

Analysis and Optimization of Mechanical Properties in Steel Structure Joint Connection Design

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Abstract: The performance of steel structure joint connections directly impacts the overall structural safety and economy. Traditional design methods struggle to effectively balance the various performance indicators of joints, which constrains the optimized development of steel structure engineering. This study establishes a refined finite element model considering initial imperfections to systematically analyze the stress distribution patterns and force transfer mechanisms within the joint connection zone, thereby revealing the hysteretic behavior and failure evolution mechanism of the joint under cyclic loading. Based on parametric analysis results, a multi-objective optimization mathematical model for joints is constructed, targeting load-bearing capacity, stiffness, and energy dissipation capacity. An optimization strategy combining surrogate models and evolutionary algorithms is adopted, yielding a balanced Pareto optimal solution set. The research results demonstrate that the comprehensive mechanical performance of the joint can be significantly enhanced through the collaborative optimization of key parameters such as end-plate thickness, bolt spacing, and stiffener configuration, thus providing a new theoretical basis and methodological support for the refined design of steel structure joints.

Keywords: Steel Structure Joints; Mechanical Performance; Parametric Analysis; Multi-Objective Optimization; Finite Element Model; Joint Design

Introduction

As the critical component connecting beams and columns, the mechanical performance of steel structure joints directly determines the safety and reliability of the overall structure. Current joint design often relies on empirical detailing requirements, making it difficult to achieve an effective balance between performance and economy. Particularly concerning the failure mechanisms and optimal design of joints under complex loading conditions, in-depth research is still required. This study establishes a refined numerical model to systematically analyze the mechanical behavior of joints under static and dynamic loads, thereby revealing the influence patterns of multi-parameter coupling effects. Furthermore, it develops a performance-based multi-objective optimization design method. This research holds significant theoretical importance for enhancing the scientific rigor and economic efficiency of steel structure joint design. It provides technical support for developing new, highly efficient joint forms and contributes to advancing the refined design development of steel structure engineering.

1. Theoretical Basis for the Mechanical Performance of Steel Structure Joints

1.1 Stress Distribution and Force Transfer Mechanism in the Joint Connection Zone

The mechanical response of a steel structure joint under load is essentially a complex process involving the evolution of a local stress field. As the core area where beams and columns converge, the joint connection zone exhibits significantly spatially heterogeneous characteristics in its stress distribution. When external loads are transferred to the joint zone via the structural members, internal forces are redistributed throughout the force transfer system—comprising bolt groups, welds, and connecting plates—according to the principle of minimum strain energy. Under typical bending moments, tension and compression forces from the beam flanges are transferred to the column flanges through end plates or welds, establishing distinct force flow paths. The web region primarily resists shear forces, facilitating load transfer through shear plates or bolt groups^[1].

This force transfer process induces significant stress concentration phenomena in geometrically discontinuous regions, specifically manifested around bolt holes, weld ends, and locations of abrupt sectional changes. The quantitative analysis of the stress concentration factor requires the integration of the plane problem theory from elasticity mechanics, while also considering the influence scope of Saint-Venant's principle. Modern joint design theory places particular emphasis on the precise description of stress flow paths. By identifying high-stress gradient zones, it effectively locates potential fatigue-sensitive areas, thereby providing a theoretical basis for the optimal design of joints.

The analysis of the force transfer mechanism requires a deep understanding at the component level. For bolted-welded hybrid connections, it is essential to clarify the collaborative working mechanism of friction-type high-strength bolts and fillet welds during different loading stages. In the initial elastic stage, the load is primarily transferred through bolt friction. After interface slip occurs, the bolts gradually enter a bearing state, while the load-sharing proportion of the welds increases significantly. This capacity for internal force redistribution is a key factor ensuring the ductile performance of the joint. A profound comprehension of the force transfer mechanism directly guides the rational configuration of stiffeners, the optimized arrangement of bolts, and the detailing of weld constructions, thereby establishing the theoretical foundation for achieving smooth force flow transition and enhancing the overall performance of the joint.

1.2 Constitutive Relationships for Nonlinear Mechanical Behavior of Joints

The nonlinear characteristics of joint mechanical behavior represent a core issue in advanced structural analysis. This nonlinearity primarily stems from the development of material plasticity beyond the elastic limit, the time-varying nature of contact states between components, and geometric nonlinear effects induced by large deformations. The development of a constitutive model capable of accurately describing this complex behavior serves as the critical link connecting the microscopic properties of materials with the macroscopic response of structures^[2].

