the development of cracks. When the stirrup yields, its restraint to the core concrete was weaken rapidly, which resulted in the rapid destruction of the bridge pier.

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