International Core Journal of Engineering Volume 11 Issue 6, 2025
ISSN: 2414-1895 DOI: 10.6919/ICJE.202506_11(6).0014

Research on Seismic Performance of Damaged Steel Columns

Hao Li[a], Jie Xiang[b], and Ziwei Wu[c]
Central South University of Forestry and Technology, Changsha 410004, China
[a]2597827865@qq.com, [b]1747295464@qq.com, [c]1622446936@qq.com

Abstract

Due to its advantages such as light weight, high strength, good seismic performance, and uniform material properties, steel structures have been widely used in various engineering structures. However, steel structures may suffer damage or even failure during service due to fire, corrosion, earthquakes, ice-snow disasters, wind disasters, or other abnormal service loads. In the 1994 Northridge earthquake in the United States and the 1995 Kobe earthquake in Japan, some steel frame structures still exhibited damage and failure of varying degrees, which prompted people to reconsider the seismic performance of steel structures. Damage can lead to the degradation of the mechanical properties of steel structures. Whether these damaged steel structures can meet normal stress requirements? Is reinforcement necessary? Or should they be demolished and rebuilt? These issues affect the rational disposal decisions for damaged steel structures and are related to people's property safety, which have always been the focus and difficulty in disaster prevention and mitigation work. A large number of studies have shown that damage will cause significant degradation of mechanical properties such as strength, stiffness, and energy dissipation capacity of components and structures, seriously affecting the bearing capacity, stiffness, stability, and seismic performance of steel structures. As the main load-bearing component, the steel column transfers the dead load (self-weight) of the superstructure, live load (service load), and additional loads (such as equipment loads) to the foundation in the form of axial force, bending moment, and shear force, forming a complete load transfer path. In seismic design, steel columns are often designed as ductile energy-dissipating components, which absorb seismic energy through local plastic deformation (such as flange buckling and web shear yielding) to avoid brittle failure of the structure. Through the synergistic effect of the column's own flexural stiffness and the frame joints, they resist the shear force and bending moment generated by horizontal wind loads and seismic actions, maintaining the overall stability of the structure. Under seismic action, once a steel column is damaged, its mechanical properties will degrade, and even cause floor collapse, seriously threatening building safety.

Keywords

H-shaped Steel Column; Damage; Low-cyclic Reversed Loading Test.

1. Research Background and Significance

Due to its unique advantages such as diversified structures, low-carbon emissions, and mechanized construction, steel structure buildings have always been the first choice for countries to construct large-span, large-space, super-high-rise, and singular buildings. The Shanghai World Expo Park, which has attracted worldwide attention, brings together many creative and varied steel structure buildings, including huge sports venues such as the Bird's Nest and the Water Cube. Their peculiarly shaped peripheral structures can almost only be realized by using steel structures. For super-high-rise

ISSN: 2414-1895 DOI: 10.6919/ICJE.202506_11(6).0014

buildings such as the CCTV Building, the Shanghai World Financial Center, and the Jinmao Tower, in order to reduce the huge load and enable the buildings to stand firm, all of them choose steel structures with light weight and high strength as their main load-bearing systems.

However, while the steel structure is developing rapidly, steel structure accidents occur frequently. Due to the inherent defects of steel, the processing and manufacturing defects of steel components, the connection defects of steel structures, the installation, use, and maintenance defects of steel structures, as well as extreme environments such as hurricanes, blizzards, earthquakes, and temperatures, the damage to the structure accumulates to a certain extent, leading to sudden events such as collapses. These accidents have caused major casualties and economic losses in various countries.

At present, the failure modes of steel frame structures under seismic actions are mainly analyzed from two perspectives: the perspective of first-passage failure analysis and the perspective of cumulative damage failure analysis. In China, the seismic research mainly focuses on the first type of failure mode. However, due to the frequent occurrence of earthquakes in recent years, whether the damaged structures can still meet the normal use requirements and whether they can withstand the impact of a second disaster has gradually attracted people's attention.

