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AIJ structural stability topics in steel structures: summary of the AIJ-SSRC collaboration

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Abstract
The Architectural Institute of Japan (AIJ) and the Structural Stability Research Council (SSRC) have collaborated on the Japanese-to-English translation of the *AIJ Stability Problems of Steel Structures*. The second edition of this publication was issued in 2013, followed by a third edition in 2022, both in Japanese. The purpose of this collaboration is to present recent research and developments conducted in Japan on structural stability, as documented in the AIJ publication, to an English-speaking audience. This paper summarizes the topics discussed in the AIJ-SSRC collaboration document, introducing three of the six topics included in the book. The first topic relates to methods for evaluating plastic deformations and high-performance specifications for steel braces in seismic applications. This section presents novel configurations for braced-frame structures based on theoretical and experimental research. The second topic examines the lateral-torsional buckling behavior of I-shaped beams with partial restraints, focusing on the influence of column stiffness on beam lateral-torsional buckling resistance in steel-framed buildings. The third topic summarizes advancements in the study of beam-columns in structural steel buildings, highlighting current research trends in Japan related to the strength and deformation capacity of beam-column members.

1. Introduction
The Structural Stability Research Council (SSRC) is an organization that brings together researchers and practitioners worldwide focused on structural stability. One of SSRC's initiatives is the work of its International Liaison, whose objective is to disseminate knowledge and remain informed about the latest developments in structural stability research and practical applications

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from different parts of the world. Recognizing the importance of disseminating these advancements, the AIJ Subcommittee for the Stability of Steel Structures and SSRC have established a collaboration aimed at bridging research developments between Japan and the global community. The primary objective of the AIJ-SSRC Collaboration is to translate into English the advancements in structural stability research conducted in Japan, thereby making these critical findings accessible to a broader audience.

The Subcommittee for the Stability of Steel Structures of AIJ, under the Managing Committee on Steel Structures, was established to continuously study stability and instability problems that govern the design of steel structures in order to respond to the development of new materials, the emergence of new structural forms, and the creation of new design concepts. The subcommittee prepared the first edition of "The Recommendations for Stability Design of Steel Structures" in 1980. Since then, these recommendations were revised in 1996, 2009, and 2018. Meanwhile, the subcommittee has been collecting the contents that were not necessarily fully clarified during the revisions, addressing new issues and the findings, and discussing the new evaluation methods and design methods that can reflect the behavior of actual structures more precisely than before. Despite the spread of the COVID-19 pandemic restricting the subcommittee's activities since the beginning of 2020, the results were published as "*Stability Problems of Steel Structures* 2022", delaying for about one year from the original schedule. The book was the fourth edition of the "*Stability Problems of Steel Structures*," which was published in 1992, 2001, and 2013, respectively. For collaboration with SSRC's International Liaison, the subcommittee established in 2023 the International Collaboration on Stability Problems of Steel Structures Working Group.

This collaboration is a work in progress, focusing on the Japanese-to-English translation of the AIJ's in *Stability Problems of Steel Structures* (AIJ, 2013 and 2022). This publication serves as a comprehensive resource documenting recent advancements in structural stability research. By providing English translations, the AIJ and SSRC aim to foster knowledge exchange and collaboration among structural engineers worldwide, encouraging the integration of innovative practices into global design standards.

The AIJ-SSRC collaboration document is a compendium of six chapters of topics in the field of structural stability, namely:

1. Methods for evaluation of plastic deformations and high-performance specifications for steel braces.
2. Lateral-torsional buckling of I-shaped beams with end restraints
3. Strength and deformation capacity of column members
4. Local buckling behavior of plate elements in building structural components
5. Influence of member stability on frame behavior
6. Flexural buckling of steel pipe piles in liquified soil

This paper focuses on summarizing three of these chapters, emphasizing their theoretical foundations, experimental findings, and practical implications for the design of steel structures. These topics include:

1. Evaluation methods for plastic deformations and high-performance specifications for steel braces in seismic applications. This section explores innovative configurations for braced-frame structures, grounded in both experimental and analytical research.
2. Investigations into the lateral-torsional buckling behavior of I-shaped beams with partial restraints, particularly examining the influence of column stiffness on beam stability in steel-framed buildings.
3. Research advancements related to beam-columns in structural steel buildings, with a focus on the strength and deformation capacity of these types of members.

