Accumulated Damage-based Experimental Study on Seismic Performance of HRBF500 Rebar Reinforced RC Bridge Columns

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Abstract. The evolution of the damage and seismic behaviour of the reinforcement concrete (RC) bridge columns reinforced with HRBF500 rebar was investigated in this paper. Nine bridge column specimens with various strengths of longitudinal reinforcement, reinforcement ratios, axial compression ratios and stirrup ratios were tested under horizontal cyclic loading. The influences of the designed parameters of the mechanical properties such as failure mode, loading-displacement curve, skeleton curve, strength and stiffness degradation and energy dissipation were analysed in the view of damage. There are four conclusions brought by the tested results. The damage process of specimens could be divided into turn-crack development stage, damage accumulation stage and failure stage. The damage will accumulate gradually and the strength and stiffness will also be degenerated, resulting in lower ductility and energy dissipation capacity of the specimens, as the displacement amplitude increases. The failure modes are similar, with plastic hinges occurrence varying from 30 to 260 mm above the concrete bases, accompanied by the steel buckling, fractured and the concrete local crushing. The good ductility and energy dissipation capacity of the HRBF500 reinforced concrete bridge columns are illustrated by the relatively plumper shuttle-shaped hysteresis curves obtained. The damage development was faster and energy was comparably larger of the specimens under the variation of displacement amplitude cycle loading, comparing with the constant displacement amplitude cycle loading. The bearing capacity of the specimens will be certain influenced by the increased reinforcement ratios and the larger energy dissipation capacity, with more longitudinal bars. The axial compression ratio also has an important influence on the damage development of the specimens. There are not considerable increments of bearing capacity, with the increment of reinforcement ratio, however, the ductility and energy dissipation ability will be improved obviously. The laws of damage development analysed by the experimental results were shown in this paper. The seismic damage assessment and seismic damage model of this kind of structural members were established by the experimental results above.

1. Introduction
The performance of the bridge piers, especially the seismic behaviour, is very important to the railway bridges construction. The bridges construction is a key part of Chinese high-speed railway network. There is a large proportion of Chinese high-speed railway constructed on the bridges, occupying an
average of more than 50%, and up to more than 90% for individual lines [1]. As a supporting structure of high-speed railway bridges, bridge piers must have high seismic performances. At present, HRB335 reinforcement with a lower strength are widely used as longitudinal reinforcement in Chinese high-speed railway reinforced concrete piers, while popular high strength reinforcement with a yield strength of 400 MPa or more in developed countries [2]. Thus, improving the strength of steel, which will bring in reduced amount of steel and in-situ construction, ensuring the quality of concrete pouring [3-4], and revealing a significant effort in environmental protection and sustainable development, is necessary.

Paper [5-14] have conducted some experimental researches and theoretical analyses of reinforced concrete piers. Many scholars at home and abroad have applied high-strength steel bars to concrete structures, mainly discussing the effect of stress of high-strength steel bars on the bearing capacity, ductility and crack width of structures or components. These researches were all conducted to study the basic seismic behaviour of ordinary concrete frame columns. However, the seismic behaviour of high-strength reinforced concrete columns, especially the damage evolution process, was hardly involved.

In order to investigate the failure process of high-strength reinforced concrete pillars under the earthquake action. Nine reinforced concrete piers, with different longitudinal reinforcement grades reinforcement ratio and axial compression ratios, were tested by low cycle repeated loading in this paper. By the experiments, the two main contributions were obtained. Firstly, The failure process was described in detail from the view of damage point. Secondly, the seismic behaviour, as well as the effects of damage on the mechanical properties of pier (including strength, stiffness and hysteretic energy) and the influence of different design parameters on component damage, were obtained by these experiments. The contribution make a considerable effort on the theoretical analysis and engineering implementation of HRBF500 steel bar in bridge engineering.

2. Introduction to the tests

2.1 Specimen design

Seven 500 ultra-fine grain reinforced concrete piers and two ordinary reinforced concrete pier comparison specimens were designed and manufactured. The specimens’ cross-sectional dimensions were all circular with diameters of 350 mm, the axial compression ratio were divided into four levels, such as 0.1,0.2,0.3,0.4. The HRBF500 and HRB335 longitudinal steel bars, as well as longitudinal reinforcement ratios of 0.94% and 1.67% were chosen. All the specimens were designed with the same parameters, such as the spiral stirrups of HPB235, the volumetric stirrup ratios of 0.295%. All the tested specimens were fabricated as down I-shaped with a height of the loading center to the bottom of 1.70m. The geometry and reinforcement of the test pieces are shown in Figure 1, the respective specific design parameters are shown in Table 1. Parameters of concrete and steel materials are shown in Table 2 and Table 3.

