
Steel Structure Node Design and Connection Performance: A Survey

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Abstract

This survey paper explores the interdisciplinary field of structural engineering with a focus on steel structures, emphasizing node design, connection performance, seismic considerations, finite element analysis (FEA), and load-bearing capacity. Steel structures are pivotal in modern engineering due to their strength, durability, and adaptability, serving crucial roles in various applications, including nuclear reactors and telescope prototypes. The paper highlights the significance of innovative node and connection designs in enhancing seismic resilience and structural integrity, supported by advanced inspection technologies like Multidirectional Bicycle Robots. It underscores the role of FEA in optimizing structural performance and discusses advanced computational techniques, including genetic algorithms, which aid in seismic performance optimization. Performance-based design frameworks are emphasized for their ability to enhance structural resilience and efficiency. The survey calls for updated design codes and extensive experimental validation to ensure the robustness of new methodologies. Future research should focus on validating advanced techniques, such as robust extended Kalman filters, and exploring material interactions to drive innovations in steel structure design. Overall, the survey underscores the importance of interdisciplinary collaboration in advancing steel structure engineering, providing insights for developing more resilient and efficient structural solutions.

1 Introduction

1.1 Significance of Steel Structures

Steel structures are fundamental in modern engineering, underpinning applications such as skyscrapers, bridges, industrial facilities, and nuclear reactors. Their widespread use stems from exceptional properties, including a high strength-to-weight ratio, durability, and design versatility, which facilitate innovative methods like 3D printing. This technology enables the creation of complex geometries and optimized connections, enhancing efficiency, minimizing construction waste, and improving structural integrity [1, 2, 3, 4]. Steel's resilience to diverse environmental conditions further solidifies its status as a preferred material for long-lasting structures.

In nuclear reactor development, steel structures face challenges such as helium accumulation, leading to embrittlement and cracking, which jeopardize structural integrity [5]. Addressing these issues is essential for the safety and reliability of nuclear power plants.

Additionally, steel structures support scientific research infrastructure, exemplified by medium-sized telescope prototypes that require rigorous testing of design and structural integrity to meet astronomical observation standards [6]. This highlights steel's role in advancing research and technology.

The adaptability of steel structures across various applications, their contribution to technological innovations, and their role in enhancing global infrastructure safety and efficiency underscore their

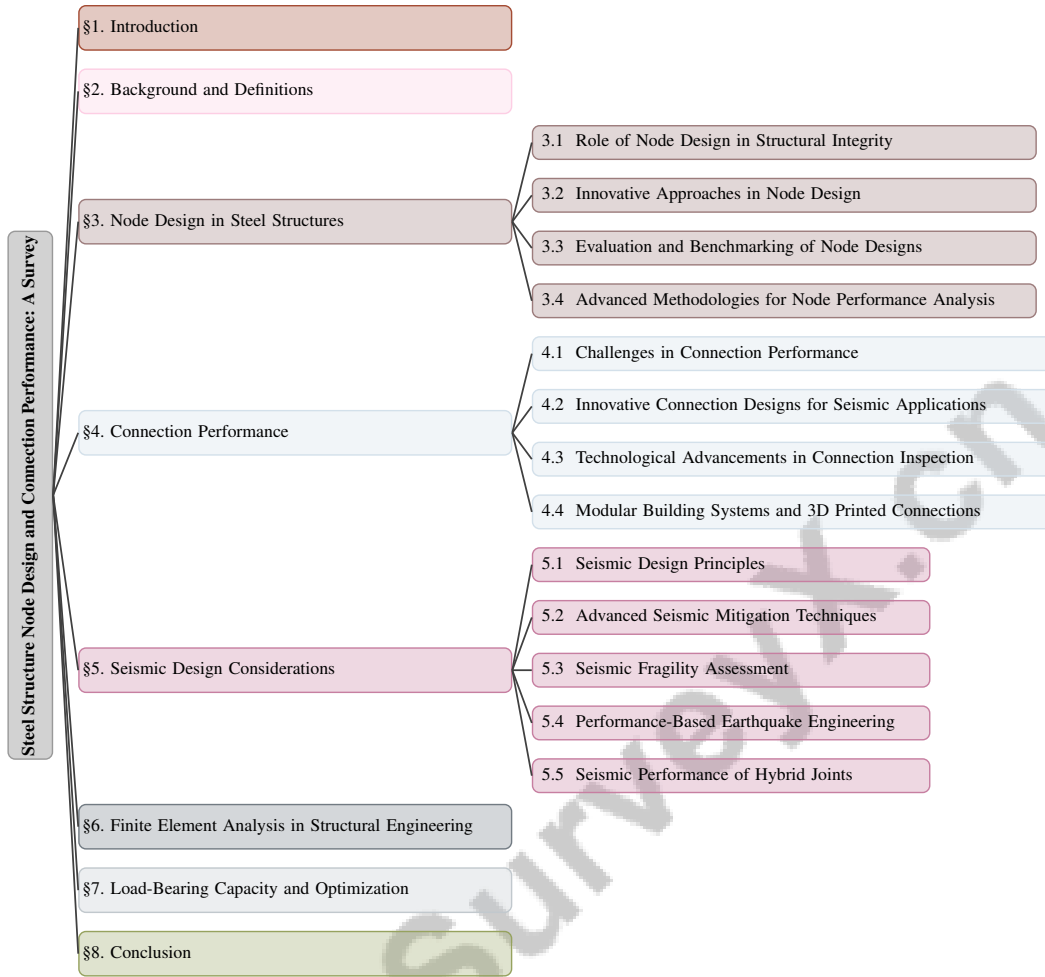


Figure 1: chapter structure

significance. Ongoing research into innovative bolted connections is vital for optimizing seismic performance and structural integrity, particularly as the industry transitions to performance-based design approaches [4, 1, 7].

