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Preface

These proceedings contain the papers presented at the TENTH INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES (ICASS 2020) held in Chengdu, China, from 21 to 23 August 2022. The international conference series on Advances in Steel Structures was initiated in 1996 under the support of The Hong Kong Polytechnic University, which remains very active in fostering its continuation—joined a few years later by the Hong Kong Institute of Steel Construction.

These proceedings bring together most recent findings in numerical, theoretical and experimental research, as well as its practical implementation in design practice in the areas of Assembled Structure, Bridge, Cold-formed Steel, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue, Fire, High-Strength Steel, Impact and Protection, Intelligent Construction, New Material, Seismic Resistance, Stability, Stainless Steel, Structure Systems, Testing & Monitoring. The papers presented in these proceedings come from a wide range of countries/regions and will be a great reference source.

Specially, the subject matter has been categorized under the broad heading of:

**Volume I:** Keynotes Lectures, Assembled Structure, Bridge, Cold-Formed, Composite, Connections, Corrosion, Fracture & Collapse, Design & Analysis, Direct Analysis, Fatigue


Each of the papers was subjected to stringent review by a panel of experts in the respective area. This peer review began with an assessment of the submitted abstracts and following this, authors were invited to submit their full manuscripts. Each manuscript was then carefully reviewed by relevant experts, and their recommendations on accepting, rejecting or modifying the submissions were strictly adhered to, before inclusion in the conference proceedings.
SEISMIC PERFORMANCE OF SPATIAL STEEL BEAM-COLUMN CONNECTIONS

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Abstract: This paper presents a finite element analysis for spatial beam-column connections in steel frame to better understand the structural behavior of spatial connections. After the simulation and validation of experimental results, a total of 7 refined 3D models, including beam-to-column connections at different positions in the steel frame, were created and analyzed cyclically through the nonlinear finite element program ABAQUS to investigate the spatial coupling effect. The moment-rotation relationships and TI index distribution across the width of beam flanges, were discussed in detail to elucidate the mechanical performance interaction between strong-axis and weak-axis connections. Results showed that there is obvious interaction between two beams in strong-axis or weak-axis connections, and the plane exterior connections has better hysteresis performance. While the interaction of strong-axis connection and weak-axis connection slightly affected each other’s hysteresis performance, and thus the coupling effect of spatial connections is not evident.

Keywords: steel frame; spatial connection; seismic performance

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1 INTRODUCTION

Steel special moment frames (SMFs) are extensively used in middle- and high-rise buildings because this systems is considered to have excellent ductility. A typical connection used in SMFs is the web-bolted flange-welded connection as it is simple to fabricate and economical, in which a complete joint penetration (CJP) groove weld was used to connect the beam flange to the column in the field, and the beam webs are field bolted to a shear tab which is already welded to the column.

Unfortunately, brittle fracture in or around the groove weld between the beam flanges (primarily bottom flange) and the column flange was observed in more than 150 steel SMRF buildings after the January 17, 1994 Northridge earthquake. Causes for the poor performance of these welded connections of Pre-Northridge were mainly conjectured as the poor workmanship leading to weld defects, and poor detailing connections producing stress concentrations at the beam flange welds [1-3].

To avoid such unexpected failure, the seismic performance of various moment connections has been extensively studied since the Northridge earthquake, including various alternatives of reduced beam section (RBS) connections [4-8] and reinforced connections [9-13] to
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improve the seismic performance of moment connections through forcing the plastic hinge a small distance away from the column face.

Nevertheless, the majority of past studies were conducted on the plane beam-column connections, mostly on strong-axis moment connections, leading to various improved connection alternatives are only prequalified for plane strong-axis connections. The actual seismic load direction may be along any direction, and thus the beam-column connections may be subjected to two-directional bending moments and shear forces transmitted by the strong-axis and weak-axis connections.

Bu et al. [14-15] reported an experimental study about the spatial semi-rigid beam-column connections with T-stub, and the results showed that the mechanical characteristics under spatial loads were different from plane semi-rigid connections. Hu et al. [16] conducted an experimental study for three types of prefabricated steel beam-column connections, and the comparison results showed that the 3D loading configuration changed the strain distribution in the strong-axis connection and made continuity plates more critical than beam flanges. Experimental results of spatial end-plate bolted connections [17-19] showed that the loads in weak-axis connections could increase the stiffness of the strong-axis connections, and spatial loads have some influence on the structural behavior of strong-axis or weak-axis connections.

The beam-column connections are basically in the form of spatial connections in practical engineering, experimental and theoretical study is still needed for the spatial beam-column connections. The primary objective of this research described herein is to examine the following two issues: (1) the structural behavior of spatial beam-column connections; (2) the effect of two strong-axis connections or two weak-axis connections; and (3) the mutual effect of strong-axis connections and weak-axis connections.

The structure of the paper is as follows. First, the validity of the finite element modeling method in this paper is verified by comparing with the experimental results. Second, the interaction of two strong-axis connections or two weak-axis connection in plane beam-column connections was discussed. Third, the interaction between the strong-axis connection and weak-axis connection in spatial beam-column connections was discussed. Finally, conclusions and future developments are drawn.