2. Research Status

2.1 Research on Seismic Performance of Steel Columns

Elkady et al.[1] established empirical expressions to estimate functions of geometric parameters and load parameters based on finite element simulation results of over 50 wide-flange steel columns under cyclic loading, thereby proposing seismic design recommendations to maintain column stability. Qin et al.[2] analyzed the failure modes, bearing capacity, hysteretic performance, ductility, and hysteretic energy dissipation of steel columns using finite element analysis, considering the influence of parameters such as flange width, web height-thickness ratio, and axial compression ratio. They proposed a hysteretic model and skeleton line degradation model for the load-displacement of corroded H-shaped steel members under cyclic loading. Hai et al.[3] developed a finite element model considering ductile fracture behavior and cyclic softening behavior to simulate cyclic loading tests of high-strength steel columns, and conducted parameter-varying analyses on axial compression ratio, flange width-thickness ratio, and web height-thickness ratio. Youde et al.[4] conducted accelerated corrosion tests and cyclic loading tests on 7 H-shaped steel columns and 20 steel plates to study the effects of corrosion on their mechanical properties and seismic performance. Keyang et al.[5] tested 10 steel columns under cyclic loading, analyzed their seismic performance based on hysteretic curves, energy dissipation capacity, etc., and proposed a ductility-based design method. Li et al.[6] carried out low-cycle reciprocating loading tests and finite element analyses on three types of H-shaped steel columns: ordinary steel columns, steel columns with sliding friction connections with cover plates at the lower end, and steel columns with sliding friction connections with cover plates at both the upper and lower ends, investigating the influence of different constraint modes on their seismic performance.Chen Yiyi et al.[7] carried out pseudo-static tests on 10 specimens to address the insufficient plastic energy dissipation capacity of high-frequency welded H-shaped steel columns due to large width-thickness ratios, and established a control criterion for component bearing capacity degradation under rare seismic actions. Li Haifeng et al.[8-9] conducted numerical simulation studies on the seismic performance of box-shaped steel columns under eccentric variable axial force loading at the column top, systematically analyzing the influence of axial force changes on their seismic performance. They proposed that the influence of axial force changes on the seismic performance of box-shaped steel columns should be fully considered in the seismic design of box-shaped steel columns for long-span spatial structures.

2.2 Research on Damage of Steel Columns

Cyclic loading can cause fatigue damage in steel. The failure process is as follows: Weak points (such as impurities and damage) inside the steel form stress concentrations under repeated sustained loads, leading to significant plastic deformation in these areas and the generation of micro-cracks. As the cracks continue to propagate, when the sectional stress exceeds the bonding force of steel grains, the steel will undergo brittle fracture. The fatigue strength of steel is not closely related to its inherent strength but is influenced by factors such as the number of load cycles, the surface condition of components, the surface condition of welds, stress concentration, residual stress, and weld defects.

Damage refers to the process of microstructural changes in materials under various external actions such as loads and corrosion. It is specifically manifested as the initiation, propagation, and convergence of micro-defects, which in turn lead to the degradation of the material's macroscopic mechanical properties, and may ultimately result in the formation of macroscopic cracks or even overall failure[10]. As an important branch of solid mechanics, damage mechanics has developed rapidly since the 1980s and achieved many research results. However, early theoretical research and practical applications of damage mechanics mostly focused on the materials themselves. In recent years, within the scope of engineering practice, people have paid increasing attention to the damage of steel columns in various aspects, and many achievements have been made in this field.

