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学 位 論 文 内 容 の 要 旨

博士の専攻分野の名称 博士（工学） 氏名 LI Jionghui

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Dynamic Analysis of Steel Moment-Resisting Frames Considering Panel Zone Yielding, Local
Stiffening due to Bracing Connections, Beam Local Buckling and Fracture

(パネルゾーンの降伏、ブレース接合部の局部補剛効果、梁の局部座屈と破断を考慮した鋼構造
ラーメンの動的応答解析)

Numerical simulation based on beam-column elements cooperated with fiber sections has been widely applied in structural analysis and design due to its high efficiency in computation. However, simulated results based on such models are generally affected by modeling schemes, such as selections of element and material models, connections between elements, simplifications of structural components, etc., and thus reasonable results always rely on appropriate models. In Japan, moment-resisting frames (MRFs) are generally constructed by square hollow-structural-section (HSS) columns and I-section beams. Seismic behavior of panel zones in such columns is typically complicated by many factors, such as interaction of axial force and biaxial bending moments, stiffening from brace connections, and presence of composite slab, etc., and thus modeling of panel zone with consideration of these factors is one of the challenges in simulation. Furthermore, steel MRFs subjected to extremely large or repeated earthquake excitations may suffer from local buckling and low-cycle fatigue at beam ends. Significant losses of structural stiffness and strength usually accompany local buckling and low-cycle fatigue, which may result to excessive deformation of structure or even collapse. Therefore, this study focuses on modeling schemes for steel MRFs taking account of panel-zone yielding, stiffening from brace connections, and beam local buckling and fracture, and examination on how closely recorded responses of shake-table tests could be reproduced.

Panel zone responses to provide reference for this study were measured from shake-table tests on a nearly full-scale, 10-story steel moment-resisting frame with buckling-restrained braces (BRBs). The specimen was subjected to the 3D JMA Kobe motion, scaled from 25% to 100%. Yielding of the interior columns and column panel zones was expected from the relative proportions of the columns and beams. At one of the interior grid points, responses of such interior column, panel zones, BRBs and connecting beams were instrumented to understand the interaction among the members under combined cyclic loading. During the 100% JMA Kobe motion, the 10-story specimen yielded in the 1st to 8th stories developing maximum story drift ratio of 0.020 rad at the 2nd story. As expected, the column and panel zones in the interior grid point yielded under biaxial forces, while the connecting beams remained elastic.

Methods to estimate panel-zone shear force were devised based on equilibriums of free-body diagrams,

where axial force of composite slab and stiffening from BRB gusset plate were considered. Elastic stiffness derived by the proposed method agreed with the theoretical stiffness. Interaction effect of axial force and biaxial shear forces of panel zone was studied by a plastic analysis method, showing that plastic shear strength in one direction was clearly affected by shear force in the orthogonal direction. Numerical simulation on the 10-story specimen was conducted with 2-D analysis in OpenSees platform. A panel zone model with a strut representing the stiffening from brace connection was calibrated to match the measured column inflection points and panel-zone deformation. Pushover analysis on the 10-story model with lateral loads based on Ai distribution exhibited same failure mechanism observed in the test: weak column-strong beam mechanism in the interior frame and strong column-weak beam mechanism in the exterior frame. Time history analysis of the frame using the calibrated model reproduced the experimental results with acceptable consistency.

Local buckling of beams was simulated by the *Hysteretic* material model in OpenSees. The *Hysteretic* model adopted a bilinear model in tension and a trilinear model with degradation in compression. The *Hysteretic* material was introduced to a beam model, which consisted of a force-based beam-column element set between the beam end and quarter point and an elastic element set between the quarter point and beam inflection point. The beam model was calibrated by cyclic loading tests on beam-and-column subassemblages extracted from a 1:2.5-scaled, 4-story steel MRF. Low-cycle fatigue of beams was simulated by the *Fatigue* material, of which the fatigue limits based on a linear cumulative damage rule. The *Fatigue* material was calibrated by the same beam-and-column subassemblages. With calibrated parameters, the model was able to capture the degradation of measured beam-end bending moment and the observed crack propagation.

To verify how closely the proposed modeling scheme can reproduce the responses measured from shake-table tests. A numerical model was built in OpenSees to simulate the 4-story steel MRF. The model consisted of a MRF and a gravity frame, and the MRF adopted the same modeling scheme of the calibration and calibrated parameters of the *Hysteretic* and *Fatigue* model. The 4-story model was subjected to the measured excitations JMA Kobe-NS from 10 to 100%, where the 100% motions were conducted for 4 times. The 4-story model reproduced the measured responses before fracture with acceptable consistency. Simulated beam of the exterior joint at 2nd floor fractured at the same excitation and same zone among the section with the experiment. Finally, limitations and suggestions for future work of the proposed beam model are provided.