Research on Safety Assessment of Residual Bearing Capacity of Reinforced Concrete Columns Considering Accumulated Damage

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Abstract. This article focuses on conducting research on the residual bearing mechanical performance of reinforced concrete column components with accumulated damage. By analyzing the essence of the current mainstream Park-Ang cumulative damage index, considering the influence of loading amplitude and cyclic load frequency, a component cumulative damage index under constant amplitude hysteresis loading is proposed. Based on the laws reflected by the residual bearing capacity of undamaged components and cumulative damaged components under hysteresis loading, a safety assessment model for residual bearing capacity suitable for this type of component has been established.

Keywords: cumulative damage; residual strength; Reinforced concrete columns.

1 Introduction

In performance-based design methods, reasonable damage indicators are needed to measure structural performance, which can not only reflect the external damage performance of the structure, but also accurately unify the damage mechanism and establish effective connections with various design parameters. The consistent view among domestic and foreign scholars [1,2] on the failure mechanism of buildings is that the degree of failure of structural components does not depend on the maximum displacement recorded under earthquake action, but also on the number of load cycles and the absorbed hysteresis energy. Based on this, the damage indicators can be distinguished into cumulative damage indicators and non-cumulative damage indicators based on the existence of cyclic load conditions [3-9]. In the analysis of the degree of minor and moderate damage to frame structures, Wang Xinling[10] introduced a coordination coefficient to define a new damage index based on the definition of damage parameters based on relative stiffness.

Four specimens were selected for this experiment. One specimen was only subjected to monotonic loading tests, while the other three specimens were subjected to constant

G. Zhao et al. (eds.), *Proceedings of the 2023 5th International Conference on Civil Architecture and Urban Engineering (ICCAUE 2023)*, Atlantis Highlights in Engineering 25,
https://doi.org/10.2991/978-94-6463-372-6_30

amplitude hysteresis loading tests under different loading amplitudes. The hysteresis curve of the experiment is shown in Figure 1. Based on the experimental results, a hysteresis restoring force model 2 and a residual bearing capacity deformation prediction model Figure 2-3 are proposed. Furthermore, a formula for calculating the cumulative damage index of components under constant amplitude hysteresis loading and a safety assessment model for residual bearing capacity are established.