Fogarty et al.[11] studied the strength and stability of locally damaged steel columns through an analytical model and calculation method of the Rayleigh-Ritz technique, and evaluated the effects of damage location, damage degree, initial defects, and asymmetric damage on the stability of steel columns. Kang et al.[12] developed a damage index and proposed an evaluation method for damage caused by local buckling in steel columns by studying the failure process of steel columns under strong and repeated loads and using an analysis method involving damage-related factors. Wang Rui et al.[13] took hot-rolled H-shaped steel columns as the research object, carried out comparative tests on the axial bearing performance of damaged and intact specimens, and established a functional expression between this parameter and the component buckling deformation parameter, providing a basis for evaluating the residual bearing capacity of impact-damaged steel components. Ding Yang et al.[14] studied the damage characteristics of constrained steel columns under indoor explosion loads, constructed a pressure-impulse-time (P-I-t) surface analysis model for evaluating the failure process of constrained steel columns under the combined action of explosion and fire, and derived the corresponding mathematical expressions. Tian Li et al.[15]studied the blast resistance of H-shaped steel columns under the coupled action of near-field explosion shock waves and prefabricated fragments, using nonlinear finite element methods to simulate the damage effects of explosion loads and fragment impacts on steel columns. Zhou Longyun[16] established a finite element model for explosive damage analysis of steel structures, analyzed the horizontal displacement and residual bearing capacity of steel columns, and further proposed a basis for determining the damage status of steel columns and divided the damage grades of steel columns. Yang Mingfei et al.[17] studied the influence of local pitting defects on the bearing performance of H-shaped steel columns, and analyzed the eigenvalue buckling and nonlinear post-buckling characteristics by numerical simulation. It was found that the mass loss rate could be used to evaluate the safety of H-shaped steel columns with local pitting damage.

3. Contents of this Study

This paper employs a combination of low-cycle reversed loading tests on damaged steel columns, finite element numerical simulations, and theoretical analysis to investigate the seismic performance of damaged steel columns. Through the tests, the deformation behavior and failure modes of damaged steel columns under cyclic loading are studied to determine whether their deformation and stiffness meet the serviceability requirements. The ABAQUS finite element software is used for simulation. After validating the reliability of the finite element model, parametric analyses are carried out to explore the key factors influencing the seismic performance of damaged steel columns.

The mechanical properties of steel under a single tensile load at room temperature and static loading conditions are the most representative. Tensile tests are relatively easy to conduct, and standard test methods and multiple performance indicators can be readily specified. Material property tests involve

ISSN: 2414-1895 DOI: 10.6919/ICJE.202506_11(6).0014

gradually applying a tensile load at a specified loading rate under room temperature and static loading conditions until the specimen elongates and fractures. Standard plate specimens are analyzed to determine key parameters such as the elastic modulus, yield strength, yield strain, ultimate tensile strength, ultimate strain, elongation, and necking ratio of the steel. These parameters provide essential inputs for experimental data analysis, finite element calculations, and theoretical modeling.

Given that this study focuses on the seismic performance of steel columns after an initial earthquake, the damaged steel column tests are equivalent to the first cycle of low-cycle reversed loading tests. Five steel column specimens of identical dimensions were designed. Four undamaged specimens were subjected to the first cycle of low-cycle reversed loading to induce different levels of damage corresponding to various yield states. The fifth specimen was tested to failure under low-cycle reversed loading.

The four damaged steel columns with varying degrees of damage were then subjected to a second cycle of low-cycle reversed loading until failure. Since the columns had already yielded, each loading step was repeated three times. The experimental data, including hysteretic curves, skeleton curves, and energy dissipation capacity, were systematically and compared.

Numerical simulations of the tested specimens were performed and validated against the experimental results to ensure the reliability and accuracy of the numerical models. Parametric analyses were conducted to evaluate the feasibility of damaged steel columns withstand subsequent seismic actions.

Based on the numerical and theoretical analyses, a restoring force model for damaged steel columns under seismic loading was developed and compared with the experimental results.

4. Conclusion

This paper systematically studies the seismic performance degradation laws and seismic damage evolution characteristics of damaged H-shaped steel columns under seismic actions through a combination of model tests, finite element numerical simulations, and theoretical analysis. Low-cycle reciprocating tests were conducted on three damaged H-shaped steel columns. The failure process of the tests was that the flange first underwent local buckling, formed a plastic hinge at failure, and the bearing capacity decreased to failure with a slow failure process, belonging to ductile failure. The ABAQUS finite element analysis software was used for verification and parametric analysis. The results show that when the flange width-thickness ratio increases, the stiffness ratio, ductility coefficient, ultimate displacement, and energy dissipation coefficient decrease; when the web height-thickness ratio increases, the hysteretic energy and yield limit capacity decline; an excessively large axial compression ratio weakens the seismic capacity, leading to a decrease in bearing capacity and limited plastic development.