2. Methods for Evaluation of Plastic Deformations and High-Performance Specifications for Steel Braces

Steel braces are integral structural elements widely utilized in steel-framed structures due to their high strength, stiffness, and cost-effectiveness. When subjected to cyclic axial loading, these braces undergo buckling in compression and plastic deformation in tension, which leads to strength and stiffness degradation. Local buckling, in particular, can result in concentrated plastic strains, potentially causing premature fractures in braces. Addressing these issues, the chapter focuses on methods to evaluate plastic deformation capacity and advanced specifications for high-performance steel braces in seismic applications.

2.1 Post-Buckling Hysteresis Behavior and Plastic Deformation Capacity of Steel Braces Simulated by One-Dimensional Element Models

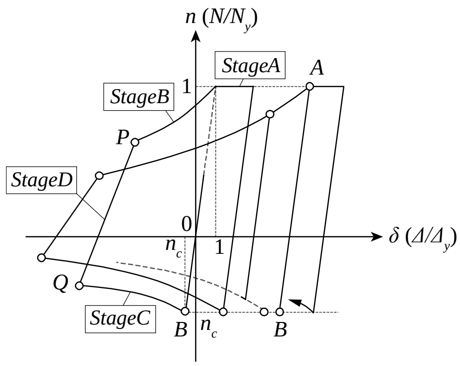
This section examines the post-buckling hysteresis behavior and plastic deformation capacity of steel braces under cyclic loading. The response of steel braces is primarily influenced by global buckling, local buckling, and subsequent fracture. These behaviors lead to strength and stiffness degradation, which are critical factors in determining brace performance during seismic events. To analyze these phenomena and enhance brace design, empirical models, including phenomenological and refined theoretical models, have been widely utilized.

Hysteresis Curve Model

The Shibata-Wakabayashi (SW) model (Fig. 1) is a phenomenological model to simulate the cyclic behavior of steel braces (Shibata et al. 1982). This model simplifies the hysteresis response into four distinct stages, making it both practical and accurate for many applications. By employing normalized force and displacement relationships, the SW model provides an efficient framework for estimating brace behavior. As discussed in the AIJ-SSRC collaboration document, updates to the SW model have addressed limitations, particularly in predicting post-buckling strength and deformation capacity. These refinements include calibrations to coefficients and considerations of cumulative plastic deformation, resulting in more precise performance predictions.

Evaluation of Plastic Deformation Capacity

Plastic deformation capacity is closely linked to local strain concentrations that occur at buckling points. As shown in Fig. 2, these concentrations are evaluated using strain concentration ratios, which account for normalized deformation and maximum tensile strain (Takeuchi et al. 2011). For braces with round-HSS or I-shaped cross-sections, equations are developed to calculate strain ratios based on material and geometric properties. Advanced methodologies also consider rotational angles and bending moments, integrating local and global buckling effects into deformation evaluations. Finite element analysis (FEA) has been extensively used to validate these theoretical approaches.



$$n = \begin{cases} 1 & \text{(Stage A)} \\ f_t\left(\delta_A - \delta\right) & \text{(Stage B)} \\ -f_c\left(\delta_B + \delta_c - \delta\right) & \text{(Stage C)} \\ n_P + \dfrac{n_P - n_Q}{\delta_P - \delta_Q}\left(\delta - \delta_P\right) & \text{(Stage D)} \end{cases}$$

Figure 1: Shibata-Wakabayashi Model

Experimental studies have provided robust validation for phenomenological and theoretical models. Tests have demonstrated that strain concentrations typically occur at the edges of buckled regions, significantly affecting deformation capacity (Hashimoto et al. 2017). Comparisons between experimental and simulated results highlight the accuracy of updated SW models, particularly in capturing post-buckling degradation and cumulative plastic strain. These refinements make the models reliable tools for understanding brace behavior under cyclic loading. The key findings of this section include the improvements made to SW models, which enhance predictions of compressive strength and post-buckling behavior, and the effective application of strain ratio equations for both round-HSS and I-shaped braces. Experimental validation underscores the accuracy of these methods, though some conservatism is noted for braces with larger slenderness ratios.

In conclusion, the integration of phenomenological models, advanced theoretical approaches, and experimental validation is essential for accurately predicting post-buckling behavior and plastic deformation capacity in steel braces. These advancements contribute to the development of more resilient structural designs, particularly for applications in seismic engineering.