2.2 Loading scheme and Loading system

The experiments were carried out in the structural laboratory of Southeast University. The vertical axial force was applied by 100T-hydraulic jack. In order to reduce the friction between the reaction beam and the hydraulic jack, a permuterm was placed between them. The horizontal load was applied by 500kN-Electro-hydraulic Servo loading System. The loading head was connected with the actuator by the pull rods to reduce the interspace. The base of the specimens was fixed to the rigid ground by two ground anchors. Manual jacks were used to tighten the base and the reaction beam, so that no slip occured in the loading process. The test set-up is shown in Figure 2.
Table 1. Designed parameters of the specimens

| Specimen number | Longitudinal reinforcement | Stirrup | Concrete strength grade | Concrete cover thickness mm | Shear span ratio λ | Axial force N/kN | Designed axial compression ratio n_ρ/ % |
|-----------------|----------------------------|---------|-------------------------|--------------------------|------------------|----------------|---------------------------------------|
| C1-S12-0.2      | 8B12                       | 0.94%   | A6@100                  | 25                       | 4.86             | 304            | 0.2                                   |
| C2-S12F-0.2     | 8D^412                     | 0.94%   | A6@100                  | 25                       | 4.86             | 304            | 0.2                                   |
| C3-S16-0.2      | 8B16                       | 1.67%   | A6@100                  | 25                       | 4.86             | 304            | 0.2                                   |
| C4-S16F-0.2     | 8D^416                     | 1.67%   | A6@100                  | 25                       | 4.86             | 304            | 0.2                                   |
| C5-S12-0.1      | 8B12                       | 0.94%   | A6@100                  | 25                       | 4.86             | 152            | 0.1                                   |
| C6-S12F-0.1     | 8D^412                     | 0.94%   | A6@100                  | 25                       | 4.86             | 152            | 0.1                                   |
| C7-S12F-0.3     | 8D^412                     | 0.94%   | A6@100                  | 25                       | 4.86             | 456            | 0.3                                   |
| C8-S12F-0.4     | 8D^412                     | 0.94%   | A6@100                  | 25                       | 4.86             | 608            | 0.4                                   |
| C9-S16F-0.4     | 8D^416                     | 1.67%   | A6@100                  | 25                       | 4.86             | 608            | 0.4                                   |

* The number format of specimens in Table1 is C-S#F-n, where C stands for RC specimen, S stands for seismic performance tests, # stands for Longitudinal reinforcement diameter, F stands for HRBF500, and n stands for axial compression ratio.

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Table 2. Properties of concrete

| Concrete design strength | Average cube compressive strength f_{cu}/MPa | Average Axis Compressive Strength f_{c}/MPa | Elastic modulus E_c/MPa |
|-------------------------|---------------------------------------------|--------------------------------------------|------------------------|
| C30                     | 31.2                                        | 22.18                                      | 3.52×10^4             |

Load-displacement dual-control loading method were used. The whole loading process could divide into three steps. The stages could be marked as the relative time to the status of yielding. Firstly, before loading, the top axial load of the column was applied by the vertical jack and kept constant, then the top horizontal load of the column was applied. Secondly, before the yielding of the specimen, the loading was controlled by the horizontal load value, the load was increased by 10-kN in each stage, until it was close to yielding. Then, 5-kN of increment per stage was applied instead until complete yielding. Thirdly, after the yielding of the specimen, the horizontal displacement value was used to control the loading, the displacement steps take an integer multiple of the yielding
displacement value, each cycle was cycled three times until the specimen's carrying capacity drops below 85% of the peak load or there was significant damage to the piece to terminate the test.

### Table 3. Properties of reinforcement bars

| Category | Diameter d/mm | Yield strength $f_y$/MPa | Ultimate strength $f_u$/MPa | Elastic modulus $E_s$ / MPa | Ductility $\Delta$/% |
|----------|---------------|--------------------------|---------------------------|----------------------------|-------------------|
| HRBF500  | 12            | 539.5                    | 687.2                     | $2.00 \times 10^5$       | 20.0              |
|          | 16            | 545.1                    | 692.3                     | $2.00 \times 10^5$       | 17.9              |
| HRB335   | 12            | 367.5                    | 529.3                     | $2.00 \times 10^5$       | 27.8              |
|          | 16            | 367.1                    | 539.6                     | $2.00 \times 10^5$       | 25.7              |
| HPB235   | 6             | 354.5                    | 447.3                     | $2.10 \times 10^5$       | 24.8              |

2.3 The main test content

The main test contents included: crack width and development, horizontal load and displacement on loading end, displacement at the trisection points of columns and base displacement.