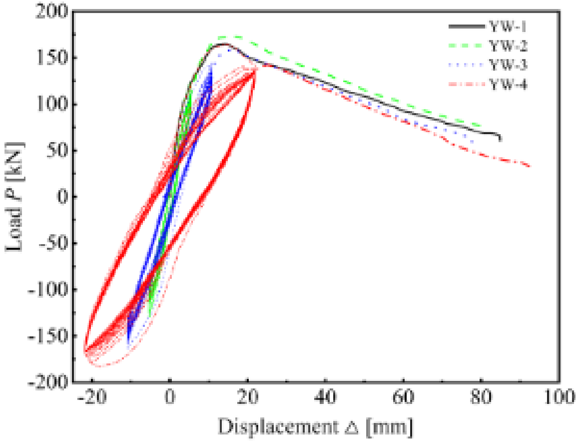

Fig. 1. Load-displacement curves before and after component damage

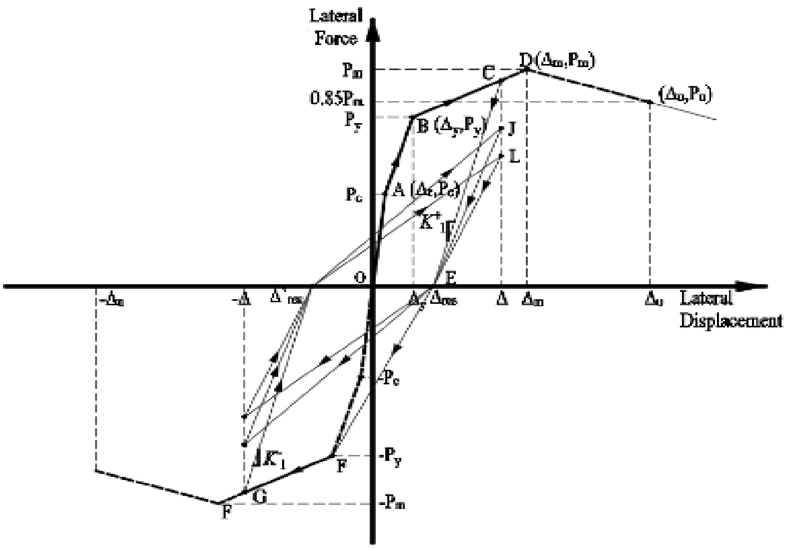

Fig. 2. Constant amplitude hysteretic force-restoring model

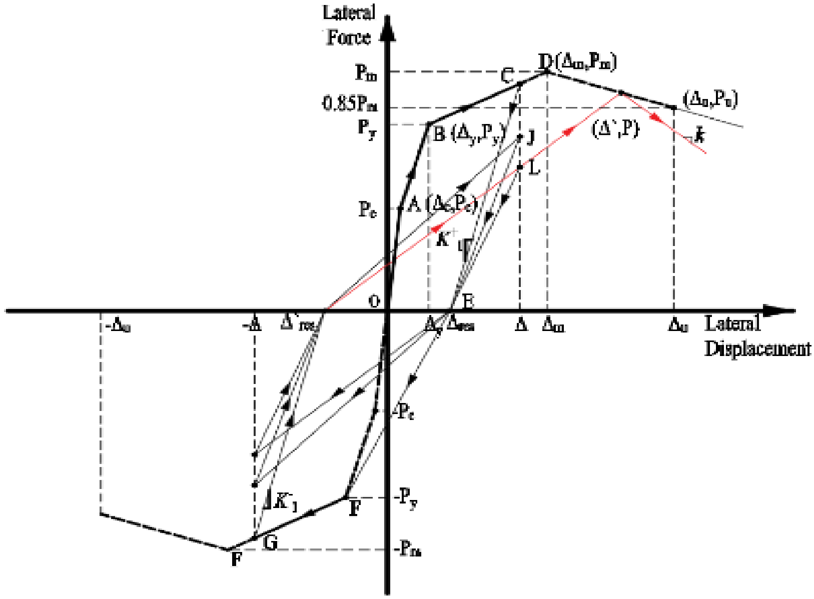

Fig. 3. Residual capacity-deformation curve model

2 Definition of cumulative damage index under constant amplitude hysteresis loading

2.1 Analysis of damage indicators

At present, the most representative failure criterion considering cumulative damage at home and abroad is the dual parameter criterion including displacement and dissipative energy proposed by Park and Ang et al., as follows:

$$D = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u P_y} \int dE \tag{1}$$

It cannot be ignored that there are certain defects in this indicator. But according to experimental analysis, it can be known that under a certain loading amplitude, the fatigue life of the component can reach several thousand or even tens of thousands of times. As shown in Figure 4, the component undergoes certain damage in the first cycle. As the number of cycles increases, the dissipated energy of the component continues to increase, and the damage value also continues to increase. Therefore, it is necessary to establish a new method of measuring damage that is more suitable for this loading situation.