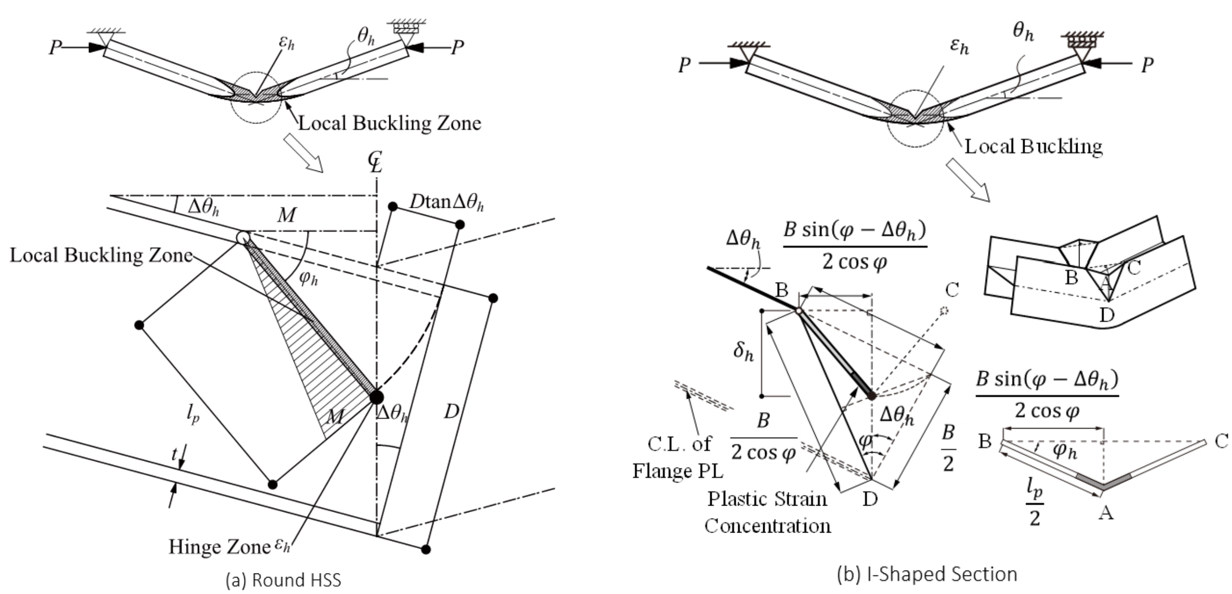


Figure 2: Strain concentration ratio concept

2.1 Steel Tube Brace with Initial Eccentricity

This section explores the concept of steel tube braces with an intentional initial eccentricity introduced to allow independent control of tensile strength and elastic stiffness in structural braces (Skalomenos et al. 2017, Shimada et al. 2018). Figure 3 illustrates the concept of the steel brace with an induced eccentricity. By introducing an offset between the brace's axis and its connection points, the relationship between stiffness and strength can be decoupled, enabling the design of braces with enhanced strength without a proportional increase in stiffness. This adjustment is critical in seismic design, where increased stiffness can lead to shorter natural periods and higher lateral force demands.

The behavior of steel tube braces with initial eccentricity is discussed in terms of axial force and deformation relationships. Due to the additional bending moments caused by eccentricity, the braces exhibit reduced initial stiffness compared to those without eccentricity. However, the post-yield stiffness is significantly higher, enhancing deformation capacity by distributing yielding more evenly across the brace material. This characteristic helps mitigate issues like story drift concentration after yielding.

Analytical models and design equations are introduced to predict the performance of braces with initial eccentricity. These models account for factors such as cross-sectional properties, initial eccentricity, and axial force. They provide formulas for elastic stiffness, yield strength, and post-yield behavior. Laboratory tests and finite element analyses (FEA) validate the accuracy of these models, demonstrating close agreement between experimental and predicted results for most parameters. However, discrepancies are noted in post-yield stiffness predictions for braces with high slenderness ratios due to assumptions about the effective cross-sectional area and eccentricity. The section also highlights the range of adjustments possible through initial eccentricity. By varying the eccentricity ratio, designers can achieve a wide range of stiffness and strength combinations while maintaining the same cross-section. This flexibility is particularly beneficial for optimizing designs in seismic applications, where balancing stiffness, strength, and deformation capacity is critical.