3. Analysis of test results

3.1 The characteristics and process of specimen damage

In the experiment, when the horizontal load reached 20% of the maximum load $P_{max}$, subtle horizontal cracks appeared in the tensile zone at the root of the specimen for distances within 20-300 mm from the bottom of the column. As the load continued to increase, the original horizontal cracks developed and extended to produce horizontal cracks in higher positions, and gradually extended to the non-loading surface, the cracks were basically connected at the column root. When the specimen yielded, the loading is replaced by displacement control loading. As the displacement increases and the reciprocating cycle, no more new cracks appear, the original crack width continues to increase, the damage continues to accumulate, the concrete sends out splitting sound, the concrete protective layer begins to crush and fall, and the bearing capacity has a certain degree of decline. During the late loading, large areas of concrete at the root fall off, the longitudinal ribs become buckling and show outer drum, the core of the concrete were crushing, longitudinal ribs of some specimens show rupture. Longitudinal bar buckling, fractures were located above the base about 10cm, which is because the concrete base of the column root has a certain constraint, causing the destruction of the surface moving up. In summary, all the specimens have a typical bending failure (Figure 3), the damage processes were relatively slow, the extreme displacements were quite large, the specimens showed with good deformation capacity and hysteresis energy dissipation.

The hysteresis curve of each test piece measured in this test is shown in Figure 4. It can be seen from the figure that the hysteresis curve of each test piece has the following characteristics:

1) The hysteretic loop of the specimen with high strength reinforcement is similar to that of the specimen with ordinary steel bar. Before the specimen reaches yield, the slope of the loading curve changes little, the residual deformation of the specimen after unloading is also very small, and the hysteresis loop is not obvious; after the specimen is yielded, the area of the hysteresis loop gradually increases, and it basically exhibits a fusiform shape, showing good plastic deformation and energy consumption; the slope of the loading curve decreases as the displacement increases, and the stiffness of the specimen degrades; under each displacement, the bearing capacity of the test piece decreases with the increase of the number of cycles, and the strength of the test piece degrades;
2) The damage accumulation of the specimen is heavily influenced by the axial compression ratio. The hysteresis loop of the specimen will show a pretty full fusiform shape, when the axial compression ratio is relatively small. The stable attenuation of strength and stiffness, large ultimate deformation and good ductility and energy dissipation capability will be shown, with the lasting load, when the maximum horizontal bearing capacity (peak load) has been reached. On the contrary, although the specimens with high axial compression ratio have full fusiform shape hysteresis loops after the peak load, the stability of the hysteresis curve is poor, the attenuation of strength and stiffness are shifted down rapidly, and the ultimate deformation and load cycles are obviously smaller than the specimens with low axial compression ratio. The main reason is that the increased P-Δ effect caused by the increased displacement amplitude will lead to further accumulation of specimen damage, under the action of higher axial force;

3) The better performance, such as decreased attenuation of strength and stiffness, the fuller hysteresis loop, the good ductility, and the enhanced accumulative energy dissipation capacity, will be realized, with the increase of the stirrup ratio after the peak load, under the same conditions.

3.2 The Skeleton Curve
The skeleton curve refers to the envelope formed by the peak point of the first cycle of each loading stage of the specimen load-displacement hysteresis curve, which can reflect the damage process of the component under repeated loading. Figure 5 shows the comparison of the skeleton curves of the test pieces in this test. $F_{cr}$, $F_y$ and $F_{max}$ are the cracking load, yielding load and maximum load of the test piece, respectively, and $\Delta_{cr}$, $\Delta_y$ and $\Delta_{max}$ are their corresponding displacements.
3.3 The Hysteresis Curve

![Hysteresis Curves](image)

Fig. 4 Hysteretic loops of specimens

1) It can be seen from the above skeleton curve that the damage of each test piece is a gradual evolution and accumulation process, which can be roughly divided into three stages: non-destructive (elastic) stage, stable growth of damage (work with crack), a period of rapid growth (destruction) of damage;

2) With the increase of longitudinal reinforcement ratio, the horizontal bearing capacity of the specimen is improved, and the decline of the descending section is also reduced. Especially when the large axial compression ratio is applied, the bearing capacity is significantly improved;

3) With the increase of the spacing of the stirrups, the bearing capacity of the specimens decreases, but the extent of the decrease is small. Therefore, increasing the spacing of the stirrups has little effect on the bearing capacity of the piers;

4) A test piece with an axial compression ratio of 0.2 has a higher horizontal load carrying capacity than a test piece of 0.1, and the rigidity in the elastic and strengthening stages is increased, and the strengthening stage is lengthened. With the increase of the displacement amplitude, due to the buckling of the longitudinal steel bars and the spalling of the concrete, the force-displacement curve...
will have a falling section, and the larger the axial compression ratio, the larger the falling extent of the falling section.