1.2 Focus on Node Design and Connection Performance

Node design and connection performance are critical for the stability and resilience of steel structures. The configuration and assembly of joints, where structural elements converge, are essential for load distribution and structural integrity under varying conditions. In seismic applications, the ability of these nodes to absorb and dissipate energy is crucial for preventing catastrophic failures. Recent innovations in bolted connections aim to enhance seismic resilience by integrating traditional practices with novel design strategies [7].

Inspection and maintenance of connections are also vital for long-term performance. Advances in inspection technologies, such as Multidirectional Bicycle Robots (MDBR), facilitate the assessment of ferromagnetic structures, providing valuable insights into node design and connection performance [8]. Such technologies are essential for ensuring the functionality of nodes and connections throughout the structure's lifespan.

Evaluating and benchmarking node designs are fundamental to structural engineering, enabling the assessment of conformity and operational parameters. For example, the design and testing of telescope steel structures require rigorous evaluation to meet application demands [6]. Additionally, integrating advanced monitoring systems, including semi-supervised damage detection techniques, enhances structural reliability and safety [9].

The focus on node design and connection performance emphasizes the importance of innovative methodologies, advanced inspection technologies, and rigorous evaluation techniques in bolstering the safety, resilience, and durability of steel structures. Recent studies indicate that optimized 3D-printed connections can enhance modular building systems by enabling complex geometries unattainable through traditional manufacturing, promoting flexibility, adaptability, and sustainability. A growing emphasis on seismic design, particularly regarding bolted connections, is crucial for ensuring structural safety during seismic events. Performance-based design approaches that consider uncertainties in joint flexibility are essential for developing robust steel structures capable of withstanding dynamic loads, thereby advancing the integrity and longevity of steel frameworks across various applications [10, 7, 11, 1, 3].

1.3 Structure of the Survey

This survey is meticulously structured to explore critical aspects of steel structure design, focusing on node design, connection performance, and seismic considerations. It begins with an **Introduction**, establishing the significance of steel structures in modern engineering, followed by a detailed discussion on node design and connection performance. The **Background and Definitions** section provides foundational knowledge, including key concepts and definitions relevant to steel structures, finite element analysis, and load-bearing capacity.

The survey thoroughly investigates , emphasizing its role in maintaining structural integrity while analyzing innovative strategies to enhance performance. It highlights the significance of connections in steel frameworks, especially in seismic applications, where recent research has focused on developing advanced connection designs to improve overall structural behavior. The survey identifies gaps in system analysis and code compliance, advocating for a shift toward performance-based design philosophies that could integrate sophisticated joints and connections, including self-centering and replaceable options, thereby advancing structural engineering [10, 7]. This is followed by an in-depth review of **Connection Performance**, discussing challenges and advancements in connection technologies, particularly for seismic applications.

Next, the survey addresses **Seismic Design Considerations**, analyzing principles and strategies for optimizing seismic performance, supported by case studies and research findings. The application of is examined, emphasizing its critical role in assessing and optimizing steel structure performance, particularly in prefabricated modular construction and seismic resilience. This analysis employs advanced software, such as ABAQUS, for nonlinear static and dynamic evaluations, ensuring structural integrity and effective load distribution through innovative connection designs. Findings underscore the importance of accurately modeling joint flexibility and material nonlinearity, as well as the potential for enhanced seismic performance through optimized connection configurations [7, 4, 11, 1, 3].

The penultimate section, **Load-Bearing Capacity and Optimization**, investigates methods for enhancing load-bearing capacity, discussing optimization techniques and their impact on structural performance. Finally, the **Conclusion** summarizes key findings, emphasizing the importance of interdisciplinary approaches and suggesting future research directions in steel structure design. This structured approach ensures a logical flow of information, facilitating a comprehensive understanding of the complexities involved in steel structure engineering. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Key Concepts in Steel Structures

Steel structures are a cornerstone of modern engineering, leveraging steel's strength for enhanced structural integrity and efficient load distribution. Prefabricated modular steel (PFMS) systems exemplify this, offering improved construction efficiency, safety, and quality, particularly in seismic applications. Advanced connection designs, such as semi-rigid and bolted joints, are vital for dynamic load performance. Additive manufacturing further revolutionizes these designs, enabling complex geometries that enhance modular systems' adaptability and resilience [4, 1, 3, 7]. Core components like beams, columns, and nodes form a robust framework, crucial for withstanding various loads, especially in seismic-prone areas.

Node design significantly impacts load distribution and stability, with innovations enhancing energy absorption and dissipation under seismic conditions to prevent failures. Advanced bolted connections have bolstered seismic resilience [7]. Connection performance is critical, reflecting joints' efficacy in load transfer between elements. Regular inspection and maintenance are essential for long-term reliability, with technologies like Multidirectional Bicycle Robots improving assessments of ferromagnetic structures, providing insights into node and connection performance [8].

Structural health monitoring and anomaly detection are crucial, with semi-supervised damage detection techniques identifying structural issues without labeled data from damaged states, enhancing steel structures' reliability and safety [9]. Validating structural integrity under varied conditions is essential, as shown in telescope prototype benchmarking, addressing performance in demanding settings [6].

