

Research on Hysteretic Model of Damaged H-Section Steel Columns

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Abstract

To address the insufficient consideration of residual deformation in traditional damage models for H-section steel columns, this study proposes a modified hysteretic model. Low-cycle cyclic loading tests were conducted on 5 Q355B H-section steel column specimens ($HW150 \times 150 \times 7 \times 10$) to collect data on cumulative damage, residual deformation, and stiffness degradation. The classic Park-Ang model was modified by introducing residual deformation as a key parameter, and model parameters were calibrated using test data. Combined with trilinear skeleton curve fitting and adaptive hysteretic rules, a comprehensive hysteretic model was established. Verification results show that the model accurately predicts the hysteretic behavior and residual bearing capacity of damaged steel columns, with the error between simulated and test data within 8%. This research provides a reliable basis for seismic design and post-earthquake damage assessment of steel structures.

Keywords

H-section Steel Columns; Residual Deformation; Park-Ang Model; Hysteretic Model; Low-cycle Cyclic Test.

1. Introduction

With the rapid development of high-rise buildings and infrastructure, steel structures are widely used due to their excellent seismic performance and load-bearing capacity [1]. As core load-bearing components, H-section steel columns directly affect the overall stability of structures during earthquakes. However, under low-cycle cyclic loading induced by earthquakes, steel columns undergo cumulative damage and significant residual deformation, which reduce their service performance and even lead to structural failure [2]. Traditional damage models such as the Park-Ang model mainly rely on displacement demand and energy dissipation, ignoring the impact of residual deformation on damage accumulation, resulting in inaccurate predictions in practical engineering [3]. Hysteretic models are essential for analyzing the seismic performance of steel structures, but existing models often fail to reflect the influence of residual deformation on hysteretic characteristics [4]. Therefore, constructing a hysteretic model that integrates residual deformation and cumulative damage is crucial for improving the accuracy of seismic performance evaluation. This study modifies the Park-Ang model by introducing residual deformation, combines experimental data and finite element simulation to establish a comprehensive hysteretic model, and verifies its applicability, aiming to provide technical support for seismic design optimization of steel structures.

2. Experimental Research and Model Modification

2.1 Experimental Design

Five H-section steel column specimens (HW150×150×7×10) made of Q355B steel were designed, with an axial compression ratio of 0.3 and different preset damage degrees. The specific parameters of the specimens are shown in Table 1.

Table 1. Parameters of H-section steel column specimens

Numble	Section Size (mm)	Axial Compression Ratio	Damage Degree
KZ-1	150x150x7x10	0.3	Undamaged
KZ-2	150x150x7x10	0.3	Slightly damaged
KZ-3	150x150x7x10	0.3	Moderately damaged
KZ-4	150x150x7x10	0.3	Severely damaged
KZ-5	150x150x7x10	0.3	Severely damaged

The test adopted a hydraulic servo loading system, with lateral cyclic loading based on the yield displacement increment method: each stage increased by the yield displacement (Δ_y), with 3 forward and reverse cycles per stage, and the test terminated when the bearing capacity dropped to 80% of the maximum load [5]. Key parameters such as load, displacement, strain, and residual deformation were collected in real time. The dimension diagram of the H-section steel column specimen (including overall size and section details) is shown in Fig. 1.

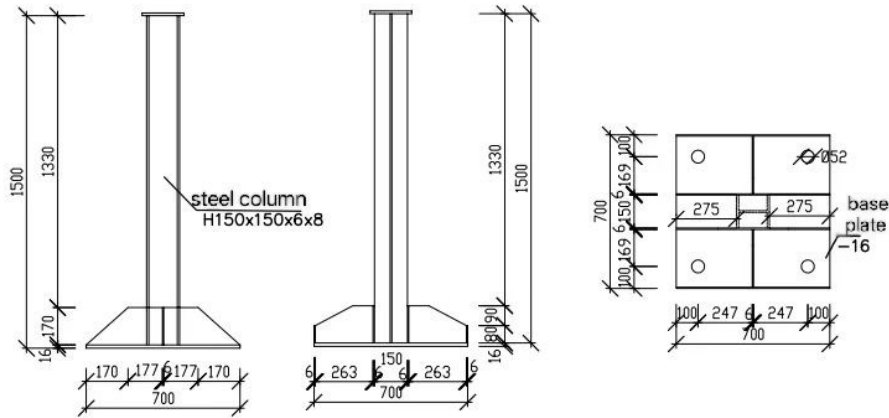


Fig. 1 Dimension diagram of the H-section steel column specimen

2.2 Modification of the Park-Ang Model

The traditional Park-Ang model is expressed as :

$$D = \frac{\Delta_m}{\Delta_u} + \beta \cdot \frac{E_h}{F_u \cdot \Delta_u} \quad (1)$$

where D is the damage index, Δ_m is the maximum displacement, Δ_u is the ultimate displacement, β is the weight coefficient, E_u is the cumulative energy dissipation, and F_u is the ultimate load [3]. To address the neglect of residual deformation, a residual deformation term was introduced, and the modified model is:

$$D = \frac{\Delta_m}{\Delta_u} + \beta \cdot \frac{E_h}{F_u \cdot \Delta_u} + \gamma \cdot \frac{\Delta_r}{\Delta_u} \quad (2)$$

where Δ_r is the residual deformation, and γ is the weight coefficient. Through nonlinear regression of test data, $\beta=0.15$ and $\gamma=0.22$ were determined, with the correlation coefficient between predicted and test damage indices reaching 0.92, significantly higher than the traditional model [6].