At the material constitutive level, it is necessary to employ classical plasticity theory to fully describe the elastoplastic behavior of steel, which includes the precise definition of the yield criterion, flow rule, and hardening rule. The Von Mises yield criterion is widely adopted due to its strong consistency with the mechanical properties of steel. Under cyclic loading conditions, material phenomena such as the Bauschinger effect, cyclic hardening, or softening must be incorporated into the constitutive relationship. Typically, a nonlinear kinematic hardening model is employed to accurately simulate the hysteretic behavior of the joint.

At the systemic response level, the moment-rotation relationship of a joint is a concentrated manifestation of its overall mechanical performance. This constitutive curve can be distinctly divided into four characteristic phases: the linear elastic phase, governed by the combined axial and flexural stiffness of the connecting components; the nonlinear transition phase, marked by stiffness degradation accompanying the gradual yielding of local areas; the plastic flow phase, corresponding to the full development of plastic mechanisms within the joint zone; and the descending branch, which reflects the occurrence of failure modes such as local buckling or fracture. The construction of an innovative constitutive model can utilize the principles of the component method, which deconstructs a complex joint into several fundamental mechanical components, each with clearly defined force-deformation characteristics. The overall mechanical response of the joint is then obtained through systematic integration. This approach not only possesses clear physical significance but also offers excellent extensibility, providing an effective theoretical tool for parametric studies and performance optimization.

1.3 Development of a Refined Finite Element Model for Joints Considering Initial Imperfections

The establishment of a refined finite element model is a crucial technical approach for in-depth research into the mechanical performance of joints. The accuracy and reliability of the model directly determine the validity of the numerical analysis results. A thoroughly validated finite element model can serve as an efficient numerical experimental platform, accurately predicting the complete mechanical response of the joint under complex loading paths.

The primary step in model development is the precise establishment of the geometric model, which must completely represent the actual geometric configurations of bolts, connecting plates, stiffeners, and welds. For welds in critical areas, solid elements should be employed to accurately simulate their deposited shape, thereby avoiding calculation deviations caused by excessive simplification. The

definition of the material constitutive relationship must be based on experimental data, incorporating the true stress-strain curve to accurately reflect the elastoplastic characteristics of the material^[3].

The issue of contact nonlinearities constitutes a technical challenge in joint simulation. All contact interfaces where relative slip may occur must be precisely defined, employing a surface-to-surface contact algorithm with appropriate friction coefficients to simulate interface behavior. The accurate application of bolt pre-tension is a critical aspect in simulating high-strength bolted connections, typically achieved by defining bolt loads or initial stress fields to ensure the authentic representation of the bolt's clamping effect and its influence on joint performance.

The introduction of initial imperfections is a crucial step for enhancing the fidelity of the model simulation. Welding residual stresses, as inherent initial stress fields, significantly impact the joint's stability bearing capacity and fatigue performance. These stresses can be simulated using either a thermal-mechanical sequential coupling analysis or an equivalent initial stress field method. Geometric initial deformations need to be introduced based on the results of an eigenvalue buckling analysis of the joint, incorporating the lowest-order buckling mode shape within the limits of permissible manufacturing tolerances specified by relevant standards. Model validation is an essential procedure to ensure its reliability, requiring systematic verification of the numerical simulation's load-displacement relationships, strain distribution patterns, and failure modes against experimental data. Building upon this validated model, innovative explorations may consider the spatial variability of material properties or introduce machine learning methods to establish efficient surrogate models, thereby paving new technical pathways for probabilistic design and optimization analysis.

2. Analysis of the Multi-Parameter Influence on the Mechanical Performance of Joints

2.1 The Effect of Joint Geometric Configuration on Bearing Capacity and Stiffness Degradation

The geometric configuration of a joint is a fundamental factor determining its mechanical performance. Variations in end-plate thickness directly affect the joint's bending moment capacity and initial rotational stiffness. As the end-plate thickness increases, the bending resistance of the joint zone is significantly enhanced, and the failure mode gradually shifts from end-plate bending deformation to bolt tensile failure. Bolt spacing exerts a controlling influence on the process of joint stiffness degradation; a rational arrangement of bolts can effectively improve the stress distribution state and delay stiffness degradation. The stiffener configuration strategy profoundly influences the stress distribution pattern within the joint zone. Column web stiffeners effectively suppress local deformation of the column flange and maintain the shear deformation of the panel zone within the elastic range.

A significant coupling effect exists among the various geometric parameters. The matching relationship between the end-plate thickness and the bolt diameter directly influences the joint's rotational capacity and failure mode. When the ratio of the end-plate thickness to the beam flange width falls below a critical value, the joint will exhibit a failure characteristic dominated by end-plate bending; conversely, when the column web thickness is insufficient, panel zone shear yielding becomes the dominant failure mode. The width-to-thickness ratio of the stiffeners needs to be controlled within a reasonable range to effectively restrain the deformation of the joint zone without exacerbating stress concentration due to excessive stiffness. This synergistic mechanism among multiple parameters provides an important theoretical basis for subsequent multi-objective optimization.