Key concepts in steel structures include node and connection design and performance, advanced inspection and monitoring technologies, and rigorous evaluation under diverse conditions. Innovative methodologies, such as performance-based seismic design considering joint flexibility, and additive manufacturing for optimized connections, enhance steel structures' robustness and adaptability. These developments improve nonlinearity management in connections, material efficiency, and enable resilient modular systems capable of withstanding seismic forces, promoting sustainability through reusability and reduced waste [7, 4, 11, 1, 3].

3 Node Design in Steel Structures

The design of nodes in steel structures is pivotal in structural engineering due to its impact on performance and stability. This section explores the role of node design in maintaining structural integrity, focusing on its significance in load distribution and resilience against external forces. By analyzing node configurations, we gain insight into their influence on structural behavior during various loading scenarios, particularly seismic activity. Table 2 offers a comprehensive comparison of various node design strategies in steel structures, emphasizing their contributions to structural integrity and innovation.

Figure 2 illustrates the hierarchical structure of node design in steel structures, emphasizing four main categories: the role of node design in structural integrity, innovative approaches, evaluation and benchmarking, and advanced methodologies for performance analysis. Each category is further divided into subcategories that highlight seismic resilience, cold-formed steel innovations, performance-based frameworks, and multiscale modeling techniques. This comprehensive framework underscores the contributions of these elements to enhancing the performance, resilience, and adaptability of steel structures, thereby reinforcing the critical nature of effective node design in contemporary structural engineering.

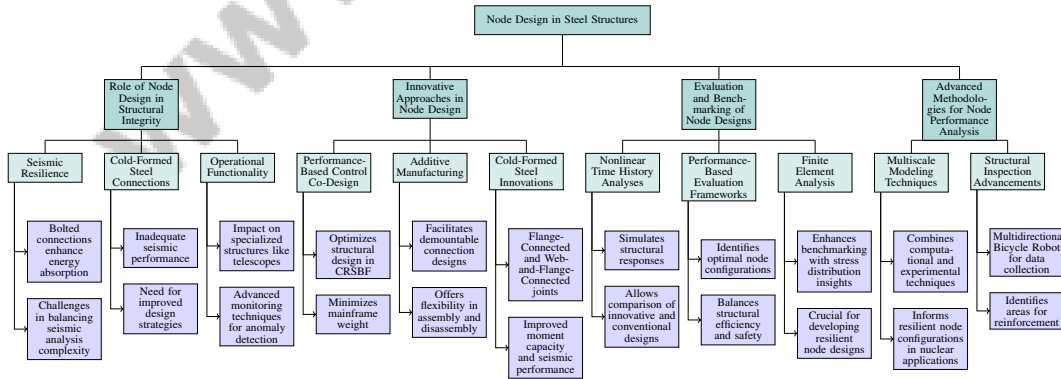


Figure 2: This figure illustrates the hierarchical structure of node design in steel structures, focusing on four main categories: the role of node design in structural integrity, innovative approaches, evaluation and benchmarking, and advanced methodologies for performance analysis. Each category is further divided into subcategories that emphasize seismic resilience, cold-formed steel innovations, performance-based frameworks, and multiscale modeling techniques, highlighting their contributions to enhancing the performance, resilience, and adaptability of steel structures.

3.1 Role of Node Design in Structural Integrity

Node design is fundamental to the integrity and stability of steel frameworks, serving as critical junctions where structural elements converge. The configuration of nodes dictates load distribution, directly affecting the structure's ability to withstand forces, including seismic activity. Advances in bolted connections have led to innovative designs that enhance seismic resilience by optimizing energy absorption and dissipation [7]. However, challenges persist in balancing seismic analysis complexity with computational efficiency, necessitating further innovation in node design methodologies [2]. Cold-formed steel (CFS) beam-to-column connections, often reliant on web connections, exhibit inadequate seismic performance, highlighting the need for improved design strategies to mitigate local buckling failures [11]. Beyond structural stability, node design also impacts the operational functionality of specialized structures, such as telescopes, with structural testing of prototypes providing insights into node effectiveness under operational conditions [6]. Advanced monitoring techniques, like Variational Autoencoders (VAEs) and One-Class Support Vector Machines (OC-SVMs), enhance anomaly detection, contributing to structural integrity maintenance through timely interventions [9].

3.2 Innovative Approaches in Node Design

Recent innovations in node design focus on enhancing steel structures' performance and adaptability through advanced methodologies and materials. As illustrated in Figure 3, these innovations can be categorized into three main approaches: performance-based control co-design for Controlled Rocking Steel Braced Frames (CRSBF), additive manufacturing for modular flexibility, and enhanced cold-formed steel connections aimed at improving seismic performance. Performance-based control co-design methodologies optimize structural design, particularly in CRSBF, by minimizing main-frame weight [12]. Additive manufacturing advancements facilitate demountable and adaptable connection designs, offering flexibility in assembly and disassembly, beneficial for applications requiring frequent modifications [3]. In cold-formed steel (CFS) structures, new connection types like Flange-Connected (F-C) and Web-and-Flange-Connected (WF-C) joints improve moment capacity and seismic performance, addressing traditional design limitations [11]. These innovative approaches underscore the integration of advanced methodologies and manufacturing techniques, such as optimized 3D printing and performance-based frameworks, to enhance steel structures' performance, resilience, and adaptability. Such advancements promote efficient construction practices while enabling easier dismantling, repair, and reuse of components [10, 7, 11, 1, 3].