2 VALIDITY OF FINITE ELEMENT METHOD

Due to the scarcity of experimental study for spatial beam-column connections, such as the complex process and large expense, the numerical simulations are being increasingly used to analyze the structural behavior. The ABAQUS software was selected to conduct the cyclic performance of spatial connections, as it is a comprehensive software with many element types and material models allow for the modeling of engineering structures. The experimental results of specimen Ⅱ reported by Hu et al. [16] were used as a reference to validate the accuracy of the finite element methods (FEM) in this study through comparing the failure mode and moment versus rotation hysteretic loops of test and FEM.

2.1 Modeling techniques

Specimen Ⅱ reported by Hu et al. [16] consisted of a 2430 mm height H700×500×20×35 column, a 2750 mm long H400×400×13×21 beam in strong-axis connection, and a 2450 mm long H400×400×13×21 beam in weak-axis connection. And the specimen Ⅱ was prefabricated with beams and column as a whole. The axial load was 2000 kN applied firstly on the top pf the column and remained constant during the test. And then the asymmetric cyclic loads were imposed on the ends of the beams through displacement control, as shown in Figure 1.
The finite element model of specimen II was shown in Figure 2. The steel profiles were modeled with 3D solid elements, and eight-node solid nonconforming elements (C3D8I) were used for all steel components. Different mesh sizes were used for this model, and a fine mesh was applied at the regions near the beam-column connection region, and a coarser mesh was used elsewhere, as displayed in Figure 2. The binding constraints were applied for the surface of the beams and the column, and the welds were not modeled explicitly. The boundary conditions were the same as in the test, with the x, y, and z directions restricted at the base of the column, and the x and y directions restricted at the top of the column, and also the lateral restraint was applied for the beams.

The plasticity model was based on the von Mises yielding criteria with the associated flow rule. The material property of steel profiles was set as multi-linear true stress-strain relationship based on the tensile coupon test results reported by Hu et al. [16]. The yield strength was 292.3, 273.4 and 349.7 MPa for the beam, column web, and column flange respectively, with the corresponding yield strain was 0.00147, 0.00134 and 0.00534. The ultimate strength was 449.0, 439.2 and 541.1 MPa for the beam, column web, and column flange respectively, with the corresponding yield strain was 0.20173, 0.19103 and 0.12727. Both material and geometric nonlinearities were considered in the FEM.

2.2 Verification of the created model

The moment ratio \((M/M_p)\) versus story drift angle \((\theta)\) hysteretic responses of the subassemblies extracted from the test are compared with that of the numerical analysis, as depicted in Figure 3. The ordinate is the test moment \(M\) normalized by the calculated full plastic moment \(M_p\) of the steel beam, where \(M\) is the bending moment at the column face, calculated as the beam end load multiplied by the distance between the loading point and the column face, and \(M_p\) is the full plastic moment, calculated as the plastic section modulus of the connected beam multiplied by the measured beam yield strength. The abscissa is the story drift angle \((\theta)\) calculated as the loading displacement divided by the distance between the loading point and the column centerline.

One can observe from Figure 3 that the initial rotational stiffness, calculated as the slope of the elastic unloading curve, of FEM and test matched well and the curves showed the same trend at the plastic stage. The maximum load in the FEM was lower than that of the test specimen, similar with analytical results simulated by Hu et al. [16]. This was probably due to the following two issues: (1) the local high residual stresses in the weld fusion zone, which was not considered in the FEM; (2) the boundary conditions in the FEM were idealized, while the boundary conditions in the test or in the actual engineering were semi-rigidity in a certain degree. It is clear that the maximum value of \(M/M_p\) was greater than 1.0, which was because of the strain hardening effect of the connection components. The hysteretic curves in the FEM
and test both showed stable and reliable cyclic response. The hysteric curves in the FEM was plumper than that of test, which was attributed to the crack of fillet welds in the test.

Figure 4 presents the local behavior of FEM and test. It is observed that beam in weak-axis connection experienced local buckling in the beam flanges and web. The numerical results showed good agreement with the test results in deformation configuration.

Overall, the results of FEM satisfactorily represented the spatial connection behavior. And then, the finite element methods were used to better understand the traditional spatial beam-column connections in steel frame.

3 COMPARATIVE ANALYSIS OF CONNECTIONS IN DIFFERENT LOCATIONS

To better understand the structural behavior of spatial beam-column connections in steel frame, a total of 7 models were created, including beam-column connections in different locations, as shown in Table 1. 7 connection subassemblies were designated as: (1) PESC, plane exterior strong-axis connection; (2) PEWC, plane exterior weak-axis connection; (3) PISC, plane interior strong-axis connection; (4) PIWC, plane interior weak-axis connection; (5) SCC, spatial corner connection; (6) SEC, spatial exterior connection; (3) SIC, spatial interior connection. The traditional welded rigid connection was used in these models.