The introduction of initial eccentricity in steel tube braces represents an innovative approach to improving seismic performance. It enables greater control over structural properties, enhances deformation capacity, and reduces stiffness-related seismic demands. While the models and equations developed provide accurate predictions, further research is suggested to address discrepancies in specific cases, such as braces with high slenderness ratios.

2.3 Mitigation of Compressive Strength Reduction in Hollow Section Braces with Single Shear Connections

Hollow Structural Section (HSS) braces play a critical role in steel frame structures by contributing to their lateral resistance. However, the compressive strength of these braces can be significantly reduced when single shear splice plate connections are employed due to eccentricity between the splice and gusset plate axes. This section explores methods to mitigate this reduction, focusing on a novel connection design using eccentrically installed cruciform splice plates (Tagawa et al. 2018). The proposed design aims to align the member axes of the brace, gusset, and splice plates to improve compressive performance.

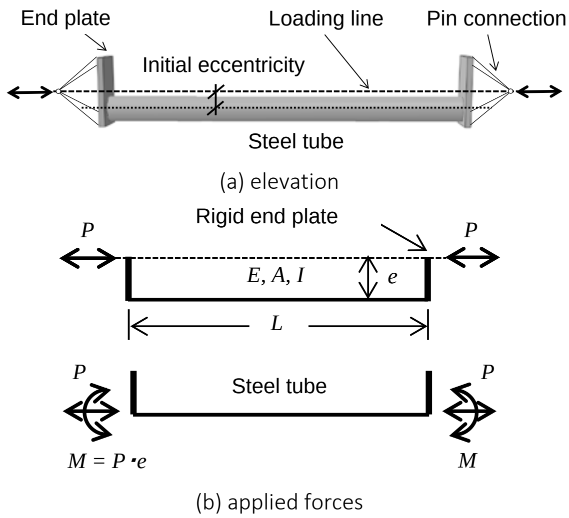


Figure 3: Concept of steel tube braces with eccentricity

In conventional connections, the eccentricity introduced by single shear splice plates leads to reductions in compressive strength and can result in undesirable local connection failures, especially during seismic events (see Fig. 4).

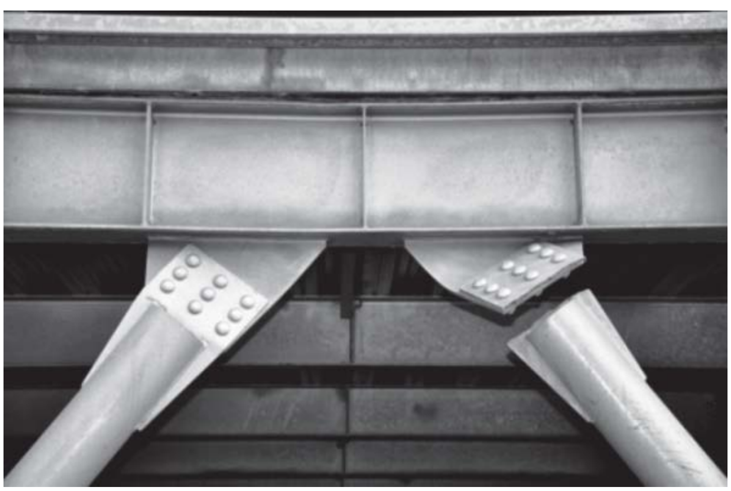
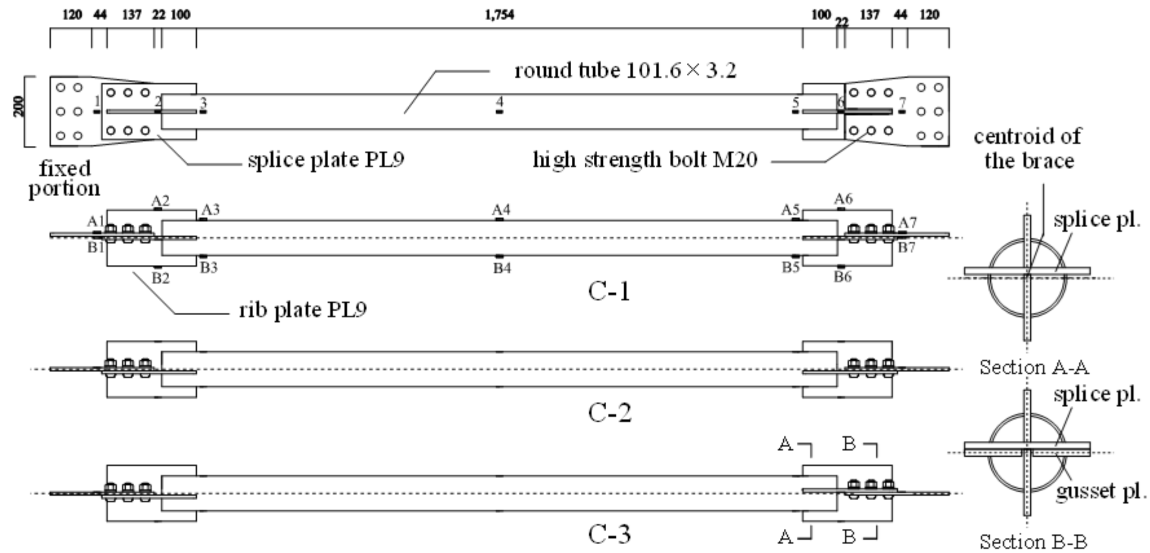