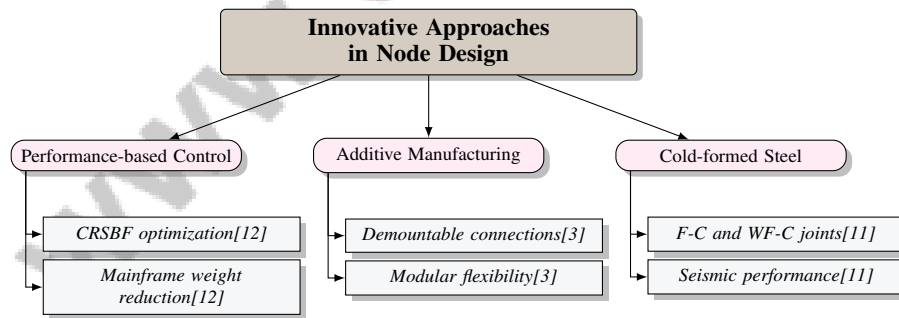


Figure 3: This figure illustrates the innovative approaches in node design, highlighting three main categories: performance-based control co-design for CRSBFs, additive manufacturing for modular flexibility, and enhanced cold-formed steel connections for improved seismic performance.

3.3 Evaluation and Benchmarking of Node Designs

Evaluation and benchmarking of node designs are crucial for verifying steel structures' performance and reliability under various conditions. Table 1 presents a structured overview of representative benchmarks, highlighting key attributes relevant to the evaluation and benchmarking of node designs. Nonlinear time history analyses simulate structural responses to artificial ground motions, allowing for direct comparison of innovative and conventional designs [12]. Performance-based evaluation frameworks help identify optimal node configurations balancing structural efficiency and safety. In

Benchmark	Size	Domain	Task Format	Metric
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Table 1: Table of representative benchmarks detailing the size, domain, task format, and metrics employed in the evaluation and benchmarking of node designs. This table serves as a comprehensive reference for comparing innovative and conventional structural designs in terms of performance and reliability.

CRSBF contexts, control co-design methodologies minimize mainframe weight, optimizing structural design [12]. Incorporating advanced computational techniques like finite element analysis (FEA) enhances benchmarking by providing detailed insights into stress distribution and deformation, crucial for developing resilient node designs [10, 1].

3.4 Advanced Methodologies for Node Performance Analysis

Advanced methodologies for node performance analysis enhance steel frameworks' structural integrity and resilience. Multiscale modeling techniques, such as the 'Multiscale Approach for Helium Diffusion in Yttria' (MADY), combine computational and experimental techniques to inform resilient node configurations in nuclear applications [5]. The Multidirectional Bicycle Robot (MDBR) offers significant advancements in structural inspection, providing critical data for evaluating node performance and identifying areas for reinforcement [8]. These methodologies highlight the importance of integrating computational models with experimental validation for a comprehensive understanding of node performance, enhancing steel structures' ability to endure dynamic forces and environmental challenges [1, 3, 7].

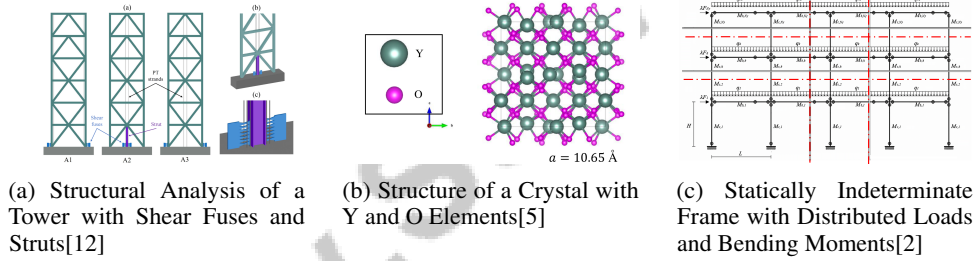


Figure 4: Examples of Advanced Methodologies for Node Performance Analysis

As shown in Figure 4, the example of "Node Design in Steel Structures; Advanced Methodologies for Node Performance Analysis" is illustrated through three distinct figures, each highlighting different aspects of structural engineering and analysis. The first figure presents a structural analysis of a tower, emphasizing the use of shear fuses and struts to enhance stability. This tower is segmented into three parts, each constructed with interconnected steel frames forming triangular sections, and connected by PT strands. The second figure shifts focus to the micro-level with a crystal structure composed of Y and O elements, depicted in a 3D lattice format. This visualization aids in understanding the arrangement and interaction of atoms within the crystal lattice, which is crucial for material science applications. The third figure demonstrates a statically indeterminate frame subjected to distributed loads and bending moments, showcasing the complexity of analyzing and designing frames that can withstand various forces. Together, these examples underscore the advanced methodologies employed in node performance analysis, essential for optimizing the design and functionality of steel structures [12, 5, 2].

4 Connection Performance

The effectiveness of connections significantly affects the performance of steel structures, especially in seismic applications. This section addresses the challenges in connection performance and explores innovative designs that enhance resilience and safety in dynamic environments.

Feature	Role of Node Design in Structural Integrity	Innovative Approaches in Node Design	Evaluation and Benchmarking of Node Designs
Seismic Performance	Enhanced Energy Absorption	Improved Moment Capacity	Simulated Ground Motions
Design Innovation	Bolted Connections	Additive Manufacturing	Control Co-design
Evaluation Method	Prototype Testing	Performance-based Frameworks	Nonlinear Time History

Table 2: This table provides a comparative analysis of different node design methodologies in steel structures, focusing on their roles in structural integrity, innovative approaches, and evaluation techniques. It highlights key features such as seismic performance enhancement, design innovations like bolted connections and additive manufacturing, and evaluation methods including prototype testing and nonlinear time history analysis. The table underscores the importance of advanced node designs in improving the performance and resilience of steel frameworks.

