

# Numerical Simulation of Chevron-Braced Moment-Resisting Frames Subjected to Dynamic Loading

ブレース付ラーメン架構の動的載荷性能を追跡する数値モデル

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## Abstract

This study develops and applies a numerical modeling framework for Chevron-Braced Moment-Resisting Frames representative of Japanese practice, with emphasis on response under dynamic loading. The model explicitly accounts for brace buckling, panel zone shear deformation, and bracing connection flexibility and is benchmarked against a series of previous Japanese experimental tests. The framework is further applied to pre-test numerical simulations of a forthcoming full-scale shake table experiment in Taiwan, with the objective of assessing its predictive capability under dynamic loading.

**Keywords: Braced frames, Bracing connections, Numerical modeling, Dynamic loading**

## 1. Introduction

Chevron-braced moment-resisting frames are commonly used in Japanese steel structures as a lateral force-resisting system. Unlike conventional concentrically braced frames, which are commonly used in Western practice, Japanese CBFs use moment-resisting beam-column connections in addition to chevron braces. Consequently, the seismic behavior of such structures is dominated by the coupling of brace buckling, beam and column flexural responses, and joint-related deformation mechanisms, such as panel zone shear deformation and bracing connection flexibility [1][2].

From previous experimental research, panel zones and gusset plate connections have been found to play an active role in the global and local response of Japanese CBFs, especially after brace buckling. These mechanisms are related to stiffness degradation, force redistribution, and story drift ratio during cyclic and dynamic loading [3][4]. However, modeling these coupled components in numerical analysis remains

difficult, especially when the aim is not only to reproduce experimental results but also to simulate structural responses to seismic loading.

Numerical modeling techniques for braced frames have been widely developed in the past decades, but most of the existing models tend to simplify or ignore panel zone deformation and bracing connection flexibility [5]. For Japanese CBFs, such simplifications may cause inaccurate estimation of stiffness, strength, and post-buckling behavior. Consequently, there is a need for numerical models that can model these mechanisms.

The aim of this research is to develop, validate, and apply a numerical modeling technique that can simulate the cyclic and dynamic response of Japanese CBFs. The proposed technique is validated by comparing with previous Japanese experimental research [1][2][3][4] and is further applied to pre-test simulations of a forthcoming full-scale shake table test [6]. By doing so, the study intends to evaluate both the validity and the predictive capability of the numerical

Table. 1 List of specimens

Author	Frame	Loading	Specimen	Brace Section	kL/r	Ductility	Bracing Connection
Muto et al. (1985)	1 bay-1 story	Cyclic	1	H-175x175x6x10	72	Moderate	Flexible
			2	H-200x200x10x12	64	Moderate	Flexible
			3	H-175x175x6x10	60	Moderate	Rigid
Inoue et al. (1988)	1 bay-2 story	Monotonic	1 and 2	H-80x80x6x6	36	Highly	Rigid
Okazaki et al. (2013)	1 bay-1 story	Dynamic	1	HSS-75x75x3.2	82	n/a	Flexible
			1	○HSS-76.3x4.2	95	Highly	Flexible
Seki et al. (2021)	1 bay-1 story	Cyclic	2	○HSS-76.3x4.2	71	Highly	Semi-rigid
			3	○HSS-76.3x4.2	85	Highly	Flexible
			4	H-75x75x6x9	94	Highly	Semi-rigid
			5	H-75x75x6x9	62	Highly	Rigid
			6	H-75x75x6x9	110	Highly	Flexible

model under dynamic loading.

## 2. Experimental database

Table 1 lists the tests used in this study: Cyclic-loading tests by Muto et al. [1] and Seki et al. [4], monotonically-loaded tests by Inoue et al. [2] and shake-table tests by Okazaki et al. [3]. All studies tested single-bay, concentrically-braced, moment-resisting frames. Muto et al. [1] tested 3 specimens that differed in the braces and bracing connections (rigid or flexible). Seki et al. [4] tested 3 specimens with round-HSS braces and another 3 with H-section braces, some with rigid and others with flexible bracing connections. Inoue et al. [2] tested two-story specimens, one with braces in inverted-V chevron and another in 2-story X arrangement (inverted-V in first story and V in second story), both specimens with rigid bracing connections. Okazaki et al. [3] tested 1 specimen with flexible bracing connections.