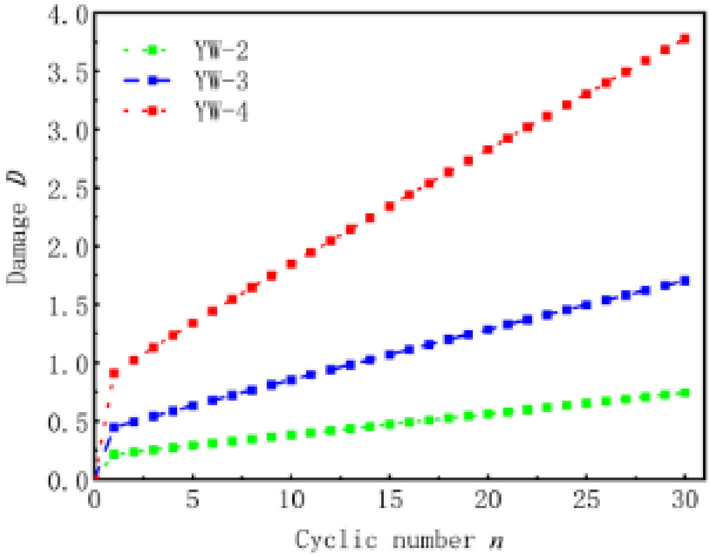

Fig. 4. Park-Ang damage index of each specimen

We have mentioned earlier that the cumulative damage index should comprehensively consider the effects of displacement and dissipated energy, but in essence, it is to reflect the degradation of component performance, that is, the greater the displacement, the more severe the degradation of component performance, and the greater the damage; The more load cycles, the greater the dissipated energy, and the more severe the degradation of component performance, resulting in greater damage. So, as long as a damage index value is established that can reflect the performance degradation of the component, it can better measure the damage situation of the component.

2.2 Definition of damage indicators

Firstly, when the damage index of the component reaches 1.0, it is considered that the component has failed. Similarly, it is believed that when the bearing capacity of a component decreases to 85%, the component fails. Therefore, this article proposes equation (2) as a damage indicator to measure the performance of components.

$$D = \frac{E_n}{E_m} \tag{2}$$

E_n refers to the positive periodic energy dissipation of the component after n cycles, as shown in the shaded area in Figure 5. E_m refers to the dissipated energy of plastic strain when the component reaches the ultimate displacement Δ_u under monotonic loading, as shown in the shaded area in Figure 6.

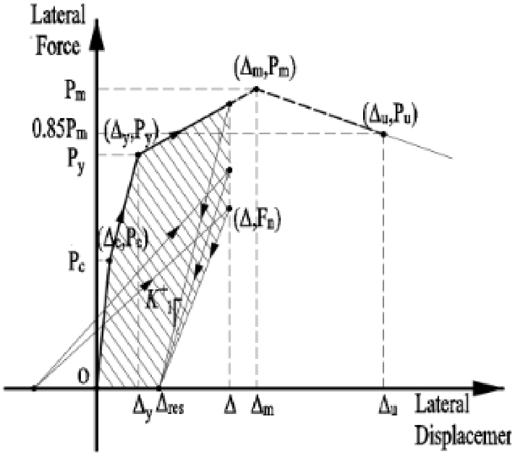

Fig. 5. Dissipated energy En

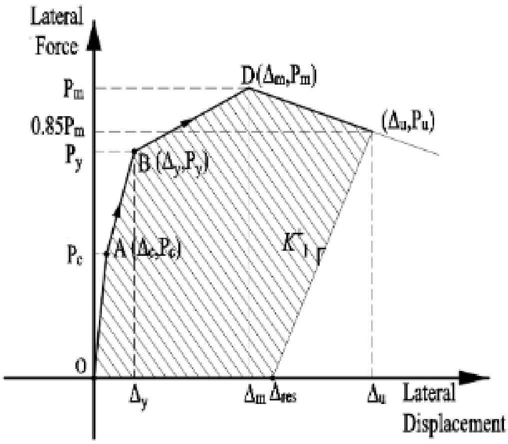

Fig. 6. Dissipated energy Em

Although equation (2) appears to only consist of dissipated energy of components, in reality, the calculation of dissipated energy En comprehensively considers the influence of component displacement and the number of cyclic loads. Firstly, the calculation of En requires determining the loading amplitude of the component, as well as the gradual degradation of the component strength to Fn as the number of cyclic loads increases. Taking the experimental components in this article as an example, the cumulative damage values of each component after hysteresis loading under corresponding loading amplitudes are calculated. The calculated damage values of each component are shown in the following figure 7.