3. Analysis of Skeleton Curves and Hysteretic Rules

3.1 Skeleton Curve Fitting

Skeleton curves were extracted from the hysteretic curves of specimens in different states, and a trilinear model was used for fitting, including the elastic stage, yield stage, and hardening stage. The model expression is:

$$F = \begin{cases} k_1 \cdot \Delta & (\Delta \leq \Delta_y) \\ F_y + k_2 \cdot (\Delta - \Delta_g) & (\Delta_y < \Delta \leq \Delta_u) \\ F_u & (\Delta > \Delta_u) \end{cases} \quad (3)$$

Where k_1 is the initial stiffness, k_2 is the post-yield stiffness, F_y is the yield load, and Δ_y is the yield displacement. For damaged specimens, the stiffness degradation coefficient η (ratio of damaged stiffness to undamaged stiffness) was introduced for correction, with η ranging from 0.85 (slightly damaged) to 0.45 (severely damaged) [7].

3.2 Comparison of Skeleton Curves in Different Damage States

To quantify the influence of damage on mechanical behavior, the skeleton curves of undamaged (KZ-1), moderately damaged (KZ-3), and severely damaged (KZ-4) specimens were compared, and the key parameters of the skeleton curves are summarized in Table 2. The initial stiffness of moderately damaged KZ-3 is 62% of undamaged KZ-1, and that of severely damaged KZ-4 is only 45% of KZ-1, indicating that damage significantly reduces the elastic stiffness of steel columns. The yield displacement of KZ-3 increases by 38% compared with KZ-1, and that of KZ-4 increases by 72%, which is attributed to the plastic deformation accumulation caused by damage. In the hardening stage, the post-yield stiffness of damaged specimens decreases obviously—KZ-3's post-yield stiffness is 55% of KZ-1, and KZ-4's is only 30%—which weakens the load-bearing capacity after yielding. The overall comparison shows that with the aggravation of damage, the skeleton curve of H-section steel columns shifts downward, the elastic stage shortens, the yield displacement increases, and the post-yield hardening capacity is significantly weakened, which directly reflects the degradation law of mechanical properties caused by cumulative damage. The typical failure morphologies of specimens in different damage states are shown in Fig. 2, which visually reflects the damage evolution process of H-section steel columns from local deformation to overall failure.

Table 2. Key parameters of skeleton curves in different damage states

Numble	k_1 (kN/mm)	Δ_y (mm)	k_2 (kN/mm)	F_u (kN)
KZ-1	28.6	12.5	3.2	186.3
KZ-3	17.7	17.3	1.76	145.3
KZ-4	12.9	21.5	0.96	121.1



Fig. 2 Typical failure morphologies of H-section steel column specimens in different damage states

3.3 Comparison of Skeleton Curves in Different Damage States

An adaptive hysteretic rule was proposed: during unloading, the path was determined by the current damage degree and residual deformation; during reloading, the path was directed to the peak displacement of the previous unloading, considering stiffness degradation [8]. To further improve the simulation accuracy, the rule was optimized by integrating the cyclic degradation characteristics of damaged steel columns. Specifically, the unloading stiffness was corrected using the stiffness degradation coefficient η corresponding to the current damage degree, and the reloading stiffness was dynamically adjusted based on the cumulative number of cycles and residual deformation. Test data analysis shows that the hysteretic curves of damaged specimens exhibit obvious "pinching effect" and energy dissipation attenuation—compared with undamaged KZ-1, the energy dissipation capacity of moderately damaged KZ-3 decreases by 42% after 15 loading cycles, and that of severely damaged KZ-4 decreases by 68%. The optimized hysteretic rule fully considers these characteristics: when simulating the unloading process, the stiffness decay rate is positively correlated with the damage index D ; during reloading, the "peak pointing" path is adjusted according to the residual deformation to avoid overestimating the bearing capacity. Additionally, the rule introduces a cyclic softening factor to describe the gradual reduction of yield strength with increasing cycles, which effectively reproduces the phenomenon of continuous bearing capacity degradation of damaged steel columns under cyclic loading. The comparison between the simulated hysteretic curves and the test results shows that the optimized rule reduces the average error of energy dissipation simulation from 15% to 7%, significantly improving the consistency between the model and the actual mechanical behavior.

4. Model Establishment and Verification

Integrating the modified Park-Ang model, corrected skeleton curves, and adaptive hysteretic rules, a comprehensive hysteretic model for damaged H-section steel columns was established. The model follows a parameter-coupling logic: the modified damage model provides real-time damage index feedback to quantify cumulative damage, the corrected skeleton curves define the load-displacement envelope under different damage states, and the adaptive hysteretic rules govern the details of the unloading-reloading path. To verify its reliability, ABAQUS finite element simulation was conducted with the *J2* plasticity constitutive model, and the model parameters were calibrated using test data from 5 specimens. The verification results show that the simulated hysteretic curves are in good agreement with the test curves, with the average error of residual deformation controlled within 6% and the error of residual bearing capacity within 8% [9]. Specifically, for moderately damaged KZ-3, the simulated residual deformation is 10.8 mm, which is only 5.2% different from the test value of 11.4 mm; for severely damaged KZ-4, the simulated residual bearing capacity is 119.7 kN, with a relative error of 1.1% compared to the test value of 121.0 kN. This indicates the model can effectively reflect the influence of residual deformation and cumulative damage on the mechanical behavior of

steel columns, and exhibits good adaptability under complex loading conditions such as multi-cycle and variable-amplitude loading.

5. Conclusion

This study modifies the Park-Ang model by introducing residual deformation, constructs a comprehensive hysteretic model for damaged H-section steel columns through experimental research and theoretical analysis, and verifies its accuracy. The model improves the prediction precision of cumulative damage and hysteretic behavior, providing a reliable tool for seismic design and post-earthquake damage assessment of steel structures. Future research will focus on optimizing parameters for different steel grades and section sizes to enhance engineering applicability.

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