In addition to past experiments, a full-scale shake table test program will be conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. This project involves a three-story steel braced moment-resisting frame and includes two testing phases with different bracing systems: SBRB and braces [6]. This forthcoming experiment provides a unique opportunity to assess the predictive capability of the proposed framework when applied prior to experimental execution.

## 3. Numerical modelling framework

Numerical simulation was conducted using OpenSees, a general-purpose structural analysis framework [7]. As an example, Fig. 1 shows a model used for Seki et al. [4]. Beams and columns were modeled using force-based fiber elements with five

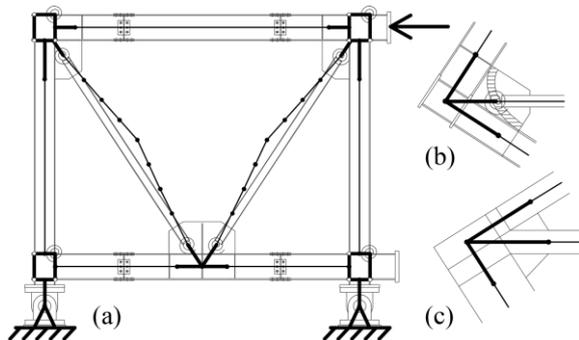


Fig. 1: Models: (a) Specimen by Seki et al. [4]; (b) Flexible bracing connection; and (c) Rigid bracing connection.

Gauss-Lobatto integration points. Braces were modeled following Karamanci et al. [8], dividing the brace into 8 displacement-based fiber elements with 5 Gauss-Lobatto integration points, and implementing an initial imperfection of 0.1% of the brace length. The flange and web of I-sections and walls of square-tube sections were discretized into  $2 \times 10$  fibers. Round-tube sections were discretized into  $4 \times 12$  fibers. All elements were assigned uniaxial material properties following a Menegotto-Pinto model adjusted to the reported yield strength. Cracks and fractures were not implemented. Stiffness and strength degradation due to local distortion of the sections were not implemented.

Panel zones were modeled following Gupta and Krawinkler [9], with rigid elements connected by three hinges and one trilinear rotational spring to represent shear response. Per Hsiao et al. [10], connections stiffened by gusset plates were represented by a rigid element over 75% of the gusset plate along the beam and 100% of the gusset plate along the column. These rigid elements were assigned three times the area and moment of inertia of the corresponding member. Flexible bracing connections were represented by a spring at the fold line. The spring was assigned the out-of-plane rotational stiffness of the gusset plate.

Geometric nonlinearity was considered using corotational transformation. The reported support conditions were replicated, and the reported loading history or ground motion was applied.

The time-history analysis replicating Okazaki et al. [3] employed a damping ratio of 3%, Newmark integration scheme ( $\beta = 0.5$  and  $\gamma = 0.25$ ) and a time increment of 0.01 s.

## 4. Benchmarking against experimental tests

Fig. 2 compares the simulation and test results for Specimens 1 and 2 by Muto et al. [1], both of which had flexible bracing connections. The simulated strength at first brace buckling was 25% and 40% higher than the corresponding strength from test, respectively. The simulation did not capture the strength degradation beyond drift angle of 0.025 rad.

Fig. 3 compares simulation and test for the dynamic tests by Okazaki et al. [3] under 70% motion. Where the simulation matched the test beyond brace buckling.

Fig. 4(a) to (c) compare the simulation and test results for Specimen 1, 2 and 3 by Seki et al. [4], respectively, which used round-HSS braces with flexible or semi-rigid bracing connections. The simulation closely matched the behavior before and

after brace buckling, but beyond the drift angle of 0.03 rad, the simulation did not capture the degradation seen in the test.