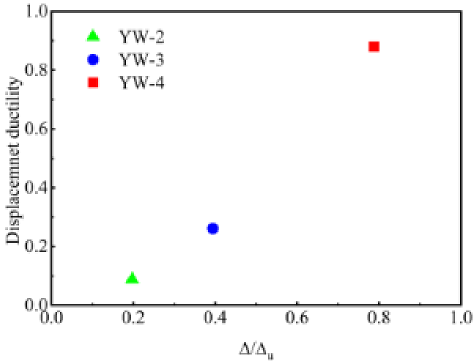

Fig. 7. Damage value of components at the end of hysteretic loading

3 Establishment of a safety assessment model for residual bearing capacity

In actual engineering structure detection and evaluation, the most intuitive and convenient measurement results are the deformation and crack situation of the component. Therefore, this article will distinguish the performance of the component into four stages based on the relationship between loading amplitude and residual bearing capacity.

3.1 No damage stage

When the component is not cracked and has little deformation, it is considered that the component is still in the elastic stage, the performance of the component does not deteriorate, and the remaining bearing capacity is the same as the peak bearing capacity of the undamaged component. At this point, the component is in the undamaged stage.

3.2 Damage development stage

When the hysteresis loading amplitude of the component is large, the residual bearing capacity of the component significantly deteriorates. In this, there must be a limit value for the development of component damage, so that when the loading amplitude of the component is less than this value, the remaining bearing capacity can be considered not to deteriorate. This article defines this limit value as damage limit Δ_{danage}, and the corresponding cumulative damage value is D_{danage}. Therefore, when $\Delta_r < \Delta < \Delta_{damage}$, the component is in the stage of damage development, but the residual bearing capacity of the component does not deteriorate. The schematic diagram of the residual bearing capacity deformation curve of the component in monotonic failure loading test is shown in the following figure 8.

$$\Delta_{damage} = c_1 \Delta_u W_n \left\{ \frac{b_1\left(\Delta_m - \Delta'_{res}\right)}{c_1 \Delta_u} e^{-\left[\frac{\Delta'_{res} + a_1\left(\Delta_m - \Delta'_{res}\right)}{c_1 \Delta_u}\right]} \right\} + a_1 \Delta_m + \left(1 - a_1\right)\Delta'_{res} \tag{3}$$

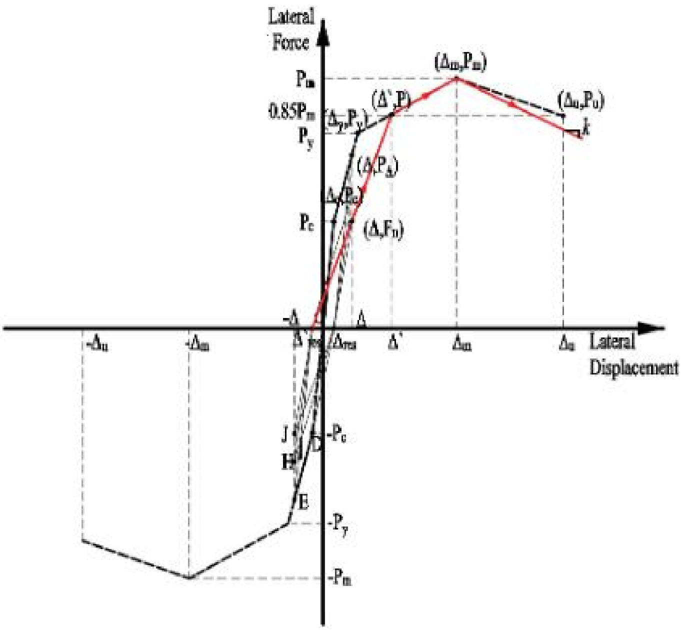

Fig. 8. Damage development stage

3.3 Performance degradation stage

Correspondingly, during the gradual degradation of component performance, there must also be a component failure limit $\Delta_{failure}$, which causes the residual bearing capacity of the component to fail. Calculate the corresponding cumulative damage value $D_{failure}$ according to equation (2). When $\Delta_{damage} < \Delta < \Delta_{failure}$, the component is in the stage of performance degradation. At this stage, the remaining bearing capacity $P < P_m$ of the component usually exhibits significant crack width and length development, concrete surface cracking and detachment, and steel yielding. It is shown in figure 9.