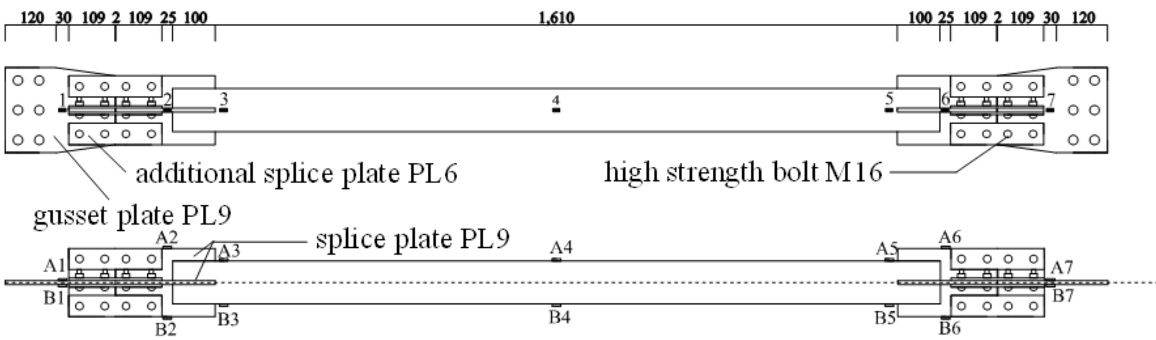
Figure 4: Damage in a steel brace due to seismic forces

Previous studies have explored various configurations, such as double splice plates and rib-stiffened designs, to address these challenges. However, these solutions often come with higher construction costs and complexity.

To evaluate the efficacy of eccentrically installed splice plates, the four test specimens shown in Figure 4 were designed and tested. Specimens included braces with and without eccentricity in the splice plates, along with rib-stiffened gusset plates to prevent local connection failures. The experimental setup applied axial compressive loads to the braces while monitoring global buckling and axial displacement. The results indicated that specimens with eccentrically installed splice plates exhibited significantly reduced out-of-plane displacements and higher compressive strengths compared to conventional designs.



a) Test specimens C-1 to C-3
Figure 5: Specimens for experimental tests



b) Test specimen C-4
Figure 5: Specimens for experimental tests (continued)

Finite element analyses (FEA) were conducted to validate the experimental results and extend the study to braces with varying slenderness ratios. The analyses confirmed the improved performance of eccentrically installed splice plates, demonstrating close agreement with experimental data. For slenderness ratios up to 172, the proposed connection design maintained higher compressive strength, closely aligning with values predicted by the AIJ Design Standard for Steel Structures.

The findings highlight the importance of aligning member axes and reinforcing gusset connections to mitigate compressive strength reduction. By using eccentrically installed splice plates or rib-stiffened configurations, designers can enhance the performance of HSS braces in steel structures. These adjustments also improve constructability and reduce the risk of local failures during seismic events.