4.1 Challenges in Connection Performance

Optimizing connection performance in steel structures is challenging, particularly under seismic loading, where connections must transmit forces effectively while maintaining system integrity. The complexity of design is heightened by limited research on system-level impacts of connection behavior during seismic events, leading to potential underperformance [7]. Modular steel building connections often lack adequate seismic resistance, emphasizing the need for improved designs that enhance lateral load resistance [4]. Traditional beam-column joints in hybrid frames frequently exhibit insufficient ductility, necessitating innovative designs to prevent brittle failure [13]. Installation complexities and limitations in lateral load performance hinder structural adaptability [3], while boundary condition variability complicates damage detection, crucial for structural health [9]. Advanced technologies like the Multidirectional Bicycle Robot (MDBR) offer potential solutions for optimal connection performance assessments, although routine integration remains challenging [8]. Addressing these challenges is vital for improving safety and adaptability in seismic applications. Innovations that account for semi-rigid behaviors and material nonlinearity are essential for enhancing seismic performance, with a growing demand for performance-based design criteria and updated European design rules [10, 13, 7, 11, 1].

4.2 Innovative Connection Designs for Seismic Applications

Innovative connection designs are pivotal for enhancing the seismic resilience of steel structures by improving load transfer, ductility, and energy dissipation. A notable advancement is a bolted joint design featuring a long tenon-gusset plate for horizontal connections and long beam bolts for vertical connections, aimed at enhancing load transfer and ductility [4]. In cold-formed steel structures, novel connections with improved flexural capacity and energy dissipation are particularly suitable for seismic applications [11]. Strategic relocation of plastic hinges in hybrid joints enhances energy dissipation and seismic performance [13]. Advanced inspection technologies like the MDBR, equipped with non-destructive testing sensors, offer promising avenues for refining connection designs [8]. These innovations underscore the importance of continuous research in achieving seismic resilience, integrating advanced materials and state-of-the-art inspection technologies to create robust connections capable of enduring seismic forces [11, 7].

4.3 Technological Advancements in Connection Inspection

Technological advancements in connection inspection have enhanced the assessment and maintenance of steel structures. The Multidirectional Bicycle Robot (MDBR) overcomes the limitations of existing robotic solutions by navigating complex geometries for detailed inspections, crucial for identifying potential connection issues [8]. Innovations in joint design, such as steel jackets and friction copper plates, improve energy dissipation under dynamic loads, facilitating easier inspection and maintenance [13]. Recent advancements emphasize integrating innovative design and inspection techniques to enhance steel structures' safety and reliability. Optimized connections via additive manufacturing offer improved adaptability and resilience for modular systems. Advanced inspection technologies, like multi-directional robotic systems, enable thorough monitoring of structural integrity, essential for addressing challenges in steel construction and ensuring compliance with evolving safety standards [13, 7, 11, 3, 8].

4.4 Modular Building Systems and 3D Printed Connections

The integration of modular building systems and 3D printed connections represents a transformative advancement in construction, enhancing flexibility, adaptability, and resilience in steel structures. Modular systems use prefabricated components for rapid assembly and disassembly, improving construction efficiency and supporting sustainable practices like dismantling and reuse. 3D printing enables the creation of optimized connections with complex geometries, enhancing structural adaptability and resilience [10, 1, 3]. Tailored 3D printed connections optimize load transfer and structural performance, creating lightweight, high-strength components that improve seismic resilience. This approach ensures effective load transfer and performance under seismic conditions, facilitating efficient assembly and reducing construction waste [11, 4, 1, 3]. Advances in manufacturing techniques and materials science expand possibilities for innovative connection designs, addressing limitations of conventional methods and enhancing steel structures' adaptability to modern challenges [3]. Integrating modular systems and 3D printing offers a transformative opportunity to enhance efficiency, sustainability, and resilience, supporting the rapid advancement of autonomous construction technologies [4, 1, 3, 7].

5 Seismic Design Considerations

5.1 Seismic Design Principles

Seismic design principles for steel structures prioritize resilience against dynamic seismic forces, focusing on optimizing connection designs, especially bolted connections, to enhance energy dissipation and ductility. The performance-based approach stresses the importance of connections that can transfer loads and accommodate deformations without compromising structural stability [7]. Balancing stiffness and flexibility in planar frames is critical; overly rigid structures fail to dissipate energy effectively, while overly flexible ones risk large deformations and collapse. Innovative connection designs engaging both flanges and webs enhance stiffness and load-bearing capacity, thus improving seismic performance [11].

Traditional deterministic models often fall short in predicting semi-rigid connections under seismic loads, necessitating advanced modeling techniques to capture complex interactions and nonlinearities [1]. Strategies like relocating plastic hinges away from joint cores help mitigate adverse effects and enhance seismic performance [13]. Rapid seismic risk evaluations using indices based on design year and location can identify structures needing detailed analysis, despite relying on strong assumptions and limited data. Tools like NODE improve understanding of regional vulnerabilities by tailoring code-based seismic performance demands to specific locations, thus informing effective risk management strategies [10, 14]. Validating assumptions in fragility curve estimation is crucial for developing effective earthquake-proofing methods.

