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Experimental study on seismic behaviors of concrete columns confined by corroded stirrups and lateral strength prediction

Li Qiang [a,*], Niu Di-tao [b], Xiao Qian-hui [a], Guan Xiao [a], Chen Shao-jie [a]

[a] Department of Civil Engineering and Architecture, Xi'an University of Science and Technology, Xi'an 710054, China
[b] Department of Civil Engineering, Xi'an University of Architecture & Technology, Xi'an 710054, China

HIGHLIGHTS

- Low-reversed cyclic loading tests were carried out on eight corroded reinforced concrete columns to study their mechanical characteristics and failure mechanisms. The test results are analyzed in detail, and the research on the decline in the seismic performance of concrete columns confined by corroded stirrups has been carried out for the first time.
- A method for predicting the lateral strength of reinforced concrete columns confined by corroded stirrups is presented based on the axial-shear-flexure interaction approach for conventional concrete columns, with modifications to consider the effect of stirrup corrosion. There was good agreement is achieved between the test results and theoretical values. For the first time, the established model introduces the corrosion parameters of the stirrup.

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ABSTRACT

To understand the seismic behaviors of concrete columns confined by corroded stirrups, low-reversed cyclic loading tests were carried out on eight corroded reinforced concrete columns to study their mechanical characteristics and failure mechanisms. The influence on seismic performance indicators such as bearing capacity, hysteresis characteristics, ductility, strength degradation, stiffness degradation, and energy dissipation was analyzed comparatively based on parameters such as stirrup diameter and stirrup-spacing changes. The experimental results showed that the restraint of concrete provided by corroded stirrups is reduced, which leads to a decline in seismic performance, and with increasing stirrup corrosion, the failure limit displacement of columns decreases. The pinch phenomenon of the hysteresis curve gradually increases, the attenuation degree of strength and stiffness increases, and the ductility and energy-dissipation capacity is reduced, while the accumulated energy increases under the same control displacement. A method for predicting the lateral strength of reinforced concrete columns confined by corroded stirrups is presented based on the axial-shear-flexure interaction approach for conventional concrete columns, with modifications to consider the effect of stirrup corrosion. There was good agreement is achieved between the test results and theoretical values.

1. Introduction

Traditional architectural design and construction management systems consider each stage of building separately. In many structures, this results in serious defects, poor performance, low durability, and short service life among other things. Consistent with the life-cycle concept, estimates of durability and residual life have become an important research area of structural engineering [1–4].

Due to long-term effects of carbonation, freeze-thaw cycles, and other factors, reinforcements in concrete structures will exhibit different degrees of corrosion damage, which leads to degradation of structural bearing capacity and ductility, and serious corrosion will threaten the security of a structure. Therefore, the degradation of concrete structures due to corrosion cannot be ignored. Progress has been made in the study of the seismic performance of reinforced concrete columns subject to corrosion [5–7]. Corrosion in the joint part of the stirrups and their transverse reinforcement is rather serious, but the effect of stirrup corrosion has been ignored. Not only does the established restoring force model not introduce the parameters of stirrup corrosion, but the preexisting analysis of the mechanism of the decline in seismic performance after stirrup corrosion has not been carried out. After a stirrup corrodes, its mechanical performance and confinement of the core

* Corresponding author.
E-mail address: liguanqiang2005@126.com (Q. Li).

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concrete and transverse reinforcement decline, which leads to a decrease in the bearing capacity and stiffness of reinforced concrete columns and a change in the failure pattern from ductile fracture to brittle failure, which could even lead to the sudden collapse of a structure. Therefore, the degradation effect of stirrup corrosion on the bearing capacity of reinforced concrete columns is greater than that of the corrosion of transverse reinforcement. The study of the influence of stirrup corrosion on mechanical performance of concrete columns has just begun, and research on the decline in the seismic performance of concrete columns confined by corroded stirrups has not been carried out.

In this paper, low-reversed cyclic loading tests have been carried out for eight corroded reinforced concrete columns to study their mechanical characteristics and failure mechanisms. The influence on seismic performance indicators such as bearing capacity, hysteresis characteristics, ductility, strength degradation, stiffness degradation, and energy dissipation have been analyzed comparatively using parameters such as stirrup diameter and stirrup spacing. A lateral strength-prediction method is proposed for reinforced concrete columns confined by corroded stirrups.