3. Lateral-Torsional-Buckling of I-Shaped Beams with End Restraints

Lateral-torsional buckling occurs when a beam's compression flange moves laterally, causing torsional deformation. The stability and strength of beams under such conditions depend significantly on their boundary conditions, including lateral bending and warping restraints provided by structural members like columns and slabs. This section compiles and analyzes studies on these effects to develop practical methods for incorporating restraint influences into design (Takeya et al. 2019, Kimura et al. 2018) .

3.1 Restraints Provided by Connecting Elements

Structural members connected to beams contribute to their stability by providing lateral, torsional, and warping restraints. The following elements are analyzed in detail:

Joists and Floor Slabs: Joists and slabs act as lateral bracing systems, reducing out-of-plane displacement and torsional rotation. Reinforced concrete slabs, in particular, enhance stability by increasing torsional resistance through their shear connectors. The composite action between the slab and beam improves the system's ability to resist lateral-torsional buckling.

Columns: Columns connected at beam ends offer lateral and warping restraints. The torsional stiffness of columns, along with the stiffness of the panel zone, directly influences the effective buckling length and resistance of the beam. Increased torsional stiffness at the beam ends significantly enhances lateral-torsional stability.

Fig. 6 depicts conceptually the effect of the end supports and the flooring system on the beam lateral-torsional buckling resistance.

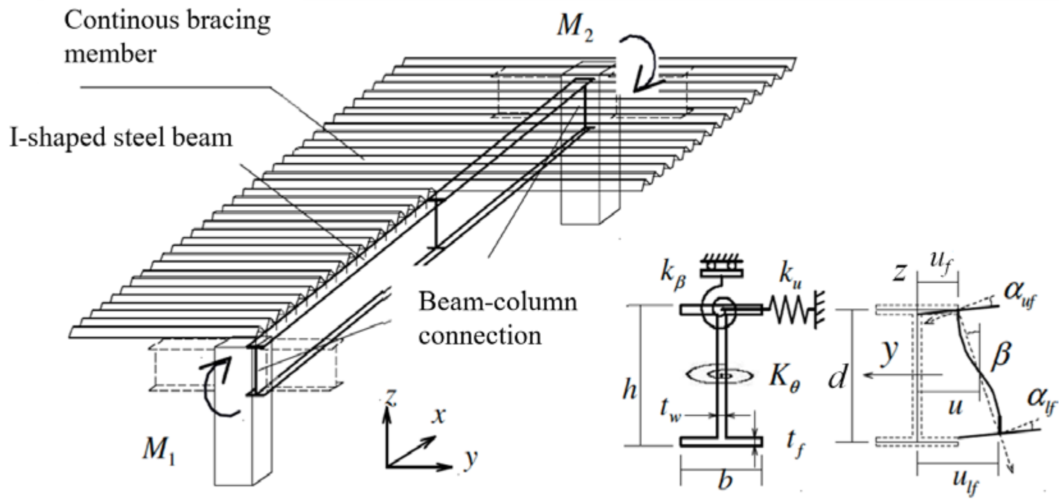


Figure 6: Lateral-torsional buckling of a continuously braced I-beam with end-restraints

3.2 Lateral-Torsional Buckling Strength

The elastic buckling strength of I-shaped beams is derived using theoretical models that incorporate the effects of end restraints. A displacement function is formulated to represent the buckling mode shape, accounting for combinations of lateral and torsional boundary conditions. Using the Galerkin method, the elastic lateral-torsional buckling strength is calculated with Eq. 1 based on the cross-sectional properties of the beam (I_y = moment of inertia about the weak axis, I_w = warping constant), the modulus of elasticity, E, and the beam length, l.

$$M_{cr} = \frac{\pi^2 E \sqrt{I_y I_w}}{l^2} K'_{cr} \tag{1}$$

In this equation, the value of K'_{cr} captures the influence of the end-restraints, as shown in the AIJ – SSRC collaboration document.

The analysis demonstrates that beams with fixed or restrained ends exhibit significantly higher elastic buckling strengths than those with simple support conditions.

Inelastic buckling behavior is also examined, considering material nonlinearities, residual stresses, and initial geometric imperfections. Numerical simulations and experimental studies show that the torsional stiffness at beam ends is a major factor in determining the beam's maximum strength and deformation capacity. Beams with higher end stiffness show improved post-buckling performance, reducing strength degradation and enhancing overall stability. The study also highlights the influence of moment gradients, which play a key role in resisting lateral-torsional deformations.