The principles guiding seismic design in steel structures emphasize optimizing connection performance, employing advanced modeling for semi-rigid joints, and assessing structural vulnerability. This approach integrates innovative connection designs, such as self-centering and replaceable joints, addressing complexities in performance-based design methodologies while ensuring compliance with updated design codes. Systematic analysis of connections at the system level and consideration of inherent fuzziness in design parameters are essential for improving structural performance during seismic events [1, 7].

5.2 Advanced Seismic Mitigation Techniques

Advanced seismic mitigation techniques are pivotal for enhancing the resilience of steel structures against seismic forces. Performance-based control co-design methodologies, considering nonlinear interactions between structural and control systems, optimize seismic responses while reducing structural weight [12]. Tuned liquid dampers (TLDs), enhanced with robust extended Kalman filters (REKF) for parameter estimation, improve seismic vibration reduction by allowing real-time damping parameter adjustments [15].

Innovative connection designs, such as new-type bolted joints, enhance seismic performance through stable load-carrying capacity and improved ductility, crucial for maintaining structural integrity during seismic events [4]. A nested genetic algorithm strategy effectively optimizes frame designs under

seismic loads, achieving superior performance metrics with computational efficiency [2]. Emerging research explores meta-barriers composed of meta-boxes to create seismic shadow zones, attenuating seismic waves to protect buildings [16]. Comprehensive design frameworks for interlocking systems and functionally graded materials, facilitated by additive manufacturing, promise future advancements in seismic mitigation by leveraging advanced materials [3].

Implementing advanced seismic mitigation techniques is crucial for safeguarding steel structures against seismic impacts. Incorporating innovative materials and state-of-the-art technologies significantly improves seismic resilience and safety, enhancing bolted connections' performance and enabling comprehensive seismic vulnerability evaluations at a regional level. Tools like NODE facilitate location-specific seismic performance demand assessments, while performance-based design accounts for joint flexibility complexities, contributing to effective risk mitigation strategies and the development of seismic-resistant structures [10, 1, 7].

5.3 Seismic Fragility Assessment

Seismic fragility assessment evaluates the vulnerability of steel structures to seismic events, estimating failure probabilities at varying seismic intensities and providing insights into potential risks. Traditional fragility approaches often assume a lognormal distribution for failure probabilities, but recent studies highlight limitations in capturing structural response complexities under seismic loading. Non-parametric approaches, such as binned Monte Carlo simulation and kernel density estimation, offer more consistent and accurate fragility estimates, serving as robust alternatives [14].

A primary challenge in seismic fragility assessment is the limited availability of comprehensive data and resources, necessitating simplified methodologies that may lead to less accurate risk assessments and potentially underestimate structural vulnerability. This reliance on simplified models underscores the need for extensive data collection and advanced analytical techniques to enhance fragility assessment precision [10]. Experimental evaluations, such as cyclic loading tests, are vital for assessing the seismic performance of structural components. Tests on hybrid joint specimens provide valuable insights into their behavior under seismic conditions and establish a basis for comparison with traditional joint designs, essential for validating analytical models and improving seismic fragility assessments [13].

5.4 Performance-Based Earthquake Engineering

Performance-based earthquake engineering (PBEE) offers a comprehensive framework for designing and evaluating steel structures to withstand seismic forces, focusing on achieving specific performance objectives during earthquake scenarios. This approach emphasizes understanding and predicting structural behavior during seismic events to ensure resilience and safety. PBEE employs sophisticated modeling techniques and cutting-edge design methodologies to enhance seismic resilience, integrating factors such as structural vulnerability and site-specific seismic demands [10, 1].

A critical aspect of PBEE involves using acoustic metamaterials, such as meta-boxes, to create seismic shadow zones around buildings. This method strategically buries these meta-boxes to attenuate seismic waves, effectively protecting structures from earthquake impacts by leveraging these materials' unique properties [16]. Incorporating such innovative materials into the design process significantly enhances the seismic resilience of steel structures.

Advanced software tools like NODE are vital in PBEE, improving the efficiency and accuracy of seismic risk assessments. NODE facilitates the evaluation of large portfolios of structures, providing a robust tool for prioritizing mitigation efforts based on assessed risk levels [10]. This capability is essential for effectively allocating resources and implementing targeted interventions to enhance seismic performance.

PBEE represents a paradigm shift in designing and evaluating steel structures, focusing on achieving defined performance objectives through integrating advanced technologies and innovative design strategies. By employing methodologies and tools such as NODE for seismic risk prioritization and advanced design principles for bolted connections, engineers can enhance buildings' resilience against seismic forces. This ensures structures meet current safety standards and maintain functionality during and after earthquakes, particularly in seismic-prone regions. Additionally, integrating non-parametric

approaches to fragility curve assessment refines understanding of structural vulnerability, enabling more accurate performance predictions under earthquake conditions [10, 14, 7].

5.5 Seismic Performance of Hybrid Joints

The seismic performance of hybrid joints is crucial in structural engineering, significantly enhancing the resilience and energy dissipation capacity of steel structures during seismic events. Recent experimental studies indicate that hybrid joints with bolted connections improve seismic performance by minimizing joint core deformation and enhancing energy dissipation, essential for maintaining structural integrity and ensuring safety during earthquakes [13].