$$\Delta_{failure} = c_1 \Delta_u W_n \left\{ \frac{P_m b_1\left(\Delta_u - \Delta'_{res}\right)}{P_u c_1 \Delta_u} e^{-\left[\frac{P_u \Delta'_{res} + P_m a_1\left(\Delta_m - \Delta'_{res}\right)}{P_u c_1 \Delta_u}\right]} \right\} + \frac{P_u \Delta'_{res} + P_m a_1\left(\Delta_u - \Delta'_{res}\right)}{P_u} \tag{4}$$

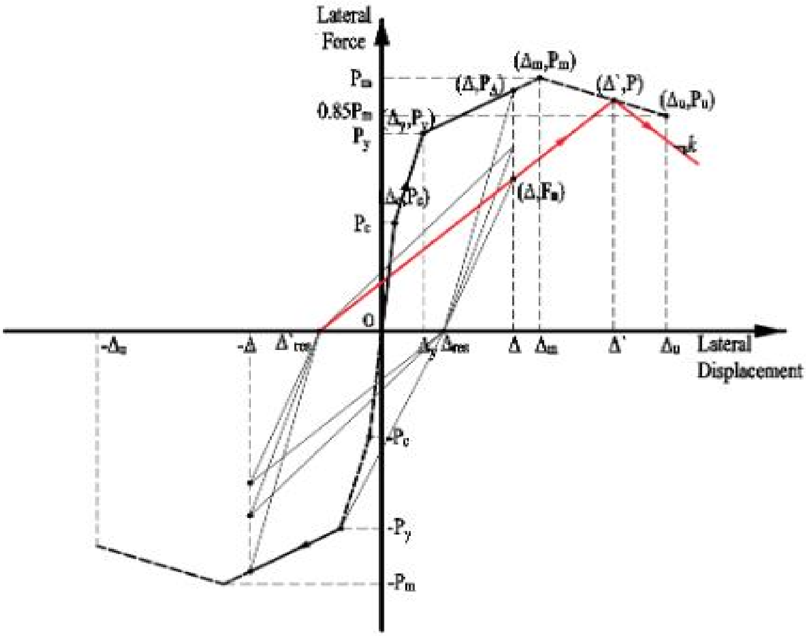

Fig. 9. Performance degradation stag

3.4 Failure stage

It is generally believed that when the bearing capacity of a component decreases to 0.85 times the peak bearing capacity, it is considered that the component has failed. At this point, the crack width and length of the component are already very obvious, accompanied by the crushing and detachment of large blocks of concrete, so $\Delta > \Delta_{failure}$ is divided into the component failure stage.

In summary, the safety assessment model for residual bearing capacity considering cumulative damage effects is shown in Figure 10.

$$\begin{cases} P = P_m, 0 \le \Delta < \Delta_{damage} \\ P_{degeneration} = \dfrac{P_m(\Delta_u - \Delta_m) - (\Delta_m - \Delta'_{res})(P_u - P_m)}{F_n(\Delta_u - \Delta_m) - (\Delta - \Delta'_{res})(P_u - P_m)} F_n, \Delta \ge \Delta_{damage} \end{cases} \quad (5)$$