2. Test survey

2.1. Model design and production

The comparison test designed eight reinforced concrete columns, whose thickness of the concrete cover is 15 mm. The section size and reinforcements are shown in Table 1.

Specimens were cast by pouring them into molds in wooden templates. To avoid transverse reinforcement corrosion, measures were taken to isolate the transverse reinforcement and stirrups, and a wire with a 4-mm diameter was connected to the corroded stirrups. They were vertically cast to ensure unique concrete specimens.

2.2. Material performance

The design strength of concrete Specimens is C25, and the basic performance is shown in Table 2. Specimens' transverse reinforcements using HRB335 steel, stirrups using HPB235 steel, the basic mechanical performance is shown in Table 3.

2.3. The corrosion rate of specimen' stirrups

The numerical corrosion rate is the average stirrups' corrosion rate within the scope of bottom plastic hinge area. The numerical corrosion rate of all specimens is shown in Table 4.

Table 1
Dimensions and reinforcement of specimens.

Specimen	Size/mm	Reinforcement/mm	Stirrup/mm
RC-1	200 × 200	6ϕ14	ϕ8@70
RC-2	200 × 200	6ϕ14	ϕ8@70
RC-3	200 × 200	6ϕ14	ϕ8@70
RC-4	200 × 200	6ϕ14	ϕ8@70
RC-5	200 × 200	6ϕ14	ϕ8@90
RC-6	200 × 200	6ϕ14	ϕ8@90
RC-7	200 × 200	6ϕ14	ϕ8@120
RC-8	200 × 200	6ϕ14	ϕ8@120

Table 2
Fundamental properties of concrete and blocks.

Material types	Bulk density/ kN/m^3	Compressive strength/ MPa	Elastic modulus/ MPa
C25	33.85	50.3	3.0×10^4

Table 3
Basic mechanical properties of reinforcement.

Grade	Diameter	Yield strength	Ultimate strength	Elastic modulus	Elongation
HPB235	8 mm	292 MPa	515 MPa	2.19×10^5	25.6%
HRB335	14 mm	359 MPa	552 MPa	1.97×10^5	18.8%

Table 4
Stirrups corrosion rate of all specimens.

Component	Average weight loss rate	Maximum weight loss rate
RC-1	0	0
RC-2	4.76%	4.76%
RC-3	12.90%	30.65%
RC-4	22.22%	46.49%
RC-5	9.23%	36.53%
RC-6	13.96%	46.87%
RC-7	15.55%	34.49%
RC-8	16.69%	48.39%

2.4. Test method and loading system

Seismic test methods [8,9] were used in the low-reversed cyclic loading test, and cantilever loading equipment was adopted, as shown in Fig. 1.

A vertical load with a fixed value of 200 kN was applied to the top of the column by a jack.

The horizontal load was applied to the upper column by means of a reaction frame with the help of hydraulic actuators.

The loading mechanism used a force-displacement hybrid control. First, the yield adopted the load-control and step-loading method; each stage of loading was 10 kN, and each stage was repeated once. After adopting displacement control, the amount of each displacement increase was a multiple of the yield displacement, and each stage of displacement was repeated three times, with the test terminating when the specimen could not bear axial pressure. The test loader is shown in Fig. 2.

3. Experimental results and analysis

3.1. Failure mode and mechanism analysis

The damage to all specimens occurred at the bottom plastic hinge area of the column, which experienced elastic, elastic-plastic, and failure stages. The ultimate destruction is shown in Fig. 3. To summarize, before the horizontal load reaches 40% of the ultimate load, the column is in the elastic state, where the load curve and the unloading curve coincide to a straight line. When the load reaches 60–70% of the ultimate load, minor cracks appear in the roots, and surface cracks of the component develop continuously with the increase of the horizontal load. When the load reaches 80–90% of the ultimate load, concrete cracks develop rapidly, and the concrete cover falls off gradually. At the ultimate stage, the external drum of reinforcements appears at the root of the specimen, the core area of the concrete is crushed, and members cannot bear the horizontal load.

The major damage feature points of each component, distribution of load steps, and surface-crack morphology during the test are shown in Table 5, and the final failure modes are shown in Table 6.

Table 5 shows that the loading step of each failure characteristic point of RC-2 is the same for RC-1, but the loading step of final destruction is postponed longer for RC-2 than for RC-1. This is because the bond between stirrups and concrete becomes stronger when the stirrups corrode slightly, which not only improves the