A key advantage of hybrid joints is their design, which facilitates easier repairs after seismic events. The strategic relocation of plastic hinges reduces stress concentration and deformation within the joint core, enhancing ductility and energy absorption capacity, and simplifying post-earthquake repair processes, thereby improving overall resilience and longevity [13]. Advanced technologies, such as the robust extended Kalman filter (REKF), further optimize the seismic performance of hybrid joints by addressing model uncertainties in estimating the dynamics of tuned liquid dampers (TLDs) integrated into hybrid joint systems for vibration control. Accurate TLD dynamics estimation plays a crucial role in enhancing the seismic performance of structures equipped with hybrid joints [15].

Moreover, the concept of artificial seismic shadow zones, created using acoustic metamaterials, offers an innovative approach to protecting structures with hybrid joints from seismic waves. Experiments demonstrate that this method significantly reduces seismic wave amplitude, providing effective protection for buildings and enhancing the overall seismic performance of hybrid joint systems [16].

6 Finite Element Analysis in Structural Engineering

6.1 Finite Element Analysis for Load-Bearing Capacity

Finite element analysis (FEA) is a pivotal tool in structural engineering, offering detailed insights into the load-bearing capacity of steel structures. This computational approach allows for the simulation of structural responses under various loading conditions, optimizing designs for enhanced performance. FEA's integration within performance-based control co-design methodologies exemplifies its role in refining structural designs while adhering to code constraints, enabling systematic evaluation and improvement of load-bearing capabilities to meet performance objectives [12].

FEA is critical for assessing seismic performance, with robust extended Kalman filters (REKF) complementing FEA to address model mismatches, crucial for accurately evaluating load-bearing capacity under seismic conditions. This synergy enables real-time parameter estimation, bolstering structural resilience against seismic forces [15].

Experimental studies, such as static and quasi-static loading tests, highlight FEA's importance in evaluating structural components' load-bearing capacity. Detailed FEA models, validated by experimental data, assess design parameters' influence on performance, ensuring optimal strength and seismic performance in prefabricated modular steel buildings [11, 4]. FEA's application in analyzing corner and middle joints provides comprehensive insights into load-bearing behavior relative to environmental factors.

FEA's utility extends to complex structural systems, as demonstrated in case studies of 5-storey single-bay frames and industrial 3D modular structures. Integrating commercial software like SAP2000 with MATLAB enhances the analysis of load-bearing capacities across various scenarios, increasing analysis accuracy and reliability [1]. FEA's role in refining bolted connections, engaging both flanges and webs, is crucial for optimizing moment-rotation behavior and seismic resilience [11].

6.2 Advanced Computational Techniques

Advanced computational techniques significantly enhance finite element analysis (FEA) by improving structural evaluations' accuracy, efficiency, and effectiveness. The nested genetic algorithm strategy notably optimizes cross-sectional sizes and seismic performance factors, integrating genetic algorithms with FEA to explore vast design spaces efficiently, identifying configurations that satisfy structural and performance criteria [2].

These advanced algorithms enhance seismic design by analyzing complex load interactions and structural responses, ensuring buildings' safety and resilience during earthquakes. They empower computational tools to process extensive data, facilitating effective regional seismic vulnerability assessments. Software like NODE enables location-specific seismic performance evaluations, while performance-based design frameworks incorporate connection uncertainties, enhancing risk evaluation accuracy. Innovative fragility curve derivation methods without traditional assumptions further refine structural vulnerability understanding, supporting informed seismic risk mitigation strategies [10, 14, 1]. Genetic algorithms optimize steel structure designs to enhance seismic resilience while adhering to performance-based principles, minimizing material use and costs.

Integrating computational techniques like machine learning and artificial intelligence with FEA presents promising advancement avenues. These technologies develop sophisticated predictive models enhancing simulation accuracy, enabling detailed evaluations of structural behavior under various loading conditions. Machine learning in Structural Health Monitoring (SHM) automates damage detection, while non-parametric seismic fragility curves provide reliable structural vulnerability estimates without traditional assumptions, guiding effective risk assessment and mitigation strategies [10, 14, 9]. Real-time data and adaptive learning mechanisms in FEA models enhance predictive capabilities, facilitating dynamic adjustments and optimizations throughout the design process.

Advanced computational techniques are indispensable in modern structural engineering, equipping professionals with tools to optimize designs, improve performance, and ensure steel structures' safety and resilience amid complex environmental challenges. As additive manufacturing advances, it is poised to enhance modular building system connections' design and performance, creating adaptable and resilient connections that facilitate component dismantling, repair, and reuse, promoting sustainable construction. Optimized 3D printed connections enable complex geometries unattainable through traditional methods, improving material properties and leading to innovative structural solutions [11, 3].

7 Load-Bearing Capacity and Optimization

7.1 Load-Bearing Capacity and Structural Optimization

Optimizing steel structures for enhanced load-bearing capacity is crucial in structural engineering, ensuring performance and resilience while meeting design specifications. Performance-based control co-design methodologies have demonstrated a 21% reduction in the total weight of a six-story frame structure, significantly improving load-bearing capacity [12]. Innovative connection designs, such as Flange-Connected (F-C) and Web-and-Flange-Connected (WF-C) connections in cold-formed steel (CFS) structures, enhance seismic performance through increased ductility and energy dissipation compared to traditional Web-Connected (W-C) connections [11]. These advanced joint designs underscore the importance of innovative strategies in optimizing structural performance under seismic conditions [4].

Preliminary prototype testing on medium-sized telescope structures indicates compliance with design specifications, though further validation of load-bearing capacity is necessary [6]. An integrated approach combining advanced design methodologies, innovative connection strategies—including semi-rigid and self-centering joints—and robust testing protocols is critical. Connections significantly influence construction costs and structural behavior under seismic loads, necessitating comprehensive system analysis and adherence to updated design codes to enhance joint performance and resilience [1, 7].