3.3 Experimental Testing

Theoretical predictions are validated through experimental tests on beams with various end restraint configurations. Fig. 7 shows the laboratory setup for one of the test campaigns developed for determining the influence of columns and top flange bracing (Yoshino et al. 2020). The tests involve cyclic and monotonic loading scenarios to evaluate the effects of both elastic and inelastic deformations.

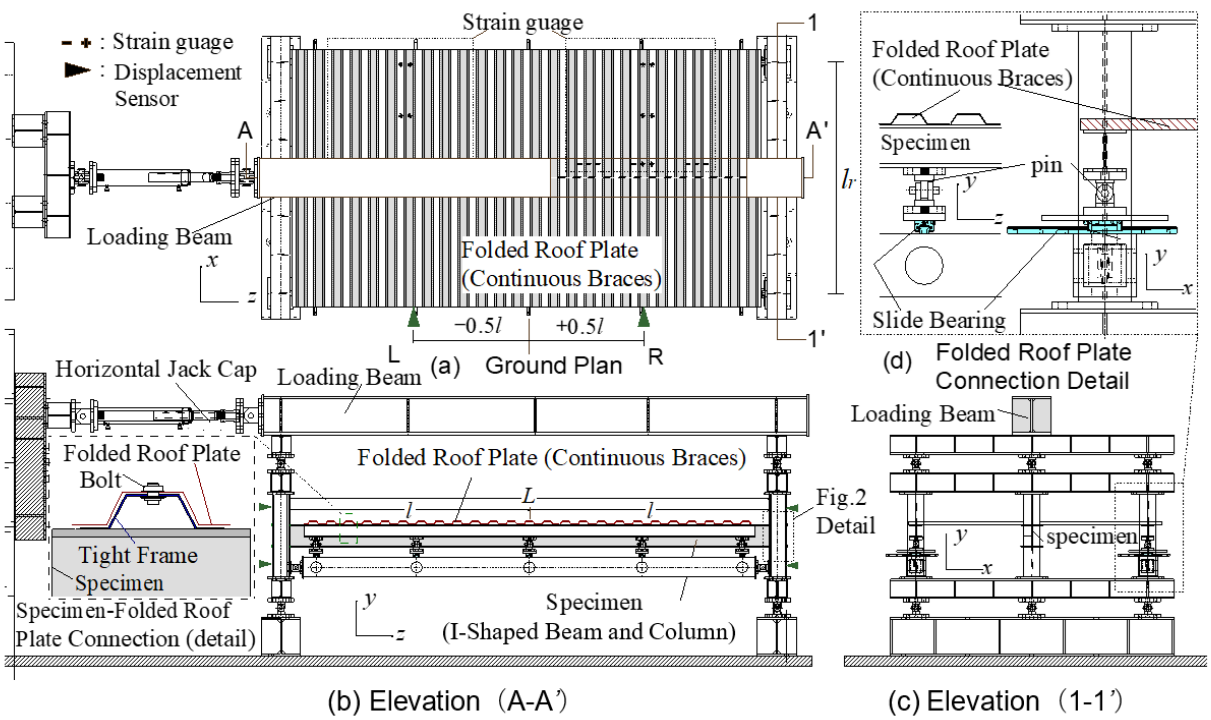


Figure 7: Test setup

A summary of the findings from the experimental results include:

- Beams with fully fixed or warping-restrained ends show significantly improved buckling resistance compared to those with simple support conditions.
- Continuous bracing along the beam's length mitigates lateral-torsional deformations and enhances post-buckling performance.

- Interaction effects between end restraints and bracing systems are critical in maintaining stability during extreme loading conditions, such as those experienced in seismic events.

The study provides practical design equations and methodologies for calculating the elastic and inelastic buckling strengths of beams under varying boundary conditions. These equations incorporate the effects of end restraints, bracing systems, and moment gradients, offering a robust framework for designing safer and more efficient structural systems. The findings highlight the importance of considering realistic end conditions and bracing effects in design practices, especially in seismic regions where lateral-torsional stability is critical.

4. Strength and Deformation Capacity of Column Members

Steel columns in buildings are designed to resist both axial and lateral forces, often requiring inelastic strength to accommodate seismic demands. Local buckling is a critical factor influencing the strength and deformation capacity of these columns. This chapter of the AIJ-SSRC collaboration document focuses on evaluating column performance under these conditions, introducing analytical models, experimental studies, and design equations for high-strength steel columns ().