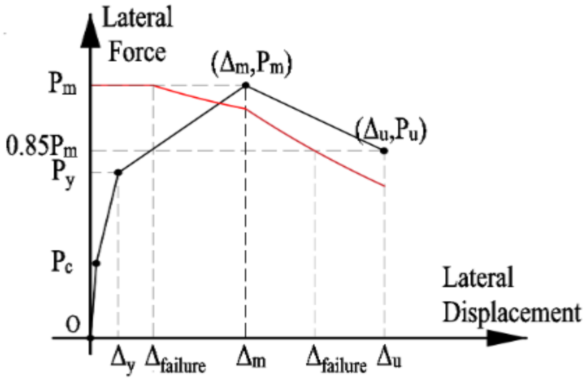

Fig. 10. Safety assessment of the residual capacity of specimens

4 Model verification

Based on the above safety assessment model, it is possible to estimate the remaining bearing capacity of components under certain deformation conditions. Force to achieve the purpose of evaluating the performance of components.

According to the comparison of the results of equal amplitude hysteresis loading using the hysteresis force recovery model, it was found that at 10.92mm, the intersection point of the rising segment of the residual load-deformation curve of the component and the skeleton curve is already very close to the peak point. So, $\Delta_0 = 10.92$ can be used as the starting point and brought into the model for iteration to obtain $\Delta_1 = f\left(\Delta_0\right)$, $\Delta_2 = f\left(\Delta_1\right)$ ... After iteration, $\Delta_{damage} \approx 10.33mm$ can be obtained. Similarly, $\Delta_{failure} \approx 25.88mm$ is obtained. It is shown in figure 11.

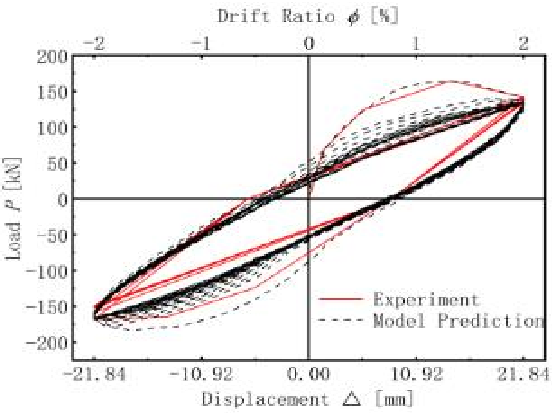

Fig. 11. Comparison of hysteretic loading results

When the displacement deformation is $11.80\text{mm}<\Delta<25.88\text{mm}$, the safety limit of the remaining bearing capacity under the corresponding displacement can be calculated according to equation (5). The calculation results are shown in Table 1.

Table 1. The results error analysis of residual capacity

Component number	displacement /mm	Results /kN	Model calculation results /kN	error
YW-2	5.46	178.12	164.51	8.3%
YW-3	10.92	159.29	163.70	2.7%
YW-4	21.84	142.38	146.22	2.6%

From the table, it can be found that the residual bearing capacity of the YW-2 component measured through experiments is 178.12kN, which is slightly higher than the peak bearing capacity of the component of 164.51kN. The reason may be the discreteness of the concrete. The tested residual bearing capacity of YW-3 and YW-4 components is lower than the predicted residual bearing capacity of the model. This is because there is usually a small arc in the measured curve near the peak point, which slows down the rate of increase in component bearing capacity. However, according to the error analysis of the comparison between the calculation results and experimental results in Tables 1, it can be seen that the error of YW-3 and YW-4 results is only 2.7% and 2.6%, indicating that the calculated results based on this model have a certain degree of reliability.

5 Conclusion

The safety evaluation of the component performance in this experimental study using this model has a small error, and the model has a certain degree of correctness and reliability. In actual engineering structures, if structural components undergo deformation, the corresponding residual bearing capacity can be calculated based on the characteristic parameters and deformation of the components to determine whether they still meet the engineering bearing requirements, in order to achieve the purpose of safety assessment. Considering the limited data obtained from experimental research, the safety assessment model for residual bearing capacity established in this chapter may have certain limitations in practical application. However, there is still great room for improvement in this model, and further research can obtain more applicable models by increasing experimental data. At the same time, it provides a good implementation idea and method for establishing a safety assessment model for residual bearing capacity.

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