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Research Progress on the Seismic Behavior of Weak-Axis Beam-to-Column Connections of H-Shaped Steel Columns

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Abstract

Weak-axis beam-to-column connections of H-shaped steel columns are important force-transferring components in steel frame structures, and their mechanical behavior directly affects structural load-carrying capacity, deformation capacity, and seismic safety. Compared with strong-axis connections, weak-axis connections mainly transfer beam-end moments through the column web and its adjacent region. Owing to the relatively low out-of-plane stiffness of the column web and insufficient restraint of the panel zone, these connections are prone to local deformation, stress concentration, insufficient rotational stiffness, and uncertain plastic development. With the development of prefabricated steel structures and low- to mid-rise steel residential buildings, the seismic behavior of weak-axis connections has attracted increasing attention. This paper reviews existing studies from the aspects of experimental research, finite element analysis, moment-rotation relationship models, and new connection configurations. Previous studies show that end plates, T-shaped connectors, U-shaped connectors, I-shaped plates, column-tree splices, reduced beam sections, and local strengthening measures can improve load-transfer paths, enhance rotational stiffness and energy dissipation capacity, and move plastic deformation away from the column face. However, unified design methods, restoring force models, and prefabricated details still require further investigation.

Keywords

H-Shaped Steel Column; Weak-Axis Connection; Beam-To-Column Joint; Semi-Rigid Connection; Seismic Behavior; Moment-Rotation Relationship

1. Introduction

Steel frame structures have been widely used in industrial buildings, public buildings, and prefabricated steel residential buildings because of their light self-weight, rapid construction, standardized components, and flexible spatial arrangement. Beam-to-column connections are key regions for force transfer, plastic

deformation, and energy dissipation under earthquake action. Therefore, their load-carrying capacity, rotational stiffness, ductility, and energy dissipation capacity are closely related to the overall seismic performance of steel frames.

Beam-to-column connections of H-shaped steel columns can be divided into strong-axis and weak-axis connections. Strong-axis connections mainly transfer beam-end moments through column flanges, and their load-transfer mechanism and design methods are relatively mature. In contrast, weak-axis connections usually transfer moments through the column web or additional connecting components. Since the column web has relatively low out-of-plane stiffness, weak-axis connections are more likely to suffer from local deformation and stress concentration.

After the Northridge earthquake, extensive research was carried out on welded steel moment connections, reduced beam section connections, end-plate connections, and prequalified seismic connections[1-4]. However, compared with strong-axis connections, studies on weak-axis connections remain limited. With the development of prefabricated steel structures and damage-controllable structural systems, weak-axis connections have gradually become an important research topic. A systematic review of existing studies is therefore helpful for clarifying their mechanical behavior and future development.

2. Research Progress on Weak-Axis Beam-to-Column Connections

2.1. Experimental Studies

Experimental research is the basis for understanding the mechanical behavior and failure modes of weak-axis connections. Early studies mainly focused on beam-to-column web moment connections, angle connections, T-shaped connector connections, and conventional welded connections. Rentschler et al[5]. tested beam-to-column web moment connections and analyzed local force transfer through the column web. Janss et al[6]. investigated the strength and deformation behavior of in-plane weak-axis joints and three-dimensional joints.

de Lima et al[7]. studied minor-axis semi-rigid beam-to-column connections through tests and mechanical modeling. Their results showed that weak-axis connections should not always be simplified as pinned connections, because many of them still possess certain moment resistance and rotational stiffness. Gilton and Uang[8] investigated weak-axis reduced beam section connections under cyclic loading and found that properly designed RBS details could move plastic deformation away from the column face.

Kim et al[9]. compared several weak-axis connection forms of H-shaped columns, including T-shaped connectors, end-plate connections, and bracket connections. They pointed out that local deformation of the column web strongly affects connection stiffness and strength. Shim et al[10]. proposed a weak-axis column bending connection with improved constructability. Oh et al[11-13]. studied

column-tree weak-axis connections and showed that proper beam splice details can make plastic hinges form away from the joint core.

Recent studies have focused more on end-plate bolted connections, cover-plate strengthened connections, and prefabricated weak-axis connections. Lu et al[14-16]. investigated composite action, cover-plate strengthening, and novel weak-axis RBS connections. Peker et al[17]. studied weak-axis moment connections with European steel profiles. Existing tests indicate that typical failure modes include column web deformation, weld cracking, end-plate bending, bolt elongation, yielding of connecting plates, beam-end plastic hinge formation, and local buckling of column flanges.

2.2. Finite Element Analysis

Because experimental studies are costly and parameter ranges are limited, finite element analysis has become an important method for studying weak-axis connections. With proper material models, contact settings, bolt pretension, weld constraints, boundary conditions, and mesh discretization, finite element models can simulate moment-rotation curves, stress distribution, plastic development, and failure modes.

de Lima et al[7]. established finite element models to study the influence of column web thickness and local strengthening on semi-rigid weak-axis connections. Kim et al[9]. combined tests and theoretical analysis to evaluate the strength of weak-axis connections, indicating that tensile bolts, connector stiffness, and column web deformation jointly influence connection behavior. Xu and Hao[18] analyzed weak-axis connections with I-shaped plates and found that this configuration could reduce stress concentration near the beam-to-column interface.