4.1 New Design Models for High-Strength Columns

A design model for columns using high-strength steel H-SA700 (F_y = 780MPa [113ksi]) was developed to address elastic buckling limits and flexural-torsional buckling. Analytical equations estimate elastic buckling loads and the in-plane elastic limit, considering parameters such as slenderness ratios and bending moments at the column ends. Interaction curves for moment and axial force (m-n curves) demonstrate the influence of slenderness and bending moment ratios on column performance. The models offer improved predictions for columns subjected to complex loading conditions.

4.2 Experimental Studies and Validation

Experimental programs examined rectangular and square hollow structural section (HSS) columns (see Fig. 8.). The studies assessed ultimate strength, inelastic deformation capacity, and collapse mechanisms. For square-HSS columns, the safety factors in design codes were found conservative due to the limited role of flexural-torsional buckling. Tests confirmed that meeting width-to-thickness ratio limits ensures plastic deformation capacity and full plastic moment achievement.

A summary of the findings from the experimental results include:

- Local buckling significantly reduces column strength and deformation capacity, particularly under high axial forces.
- The position of maximum bending moment shifts from the column ends to the midsection during ultimate deformation, indicating the influence of the P-δ effect.
- Design limitations specified in the AIJ Recommendations for Plastic Design (PD) and Limit State Design (LSD) are generally conservative, particularly for columns nearing width-to-thickness ratio limits.
- The proposed design methodologies discussed in the AIJ-SSRC collaboration document incorporate flexural-torsional buckling and in-plane elastic limits, improving safety and efficiency in column design. These models, validated through experiments and numerical

simulations, provide reliable tools for engineering practice, particularly for high-strength steel columns in seismic applications.

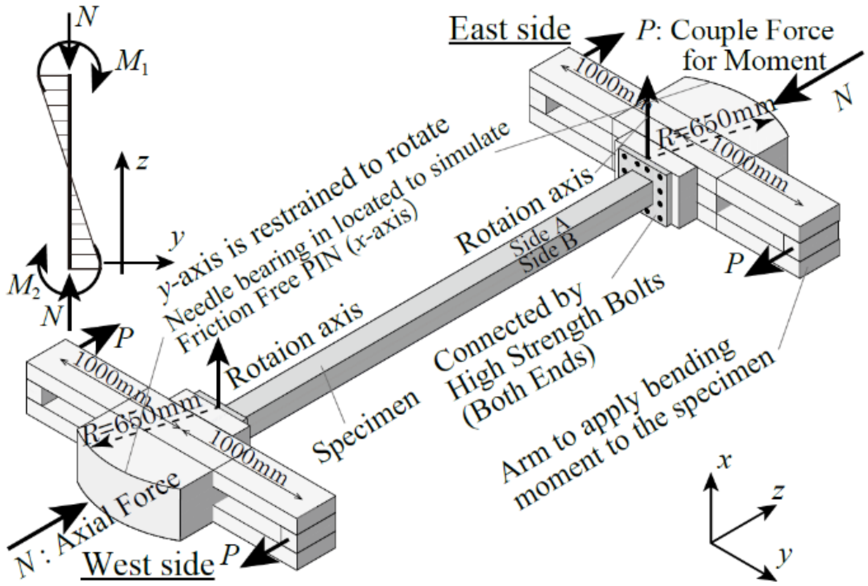


Figure 8: Beam-column test setup

5. Conclusions

The AIJ-SSRC collaboration highlights significant advancements in structural stability research, bridging critical knowledge from Japan to the international community. By translating and summarizing key findings from the AIJ *Selected Structural Stability Topics in Steel Structures*, the collaboration aims to contribute to the understanding of structural stability in steel structures, particularly in seismic applications. The summarized topics emphasize the integration of theoretical models, experimental validation, and practical design methodologies to facilitate the development of innovative solutions that enhance safety and resilience in seismic regions worldwide.

Acknowledgments

Gratitude is extended to the Architectural Institute of Japan (AIJ) for their invaluable support and collaboration in the translation of the AIJ *Selected Structural Stability Topics in Steel Structures* from Japanese into English. This effort has made significant advancements in Japanese structural stability research accessible to a broader, international audience.

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