### 5. Predictive simulation of the Taiwan shake table test

In addition to benchmarking against past experiments, the numerical modeling framework was applied to pre-test simulations of a forthcoming full-scale shake table experiment to be conducted at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan [6]. The test specimen was a three-story steel braced moment-resisting frame designed according to Japanese practice and adapted to the constraints of shake table testing.

The predictive simulations adopted the same modeling assumptions, element formulations, and material models established through benchmarking against Japanese experimental data, without additional calibration, just using the Mills test report for material strength.

Several ground motions were examined to identify suitable candidates for the shake table testing, considering spectral demand relative to the fundamental period, nonlinear response under amplified excitation, and compatibility with the operational limits of the shake table.

The ground motion chosen was the JMA Kobe NS due to its high-level of damage imposed to the specimen with just 100% of the record, and due to its relatively low velocity and displacement.

A sequence of increasing-intensity JMA Kobe NS compatible with the capacity of the NCREE shaking table was applied to evaluate the expected seismic response (5%, 10%, 25%, 50%, 100% x3). The analyses focused on global response quantities, including story drift ratios, story shear distribution.

Figure 5 shows the global response of the specimen at the 50% excitation and the first 100% excitation. It shows progressive strength degradation and accumulation of residual drift. These trends are consistent with the behaviour observed in dynamic test. The predictive analyses were intended to assess the capability of the numerical model to capture dominant response mechanisms prior to experimental execution. Detailed comparison with measured shake table results will be performed following completion of the experimental program.

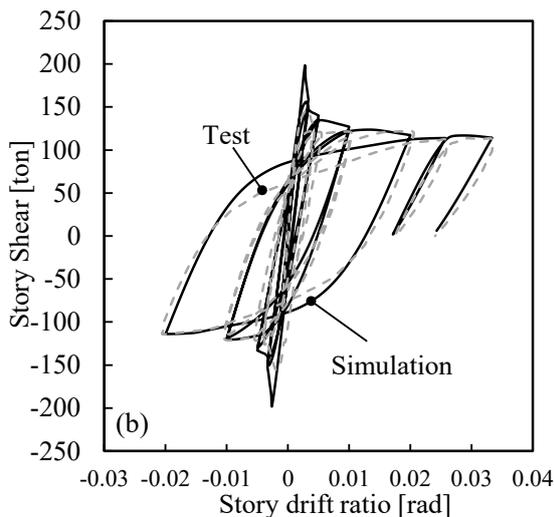
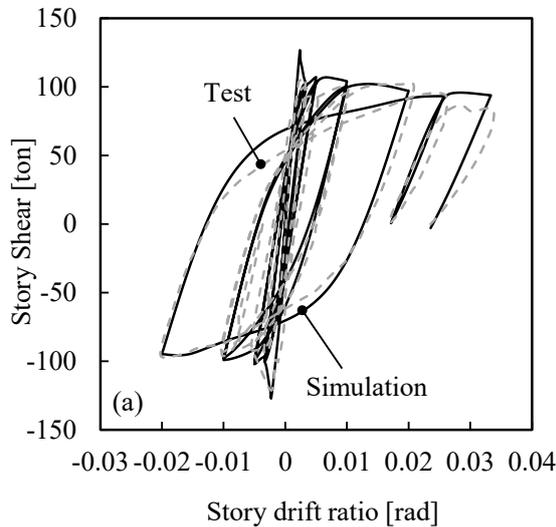


Fig. 2 Specimens by Muto et al. [1]: (a) Specimen 1 and (b) Specimen 2

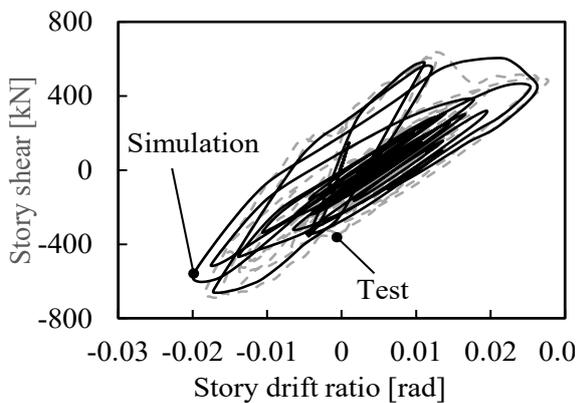


Fig. 3 Specimen by Okazaki et al. [3]:  
70% Motion

## 6. Conclusions

A simulation methodology for concentrically braced moment-resisting frames was examined against 12 specimens, some loaded statically others loaded dynamically.