References

[1] Elkady A, Lignos G D. Improved Seismic Design and Nonlinear Modeling Recommendations for Wide-Flange Steel Columns. Journal of Structural Engineering, Vol. 144 (2018).

[2] Qin G, Lan T, Qin Q, et al. Degradation Model and Evaluation Criteria for the Seismic Behavior of Corrosion H-section Steel Column. KSCE Journal of Civil Engineering, Vol. 23 (2019) No. 8, p. 3694-3705.

[3] Hai L, Wang Y, Li G, et al. Numerical investigation on cyclic behavior of Q690 high strength steel beam-columns. Journal of Constructional Steel Research, Vol. 167 (2020) p. 105814-105814.

[4] Youde W, Tao S, Biao N, et al. Seismic performance of steel columns corroded in general atmosphere. Steel and Composite Structures, Vol. 40 (2021) , 217-241.

[5] Keyang N, Lu Y, Huiyong B. Seismic Performance of Welded Stainless Steel H-Section Columns under Cyclic Horizontal Loading. Journal of Structural Engineering, Vol. 147 (2021).

[6] Li Y C, Huang S, Hu P Y, et al. Seismic performance of H-shaped steel columns with slip friction connections at column ends. Journal of Constructional Steel Research, 2024, 217108664.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202506_11(6).0014

[7] Chen Yiyi, Ma Yue, Zhao Jing, et al. Experiment and seismic bearing capacity evaluation of thin and flexible high-frequency welded H-shaped steel column. Journal of Tongji University (Natural Science), Vol. 11 (2006), p. 1421-1426.

[8] Li Haifeng, Luo Yongfeng, Li Dezhang, et al. Mechanical performance analysis and seismic design recommendations for box-shaped steel columns. (Journal of Building Structures Press, China 2013), Vol 34(01), p. 93-100.

[9] Li Haifeng, Luo Yongfeng, Chen Lincong, et al. Influence of axial force variation on seismic performance of box-shaped steel columns. (Journal of Southwest Jiaotong University Press, China 2014), Vol 49(03), p. 425-431.

[10] Yu Shouwen, Feng Xiqiao. Damage Mechanics. Beijing: Tsinghua University Press, 1997, p. 1-6.

[11] Fogarty J, Yossef N M, El-Tawil S. Collapse resistance of locally damaged steel columns. Journal of Constructional Steel Research, Vol. 82 (2013), 195-202.

[12] Park Y S, Kang D H. Method for evaluating damage caused to steel columns by local buckling. KSCE Journal of Civil Engineering, Vol. 22 (2018), 3592-3599.

[13] Wang Rui, Guo Zhaosheng, Pei Chang. Experimental study on the influence of local buckling deformation damage on the vertical residual bearing capacity of H-shaped steel columns. (Building Structure Press, China 2014),Vol 44(21), p. 17-22.

[14] Ding Yang, Chen Ye, Shi Yanchao. Damage assessment of constrained steel columns under combined indoor explosion and fire effects. (Journal of Vibration and Shock Press, China 2017), Vol. 36(05), p. 79-86.

[15] Tian Li, Zhang Hao. Analysis of damage effects on H-shaped steel columns under combined shock wave and prefabricated fragment action. (Journal of Tongji University Press, China 2018), Vol 46(03), p. 289-299.

[16] Zhou Longyun, Shi Lei, Xu Lingyu, et al. Rapid assessment of damage grades of H-shaped steel columns under explosive impact. (Journal of Disaster Prevention and Mitigation Engineering Press, China 2019), Vol. 39(05), p. 851-857.

[17] Yang Mingfei, Wang Xin, Chen Yiwang, et al. Study on the bearing capacity of H-shaped steel columns with local pitting damage. (Journal of Disaster Prevention and Mitigation Engineering, China 2021), Vol 41(05), p. 1020-1027.