Modeling methods, geometry of beam and column, boundary conditions, and loading protocol for the all connections were the same as described for specimen II. The mesh generation of model SIC was shown in Figure 5 for example. The moment ratio ($M/M_p$) versus story drift angle ($\theta$) hysteretic responses, and the triaxiality index (TI), a measure of triaxial state of stress, was selected to evaluate the mechanical behavior and the local stress concentration and strain demand, which could be obtained according to Kim et al. [20].
Table 1: Connection forms.

<table>
<thead>
<tr>
<th>Model number</th>
<th>PESC</th>
<th>PEWC</th>
<th>PISC</th>
<th>PIWC</th>
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<td><img src="image3.png" alt="Diagram" /></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Model number</th>
<th>SCC</th>
<th>SEC</th>
<th>SIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connection form</td>
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<td><img src="image6.png" alt="Diagram" /></td>
<td><img src="image7.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

3.1 Plane beam-column connections

Moment ratio \((M/M_p)\) versus story drift angle \((\theta)\) hysteretic curves comparison of plane beam-column connections was illustrated in Figure 6. It is clear from the comparison that the cyclic performance of plane exterior connections and plane interior connections showed significant differences. No matter for plane strong-axis connections or plane weak-axis connections, the \(M/M_p-\theta\) hysteretic loops of the plane interior connections exhibited obvious pinching effect, and thus the plane exterior connections dissipated larger amounts of energy than that of the plane interior connections, indicating that there is obvious interaction between two beams in strong-axis or weak-axis connections.

![Graph](image8.png)
(a) Plane strong-axis connection

![Graph](image9.png)
(b) Plane weak-axis connection

Figure 6: \(M/M_p-\theta\) hysteretic curves comparison of plane beam-column connections.
Figure 7 plotted the equivalent plastic strain (PEEQ) comparison of plane beam-column connections at the moment of 5 times of yield displacement. One can observe that the failure mode of plane exterior connections was obviously different from that of plane interior connections. For plane exterior connections, the deformation concentrated on the beams near the beam-column interface, while the deformation concentrated on the panel zone for interior connections. It is clear from the comparison of Figures 7b and 7d, the deformation of panel zone of model PISC was much obvious than that of PIWC, which was attributed to the fact that the panel zone of weak-axis connections has two column flanges, much stiffer than the column web, considered as the panel zone of strong-axis connections.

![Figure 7: Equivalent plastic strain (PEEQ) comparison of plane beam-column connections.](image)

3.2 Spatial beam-column connections

Figure 8 shows the moment ratio ($M/M_p$) versus story drift angle ($\theta$) hysteretic curves for plane connection and spatial corner connections. “-S” in Figure 8 denoted the strong-axis connection in spatial connections, and “-W” denoted the weak-axis connection in spatial connections. As illustrated in Figure 8, plane exterior connection and spatial corner connection showed a comparable cyclic performance, indicating that interaction of strong-axis connection and weak-axis connection slightly affected the connection behavior.

$M/M_p$-$\theta$ hysteretic curves of spatial beam-column connections was provided in Figure 9. By comparing the hysteretic curves, we can observe that there seems to be nearly no interaction between the strong-axis connections and weak-axis connections, and there was significant interaction for two strong-axis connections or two weak-axis connections.

Figure 10 plotted the TI comparison along the width of the beam flange in the beam-column interface at the moment of 5 times of yield displacement. According to Kim et al. [20], TI values between -0.75 and -1.5 can cause reductions in the rupture strain of metals. It is observed from Figure 10a that the TI value of the plane strong-axis connection was much smaller than that of the spatial connections, and less than -0.75, indicating that the beam-column welds in plane connections seems to be more prone to fracture. The change regularity for weak-axis connection as shown in Figure 10b was not obvious, and the minimum TI value was slight larger than -0.75.

![Figure 8: $M/M_p$-$\theta$ hysteretic curves comparison of plane connection and spatial corner connections.](image)
4 CONCLUSION

This study aims to better understand the structural behavior of spatial beam-column connections in steel frame. Finite element analysis was conducted preliminary for beam-column connections at different locations. Major observations obtained from this study are summarized as follows. Extrapolation of the below conclusions to a substantial different size or configuration should be undertaken with care.

1. The results of FEM satisfactorily represented the spatial connection behavior, indicating the finite element methods described in this paper is effective.

2. There is obvious interaction between two beams in strong-axis or weak-axis connections, and the plane exterior connections has better hysteresis performance. The conclusion resulted from the experiments or finite element analysis of plane exterior connections does not apply to other connection forms.

3. The interaction of strong-axis connection and weak-axis connection slightly affected the connection behavior. The coupling effect of spatial connections might can be ignored.

4. For plane exterior connections, the deformation concentrated on the beams near the beam-column interface, while the deformation concentrated on the panel zone for interior connections.

5. Further research is needed to address the spatial coupling effect for beam-column connections with various connection details to different sizes of beams and columns.

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REFERENCES


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