More recent finite element studies have focused on new connection configurations. Nie et al[19]. proposed an end-plate connection using a U-shaped connector and showed that the U-shaped connector, together with the column flanges and web, could form a box-like joint region and improve weak-axis panel zone stiffness. Vatansever and Kutsal[20] studied I-shaped adapters combined with reduced beam sections, while Yılmaz[21] proposed a weak-axis end-plate connection with a T-adapter.

Overall, finite element analysis helps reveal the internal stress distribution and plastic development of weak-axis connections. However, for bolted end-plate connections, bolt-hole clearance, contact slip, friction, and cyclic degradation should be carefully considered. Otherwise, the calculated hysteresis loops may be overly full, and slip or pinching behavior may be underestimated.

2.3. Moment-Rotation Relationship and Calculation Methods

The moment-rotation relationship is essential for evaluating the semi-rigid behavior of weak-axis connections. The total rotation of a weak-axis connection may include

out-of-plane bending of the column web, deformation of connecting plates, end-plate bending, bolt elongation, contact slip, and beam-end deformation. Therefore, its moment-rotation curve usually exhibits obvious nonlinearity.

Eurocode 3 adopts the component method for joint design, in which a joint is divided into several basic mechanical components and the overall joint behavior is obtained by combining the stiffness and resistance of these components[22]. Based on this concept, de Lima et al[7]. included weak-axis-specific components such as column web bending in their model, providing a useful reference for the calculation of weak-axis semi-rigid connections.

For end-plate bolted connections, Ghobarah et al[23]. studied extended end-plate connections under cyclic loading. Sumner and Murray[24] further investigated stiffened extended end-plate moment connections and showed that end-plate thickness, bolt arrangement, and stiffener configuration significantly affect connection strength, stiffness, and ductility. These studies provide useful references for weak-axis end-plate connection modeling.

At present, most moment-rotation models are still based on ordinary semi-rigid or strong-axis connections. For weak-axis connections with shifted end plates, U-shaped connectors, T-adapters, or I-shaped plates, further studies are needed to consider column web deformation, prying action, bolt slip, and plastic hinge relocation.

2.4. New Connection Configurations and Strengthening Measures

To improve the performance of weak-axis connections, various strengthening measures and new connection details have been proposed, including column web stiffeners, cover plates, T-shaped connectors, U-shaped connectors, I-shaped plates, box-like joint regions, column-tree splices, and reduced beam sections.

The reduced beam section connection aims to move the plastic hinge away from the column face and weld region. Studies by Gilton and Uang[8], Oh et al.[11], and Lu et al[16]. show that RBS details can improve the seismic deformation capacity of weak-axis connections. Column-tree connections can improve construction quality by using factory-welded short beam segments and on-site bolted splices[11-13].

End-plate bolted connections are convenient for prefabricated steel structures because of their simple assembly and controllable construction quality. Nie et al[19]. improved weak-axis end-plate connections by using U-shaped connectors, while Yılmaz[21] proposed a T-adapter connection. Xu and Hao[18] showed that I-shaped plates can reduce stress concentration and move plastic deformation to a more controllable beam-end region.

In general, new weak-axis connection configurations mainly develop in three directions: improving prefabrication through end plates and connectors, enhancing column weak-axis stiffness through local strengthening, and controlling plastic hinge positions through RBS, column-tree splices, or shifted end-plate details.

3. Existing Problems and Development Trends

Although progress has been made in weak-axis connection research, several problems remain. First, the existing studies are relatively scattered. Different connection types, section sizes, loading protocols, and evaluation indices make it difficult to compare results directly.

Second, the load-transfer path of weak-axis connections is complicated. Beam-end moments may be transferred through the column web, end plate, bolts, connecting plates, stiffeners, and column flanges. If the plastic development region is not properly controlled, premature damage may occur in the column web or column flanges.

Third, the moment-rotation relationship and restoring force model of weak-axis connections need further improvement. Existing component methods and hysteretic models cannot fully describe column web out-of-plane deformation, end-plate slip, bolt elongation, and pinching effects.

Future studies should focus on full-scale quasi-static tests of prefabricated and damage-controllable weak-axis connections, establishment of experimental databases, development of reliable moment-rotation and hysteretic models, and proposal of new connection details with clear force transfer, simple construction, and controllable damage.

4. Conclusions

(1) Weak-axis beam-to-column connections of H-shaped steel columns are important connection forms in steel frame structures, and their behavior is affected by column web stiffness, connector configuration, end-plate and bolt parameters, strengthening measures, and loading protocols.

(2) Compared with strong-axis connections, weak-axis connections have more complicated load-transfer paths and weaker panel zone restraint, making them more prone to column web deformation, stress concentration, and insufficient rotational stiffness.

(3) Existing studies show that common failure modes include column web deformation, weld cracking, end-plate bending, bolt elongation, connecting plate yielding, and beam-end plastic hinge formation.

(4) Finite element analysis can reveal stress distribution, plastic development, and parameter influence laws, but contact slip, bolt-hole clearance, and cyclic degradation should be considered carefully.

(5) End-plate connections, T-shaped connectors, U-shaped connectors, I-shaped plates, column-tree connections, and reduced beam sections can improve weak-axis connection behavior. Future research should further develop simple, prefabricated, and damage-controllable weak-axis connections.

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