7.2 Integration of Structural Optimization and Control Systems

The integration of structural optimization with control systems represents a significant advancement in enhancing steel structures' performance and resilience. This interdisciplinary approach combines structural engineering with control theory to achieve optimal design solutions that minimize material usage and construction costs while meeting performance criteria. The performance-based control co-design methodology exemplifies this integration, effectively reducing structural weight while enhancing load-bearing capacity and seismic resilience [12].

Control systems enable real-time adjustments to structural responses under dynamic loading, such as seismic events. Advanced strategies, including tuned liquid dampers (TLDs) with robust extended

Kalman filters (REKF), enhance energy dissipation and stability [15]. Genetic algorithms facilitate design space exploration, identifying optimal configurations that improve structural performance while adhering to constraints [2]. The integration of optimization and control systems transforms steel structures, enhancing adaptability and resilience. Tools like NODE allow rapid seismic risk prioritization using easily obtainable data, while advancements in additive manufacturing enhance connection designs in modular systems, promoting flexibility, adaptability, and sustainability [10, 3].

7.3 Performance-Based Design and Optimization

Performance-based design and optimization are pivotal in structural engineering, focusing on achieving specific performance objectives while optimizing steel structure designs. This approach employs advanced computational techniques to enhance efficiency, resilience, and safety under diverse loading conditions, including seismic events, through performance-based principles, non-parametric fragility assessments, and tailored optimization algorithms [10, 2, 1, 14].

Key to performance-based design is tailoring structural configurations to meet predefined criteria, ensuring compliance with design codes while delivering superior real-world performance. The integration of genetic algorithms with finite element analysis (FEA) allows efficient exploration of design possibilities, identifying configurations that enhance load-bearing capacity and seismic resilience while minimizing material usage and costs [2]. Performance-based methodologies address seismic design challenges by focusing on objectives such as minimizing structural weight and maximizing energy dissipation, facilitating effective connection designs and joint configurations that enhance seismic performance [12]. Advanced control strategies, such as tuned liquid dampers with robust extended Kalman filters, further exemplify performance-based approaches in optimizing structural designs for improved seismic resilience [15].

Performance-based design and optimization enable the creation of modular structures that are efficient and resilient, capable of addressing complex environmental challenges. This includes integrating advanced materials developed through 3D printing to enhance connection designs, improving flexibility, adaptability, and sustainability. Performance-based frameworks accounting for uncertainties in joint flexibility optimize structural integrity under seismic conditions, while genetic algorithms facilitate optimal plastic design for enhanced seismic resistance. These advancements promote the development of structures that withstand diverse environmental stresses, fostering a more sustainable construction industry [10, 12, 2, 1, 3].

7.4 Genetic Algorithms in Seismic Performance Optimization

Genetic algorithms (GAs) are powerful tools for optimizing the seismic performance of steel structures, adeptly navigating the complex design space associated with seismic load considerations. These algorithms use a nested genetic framework to mimic natural selection, effectively identifying optimal design configurations that enhance structural resilience and material efficiency in earthquake engineering contexts [10, 12, 2, 14, 1]. GAs allow simultaneous optimization of multiple performance criteria, such as minimizing structural weight while maximizing seismic resistance, achieving efficient and reliable designs.

The nested genetic algorithm strategy combines two genetic algorithms to optimize frame designs subjected to seismic loads, enhancing performance by balancing structural integrity and material efficiency while reducing computational demands [2]. By leveraging GAs, engineers can explore a vast array of design possibilities, identifying configurations that provide superior seismic performance without compromising critical design aspects.

GAs are particularly beneficial for addressing complexities associated with diverse loading conditions and nonlinear structural responses, efficiently navigating interactions between seismic hazards and vulnerabilities. This capability is crucial for large-scale seismic risk prioritization, where traditional mechanics-based methods may be infeasible due to extensive data and computational demands. GAs enhance assessments of seismic fragility and performance, allowing robust evaluations that consider various factors, including evolving seismic classifications and specific building demands [10, 14]. Incorporating advanced computational techniques, such as finite element analysis, GAs facilitate detailed evaluations of structural behavior under seismic forces, fostering innovative solutions that enhance the resilience and safety of steel structures. As research progresses, GAs will play a pivotal

role in advancing seismic performance optimization, contributing to the development of robust and efficient design methodologies.

8 Conclusion

The survey underscores the transformative impact of interdisciplinary methods in steel structure design, highlighting how innovative node designs and connection performance strategies significantly enhance seismic resilience and load-bearing capabilities. Experimental studies, such as those on medium-sized telescope prototypes, affirm the practicality of these novel design approaches, offering crucial insights for future structural applications. The shift towards performance-based design methodologies, particularly the PBFD approach, has substantially advanced the comprehension of seismic behavior, especially in contexts where connection flexibility is paramount.

The survey emphasizes the urgent need for contemporary design codes to integrate performance-based criteria, underscoring the role of experimental validation in the development of new design techniques. Future research should focus on comprehensive experimental studies to validate the robustness of advanced methodologies, such as the robust extended Kalman filter (REKF), across varied conditions, which could herald significant innovations in seismic design. Furthermore, exploring the interactions between helium and defects in yttria, alongside complex diffusion models, promises to drive substantial advancements in steel structure design.

Ultimately, this survey highlights the critical role of interdisciplinary collaboration in driving innovation and addressing the intricate challenges in steel structure design, setting the stage for more resilient and efficient structural solutions.

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