The benchmark showed that the modeling scheme can reproduce the primary response trends observed in experiments.

The proposed simulation framework was used to predict the behavior of a full-scale 3-story Chevron-Braced Moment-Resisting Frame specimen.

This predictive application demonstrated that the proposed approach can be consistently extended to multi-story structures subjected to dynamic ground motion excitation. Although, quantitative accuracy will be assessed after completion of the experiments.

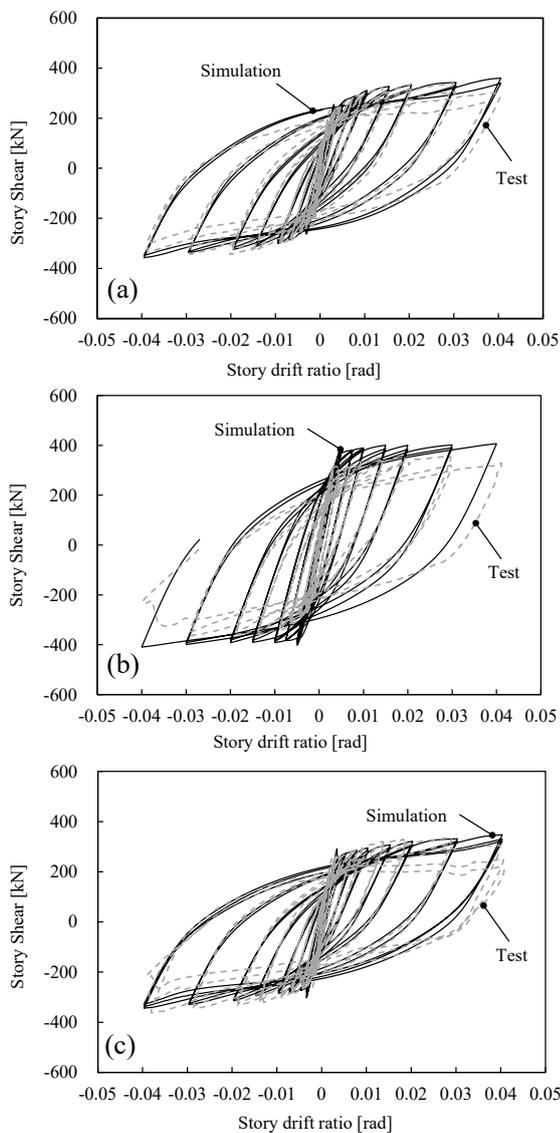


Fig. 4 Specimens by Seki et al [4]: (a) Specimen 1; (b) Specimen 2 and (c) Specimen 3

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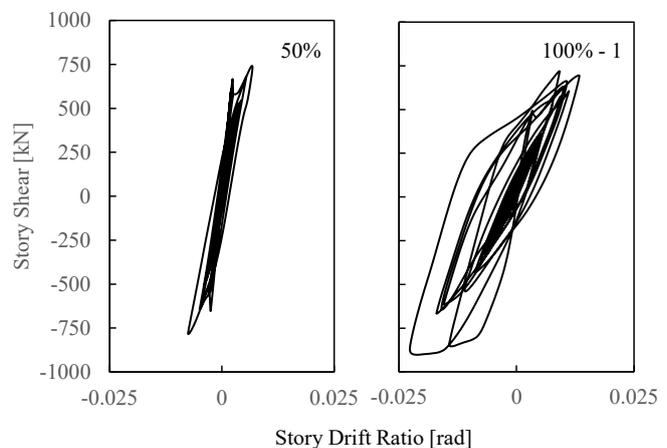


Fig. 5 Numerical simulation: Global response of Taiwan specimen for 50% and 100%-1 JMA Kobe NS