学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

Seismic Performance and Design of Japanese Steel Chevron-Braced Moment-Resisting Frames
(ブレース付ラーメン鋼架構の耐震性能と設計 )

Steel braced frames are widely used for buildings in high-seismicity regions due to their versatility in meeting stiffness and strength requirements. Japanese engineers often choose to place the braces in a "chevron" (or V or inversed-V) arrangement within a moment-resisting frame (MRF). In such systems, hereafter referred to as chevron-braced MRFs, the design of the beam intersected by braces poses a design challenge because this beam yields due to forces delivered by the tension and compression braces in combination with forces produced by moment-frame action. The energy dissipating mechanism of chevron-braced MRFs is dependent on the loading history owing to the statically indeterminate nature of the structural system and highly complex cyclic-loading response of the steel braces. Despite the very wide use, limited design guidance is provided by the Japanese design codes and standards on how to proportion the beams and braces and how to detail the bracing connections. The lack of guidance has allowed engineers to choose a very wide variety of designs, and this situation is at least partly responsible for the damage observed in steel chevron-braced MRFs after even the most recent earthquakes.

In order to address the above-mentioned concerns, a computational study was conducted with the following objectives: (1) to further the understanding of the seismic performance of steel chevron-braced MRFs, and thereby identify design concerns; (2) to derive proportion rules for the beams and braces in steel chevron-braced MRFs; (3) to derive bracing requirements to control the beam intersected by braces against severe transverse forces and torsional moments delivered by the braces, and bending moments arising from moment-frame action; and (4) to assess the seismic performance of Japanese steel buildings that employ steel chevron-braced MRFs. The computational study comprised two schemes, 3D nonlinear finite-element-method models to examine the interaction between chevron braces and MRF, and 2D nonlinear frame models with fiber elements to examine the time-history response of building systems under strong ground motions. Both schemes utilized general-purpose software, the former a commercial package ADINA and the latter an open-source platform OpenSEES. In both schemes, basic models were validated against data and observations from an experimental study on steel chevron-braced MRFs.

The dissertation presents the research in 7 chapters as follows.

Chapter 1 discusses the background and scope of the research, research gaps to be addressed, and the primary objectives. Chapter 2 presents the current state of knowledge through analysis of the literature and code provisions.

Chapter 3 discusses a set of proposed design equations for estimating the plastic strength of chevron-braced MRFs and the corresponding force demand on the beam intersected by braces. Nonlinear finite-element-method models were built and validated against experimental data. The validated models were used to conduct a parametric study to validate the above-mentioned equations over a wide range of design possibilities. The 16 models representing a range of different brace sections, beam and brace proportions, and bracing connections were subjected to three different loading protocols (Monotonic, symmetric cyclic, and ratcheting cyclic). The results were used to adjust the equations to represent various design cases and earthquake demands.

Chapter 4 examines lateral bracing requirements for the beam intersected by braces. The numerical procedure validated in Chapter 2 was used to generate 3 chevron-braced MRF models employing different bracing connections with different brace-end fixity that orient the braces to buckle either in-plane or out-of-plane. Each model was provided with different translational and rotational bracing at the chevron braces-to-beam joint. The results showed that lateral bracing of the beam is a concern when the bracing connection is rigid and the braces buckle out of plane, but lack of lateral bracing may not affect the hysteretic response of the chevron-braced MRF system. The results were used to derive bracing requirements at the brace-to-beam joint.

Chapter 5 describes a design procedure for steel chevron-braced MRFs. The design procedure was used to design 21 low- and mid-rise steel braced frames adopting one of three systems: (a) chevron-braced MRFs following earlier Japanese regulations, (b) chevron-braced MRFs utilizing the equations proposed in Chapter 3, and (c) concentrically-braced frames (CBFs) per definition in the US where lateral-load resistance relies solely on the chevron braces. The chevron-braced MRFs in (a) and (b) were varied in the proportion of lateral-load resistance derived from the chevron braces and from the MRF.

Chapter 6 assesses the seismic performance and safety of the design outcomes from Chapter 5. Two-dimensional nonlinear structural frame models built using 2D fiber elements were subjected to monotonic pushover and time-history response analysis, the latter using a suite of 28 near-field earthquake ground motion records. All models exhibited good seismic performance with the median of extracted maximum story drift less than 2% rad drift under Level-2 demands. Therefore, all building models meet the design requirements stipulated by the Japanese code. Between the three systems, the CBFs according to US specifications exhibited better performance at the cost of considerably larger amount of steel than the other two systems. The low-rise models developed larger story drift than the mid-rise models.

Chapter 7 presents the main conclusion derived from the research. Recommendations for future work and limitations of this research are discussed.