2.2 Hysteretic Behavior and Energy Dissipation Capacity of Joints Under Different Loading Conditions

The hysteretic behavior of joints under cyclic loading is a core indicator of their seismic performance. The mechanical response of joints under different loading histories exhibits fundamental differences, primarily manifested in the modes of stiffness degradation, patterns of strength decay, and mechanisms of energy dissipation. Subjected to low-cycle reversed loading, joints undergo a complex process of cumulative damage, and the shape of their hysteresis curves directly reflects the quality of their seismic performance.

The loading amplitude and path exert a decisive influence on the performance degradation of joints. The damage mechanisms induced by large-displacement cycles under major earthquakes are significantly different from those caused by small-displacement cycles under moderate or minor earthquakes. The former primarily triggers macroscopic plastic deformation and local buckling,

whereas the latter may lead to fatigue damage at the connections. When the displacement amplitude exceeds twice the yield displacement of the joint, the rate of stiffness degradation accelerates markedly, and the equivalent viscous damping coefficient also increases. The energy dissipation capacity of a joint can be quantitatively evaluated through the energy dissipation coefficient and cumulative energy dissipation capacity. An optimized joint should exhibit a full, spindle-shaped hysteresis curve, indicating favorable plastic deformation capacity and stable energy absorption characteristics. This stable energy dissipation mechanism is of significant importance for controlling the dynamic response of structures under seismic action^[4].

2.3 Failure Modes and Their Evolution Mechanisms in Vulnerable Areas of the Joint Panel Zone

Failure in the joint panel zone is a progressive process evolving from micro-damage to macro-failure, exhibiting distinct stage-specific characteristics and path dependency. During the process of increasing load, the various components of the joint sequentially enter a plastic state, forming a specific failure path. Typical failure modes include bolt fracture caused by excessive bending of the end-plate, distortion of the panel zone induced by shear yielding of the column web, and brittle cracking in the heat-affected zone of the welds.

The evolution of the failure process is significantly influenced by initial geometric imperfections and welding residual stresses. These initial defects cause the joint to exhibit a specific deformation tendency from the early stages of loading. This tendency continuously intensifies as the load increases, ultimately steering the joint towards a specific failure mode. Damage typically initiates in areas with the most severe stress concentration, such as the edges of bolt holes and the ends of welds. It subsequently propagates along the path of maximum shear stress, ultimately leading to the formation of through-thickness cracks or causing component instability.

The mapping relationship between failure modes and design parameters, established through parametric analysis, provides a theoretical basis for achieving the intended failure mode through the proactive control of design parameters. This failure-mechanism-based design philosophy helps prevent the occurrence of brittle failure, ensuring that the structure maintains sufficient overall stability even under extreme loading conditions.

3. Design Strategies for Enhancing Joint Performance Based on Multi-Objective Optimization

3.1 Establishment of a Performance-Oriented Multi-Objective Optimization Mathematical Model for Joints

Joint optimization design is inherently a typical multi-objective decision-making problem, requiring the simultaneous consideration of the balance between structural performance and economic efficiency. The establishment of the mathematical model requires the clear definition of the types and ranges of the design variables, which include key geometric parameters such as end-plate thickness, bolt diameter, and stiffener configuration. Each design variable must be assigned reasonable value boundaries, which are derived from constraints imposed by code requirements, detailing limitations, and fabrication processes.

The formulation of objective functions must comprehensively reflect the comprehensive performance characteristics of the joint. The joint weight is typically adopted as the economic indicator, while the ultimate bearing capacity, initial stiffness, and ductility coefficient serve as the structural performance indicators. These objective functions share an inherently competitive relationship; for instance, pursuing higher bearing capacity often leads to an increase in joint weight, while overemphasizing economy may compromise the joint's safety margin. This inherent contradiction constitutes the core problem that multi-objective optimization aims to resolve.

The setting of constraint conditions must encompass multiple aspects, including strength, stiffness, stability, and detailing requirements. Strength constraints ensure the joint does not fail under ultimate limit states, stiffness constraints control the deformation capacity of the joint under serviceability limit states, and stability constraints prevent local buckling of the plates. It is particularly crucial to establish failure mode control constraints, which guide the joint towards the intended ductile failure mode by setting appropriate parameter limits^[5].