**Figure 5.** Skeleton curves of specimens

### 3.4 Bearing Capacity and Ductility

The ductility refers to the inelastic deformation ability of the structure without significant degradation of the initial strength. The displacement ductility coefficient $\mu_{\Delta}$ is usually used to measure the ductility of the pier column structure, which is defined as the ratio of the ultimate load to the yield displacement.

The measured values of cracking load, yielding load, yielding displacement, maximum load and ultimate displacement obtained from the skeleton curve of each test piece are shown in Table 4. The limit displacement takes the corresponding displacement of the specimen to the maximum load of 85%. It can be seen from the table that the displacement ductility coefficients of all the test pieces are not less than 4.0 and have good ductility.

The following is a detailed analysis of the effects of different parameters on the bearing capacity and ductility of the test piece:

1) Test pieces C1, C2 and C3, C4 with the same reinforcement ratio, test pieces C2 and C4 with high-strength steel bars are respectively increased by 24.7%, 22.1%, and the ultimate load of the test pieces C1 and C3 of the common stock steel bar. Increased by 19.5%, 17.8%, but its limit displacement decreased by 11.4 and 9.7%, respectively. It shows that the high-strength steel bar can increase the bearing capacity of the pier, but the deformation capacity is reduced;

2) Comparing the test pieces C2 and C6 with different reinforcement ratios, the yield load and ultimate load of the latter were increased by 12.1% and 12.4%, and the ultimate displacement was reduced by 6.8%. It shows that with the increase of the reinforcement ratio, the yield load and ultimate load of the specimen are improved, but the deformation capacity is decreased.
3) Comparing the stirrup ratios of different specimens, the cracking load, yielding load and peak load of the two specimens are very close, but the ductility coefficient of the specimen C8 is 32.2% higher than that of C2. It is indicated that the addition of the stirrup in the plastic hinge area of the pier can greatly improve the deformation capacity of the pier.

3.5 Stiffness Degradation
The average stiffness $K$ of the test piece under a certain displacement is calculated according to the following formula:

$$K = \frac{1}{nu} \sum_{j=1}^{n} F_{j,i}$$

(1)

$F_{j,i}$—the $j$-th stage displacement loading, the $i$-th cycle peak point load value;

$u_j$—the $j$th displacement control value;

$n$—The number of cycles at the same displacement.

In order to study the influence of different factors on the stiffness of the pier column, the average stiffness degradation curves of each test piece were compared, as shown in Figure 6. As can be seen from the figure:

1) The stiffness degradation law of high-strength steel specimens is similar to that of ordinary steel specimens. The average stiffness decreases with the increase of loading displacement, and the degradation curve is smoother; at the initial stage of loading, the stiffness decreases rapidly, and the stiffness degradation is relatively small in the later stage, and the degradation rate shows a decreasing trend.

2) Increasing the reinforcement ratio and increasing the axial compression ratio can increase the stiffness of the pier column. The effect of increasing the axial compression ratio is the most significant, and the increase of the hoop ratio has little effect on the stiffness of the pier column.

4. Conclusions
In this paper, through the experimental study of damage of high-strength reinforced concrete piers and columns under low-cycle repeated loading, the following main conclusions are drawn:

1) Under low cyclic repeated loading, high strength reinforced concrete piers with shear span ratio of $\lambda > 3.0$ usually suffer bending failure, and the hysteretic loops of the specimens are full shuttle-shaped, which indicates that they have good energy dissipation capacity and ductility. The damage process of piers can be divided into three stages: non-destructive, stable damage growth and rapid damage growth.

2) The seismic behavior of reinforced concrete piers with HRBF500 steel bars is basically the same as that of reinforced concrete piers with HRB335 steel bars, and the seismic performance is good.

3) With the increase of cycle number and displacement amplitude, the damage of high-strength reinforced concrete pier gradually accumulates, which makes its strength and stiffness deteriorate, energy dissipation capacity and ultimate deformation capacity decrease.
4) With the increase of axial compression ratio, the strength and stiffness of high-strength reinforced concrete piers decrease rapidly, the energy dissipation capacity decreases, and the ductility decreases.

5) With the increase of reinforcement ratio and stirrup ratio, the peak load of high-strength reinforced concrete piers increases, and when the peak load reaches, the strength and stiffness attenuation of members decreases, and the cumulative energy dissipation capacity increases.

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