The completeness of the mathematical model is further reflected in its consideration of the interactions among design variables. Complex coupling effects exist between the various geometric

parameters, and these coupled relationships must be represented through appropriate mathematical expressions. The model should also incorporate practical factors such as manufacturing processes and construction feasibility, ensuring that the optimization results are not only theoretically viable but also possess value for engineering application.

3.2 Optimization Solution Process Based on Surrogate Models and Evolutionary Algorithms

Given the highly nonlinear and computationally intensive nature of the joint optimization problem, it is necessary to adopt advanced numerical optimization strategies. Surrogate model technology provides an effective approach to address computational efficiency issues. This involves performing scientific sampling design within the design space to obtain representative training sample points. Commonly used sampling methods include Latin Hypercube Sampling and orthogonal experimental design, which can sufficiently explore the design space with a relatively small number of sample points.

Based on the finite element analysis results from the sampling points, it is possible to establish an approximate mapping relationship between the design variables and the performance indicators. The Response Surface Methodology model is suitable for relatively smooth design spaces, the Kriging model can effectively handle nonlinear problems, and the Radial Basis Function model demonstrates good adaptability when fitting complex response relationships. The accuracy of the surrogate model must be validated using independent test samples to ensure its predictive reliability.

Evolutionary algorithms demonstrate unique advantages in addressing multi-objective optimization problems. The Non-dominated Sorting Genetic Algorithm classifies solutions into hierarchical levels through Pareto dominance relationships, while incorporating crowding distance calculation to maintain the diversity of the solution set. The setting of algorithm parameters requires careful consideration; the population size influences the search scope, and the crossover and mutation operators control the granularity of the search. The optimal configuration of these parameters is crucial for the performance of the algorithm.

The collaborative operation of surrogate models and evolutionary algorithms forms an efficient optimization framework. The surrogate model provides rapid performance evaluations, significantly reducing the number of direct finite element calculations required. The evolutionary algorithm performs a global search based on this foundation, progressively approximating the true Pareto optimal front. This hybrid optimization strategy ensures both computational efficiency and optimization quality, offering a practical solution for complex engineering optimization problems.

3.3 Performance Trade-off Analysis of the Optimal Solution Set and Robustness Design Verification

The Pareto solution set generated by the optimization process contains rich design information, which requires systematic analytical methods to extract valuable design principles. The geometric characteristics of the Pareto frontier reflect the degree of conflict among the objective functions. A smooth and continuous frontier indicates good trade-off characteristics exist between the objectives, while a frontier with concave regions suggests that certain performance combinations are difficult to achieve simultaneously^[6].

The analysis of the solution set requires the establishment of scientific decision support methods. The ideal point method ranks solutions by measuring their distance to the ideal solution, the entropy weight method can objectively determine the weight coefficients of each objective, and multi-attribute decision theory provides a systematic evaluation framework for solution selection. These methods assist designers in screening the most suitable scheme from numerous non-dominated solutions according to specific engineering requirements.

Robustness evaluation constitutes a critical step in optimal design, ensuring that the design solution maintains stable performance even in the presence of parameter fluctuations. Sensitivity analysis can identify the design parameters that have the greatest impact on performance variation, thereby providing a basis for manufacturing precision control. Monte Carlo simulation evaluates the performance distribution characteristics of a design solution through statistical methods, thus quantifying its level of robustness.

The verification of the final design solution requires the establishment of a multi-level validation system. First, the predictive accuracy of the surrogate model is verified through high-precision finite element analysis to ensure the reliability of the optimization results. Second, it is necessary to check

whether the optimized solution satisfies all constraint conditions, including both explicit and implicit constraints. Finally, the engineering applicability of the optimized solution must be assessed to ensure its conformity with construction processes and economic benefit requirements.

Conclusion

This study achieves significant performance improvement in steel structure joints through systematic analysis of their mechanical behavior and the establishment of a multi-objective optimization design method. The research demonstrates that a refined finite element model combined with parametric analysis can accurately predict the stress distribution, hysteretic behavior, and failure modes of the joints. By constructing a multi-objective optimization mathematical model and adopting a solution strategy that integrates surrogate models with evolutionary algorithms, the study effectively resolves the challenge of balancing various performance indicators in joint design. The optimization results indicate that the rational configuration of parameters such as end-plate thickness, bolt spacing, and stiffeners can enhance the economic efficiency of the joints while ensuring their safety. Future research could further investigate the coupling effects between material constitutive models and dynamic responses, refine the methods for assessing the fatigue life of joints under extreme loading conditions, explore intelligent optimization design systems based on machine learning algorithms, and validate the feasibility and reliability of the optimized solutions through engineering applications. These efforts would promote the development of steel structure joint design towards greater precision and systematization, providing theoretical support for enhancing the whole-life-cycle performance of building structures.

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