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Seismic evaluation of modular steel buildings

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ABSTRACT

Modular steel construction is a relatively new construction technique that considerably reduces the time spent on the construction site. However, due to the detailing and assembly requirements of multi-story modular steel buildings (MSBs), these systems are prone to undesirable failure mechanisms during large earthquakes. In this paper a 4-story MSB is designed considering realistic constraints posed during the modular construction. Using a detailed model in OpenSees an assessment of the seismic demand and capacity of this MSB is provided by performing nonlinear static pushover and incremental dynamic analyses (IDA) in two and three dimensions. Diaphragm interactions, relative displacements and rotations between modules, the force transfer through horizontal connections, column discontinuity coupled with possible high inelasticity concentration in vertical connections are some other important aspects that are specifically considered. The results that are summarized with relevant conclusions provide a better insight to the dynamic behavior of multi-story MSBs.

1. Introduction

The modular method of construction is a fast evolving technique, and it is an alternative to traditional on-site construction. A modular building contains multiple prefabricated units called "modules". Modules are prefabricated in a remote facility, transported to a site with a ready foundation and assembled on-site to produce permanent residential or commercial buildings. Each unit is often fully equipped with facilities such as plumbing, flooring, and lighting at the factory. The applications of modular construction include apartments, schools, hotels, hospitals, offices, military and any other buildings where cellular and repetitive units are preferred. Improved accuracy and quality, fast on-site installation, and lower waste material are the main motivations for owners to prefer modular construction. Although modular steel building systems differ significantly from traditional on-site buildings in terms of their behavior, detailing requirements and method of construction, limited studies have been conducted to evaluate the seismic behavior of these structures [1,2].

To provide insight to the modular steel building (MSB) structure's capacity and understand the system behavior from a global perspective, a comprehensive study has been conducted on a typical MSB structure designed considering realistic constraints imposed by modular construction. In the first step, the 4-story MSB structure has been modeled in [3] OpenSees in two (2D) and three dimensions (3D). Then, to assess the global capacity of the structure and to have an understanding of its safety in comparison with traditional steel buildings, numerical simulations using incremental dynamic analysis (IDA) have been carried out. The effects of considering horizontal and vertical connections and their contribution in the overall structural response have also been evaluated. Using the 3D model, the diaphragm interactions in the MSBs and the interaction between the modules, the axial and shear forces in the connections that occur due to the relative displacements and rotations between the modules have also been captured [4]. This is followed by nonlinear static pushover analysis of the structure to investigate the relationship between the global result of the IDA and static pushover. As a widely adopted method in engineering practice, static pushover is used to determine the ultimate lateral load resistance of the structure. The results obtained from pushover analysis can be compared to the results from IDA. In this paper the results from all analyses are summarized with relevant conclusions.

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2. Design and modeling of a typical MSB

Due to the complexity of the structural interaction within a group of modular units a detailed model of the entire structure is required to provide more realistic and reliable results. In a MSB structure, units are tied at their corners so that they act together to transfer lateral loads. Horizontal forces may be transferred by tension and compression forces in the ties at the corner of the modules and through the horizontal connections implemented in between them. By utilizing the diaphragm action of the floor and ceiling of each module, these forces are transferred to the corner connections. Because of potential articulation through the bolts and connecting plates at the connections, relative displacements and rotations may occur in between the modules (both horizontally and vertically).

In structural analysis, two-dimensional and three-dimensional computer models can be used. When P–Δ effects are to be considered in the analysis, two-dimensional models must include the tributary gravity carrying system of the Seismic Force Resisting System (SFRS) elements. The gravity system can be explicitly modeled or represented by means of leaning P–Δ columns. However, considering the advanced modeling and analysis tools that are now available, it is generally preferable to use a three-dimensional model of the entire structure for seismic analysis, even if independent analyses are performed along each orthogonal direction [5]. Analyzing the 3D model of a structure has several advantages. For instance, it provides a three-dimensional representation of the structure stiffness (for any analysis), mass (for dynamic analysis), and strength (for nonlinear analysis) properties. Therefore, the torsional response of the structure is explicitly included in the analysis and the distribution of the seismic effects in the various components of the SFRS is directly obtained from the analysis.

To conduct a nonlinear analysis, essential characteristics of all elements such as load-deformation or moment curvature characteristics in the model are required. To achieve the most reliable and realistic results different elements and materials have been tested both separately and in interaction with other components in the numerical analyses. In this study, a four story MSB structure is designed, introduced, and evaluated in both 2D and 3D with IDA and pushover analysis methods.

2.1. Model description

Considering earthquake forces and gravity loading, members of the 4-story braced MSB are seismically designed based on the National Building Code of Canada [6] (NBCC 2010). The seismic force resisting system of the 4-story braced MSB is shown in Fig. 1. There are 12 modules at each level dimensioned 3.5 m by 4 m with a height of 3.5 m. Since each module has its own columns installed off-site (i.e., at a remote factory), there may be more than one column at each axis of the building when the units are installed next to one another on-site (see Fig. 1a). The column sections comply with the maximum practical size of the columns which is 150 × 150 × 12.5 mm and are installed with a horizontal center to center distance of 0.35 m. Table 1 lists the frame sections for the columns, beams and braces for the MSB structure. Square Hollow Structural Sections (HSS), which are commonly used in MSB structures, are chosen for all the columns and braces and wide flange sections (W shape) are used for the ceiling and floor beams. The design load of floor materials is based on a typical floor system where the weights of the concrete floor, insulation, a steel deck, self-weight of the frame members, and an all-around metal curtain wall have been considered. Superimposed dead loads of 0.75, 0.32, and 0.7 kN/m^2 are introduced to account for additional loads on floor, roof, and ceiling respectively. The design live loads of 1.9 kN/m^2 for the rooms, 4.8 kN/m^2 for the corridors, and a snow load of 1.0 kN/m^2 are assumed in accordance with NBCC (2010) and the seismic loads are for the city of Vancouver, Canada. CISC Grade 350 W steel with a specified yield stress, F_y, of 350 MPa is assigned to all the structural members.

2.2. Vertical and horizontal connections

In a MSB structure, units are tied at their corners so that they act together to transfer lateral loads. In some cases, for corner supported modules, a gap between the floor and ceiling beams are allowed to facilitate bolting or welding and let the mechanical and electrical facilities run along the building. Therefore, in this model a 0.15 m clear space between the floor and ceiling beam is provided. The modules are connected to each other in the vertical direction through the vertical connections of the columns (Fig. 2a).

Table 1
Member sections from the seismic design.

4-Story MSB			
Story #	Columns	Braces	Beams
4	HSS 76 × 76 × 5	HSS 51 × 51 × 5	W 100 × 19
3	HSS 102 × 102 × 6	HSS 51 × 51 × 5	W 100 × 19
2	HSS 102 × 102 × 6	HSS 76 × 76 × 5	W 100 × 19
1	HSS 127 × 127 × 5	HSS 76 × 76 × 5	W 100 × 19

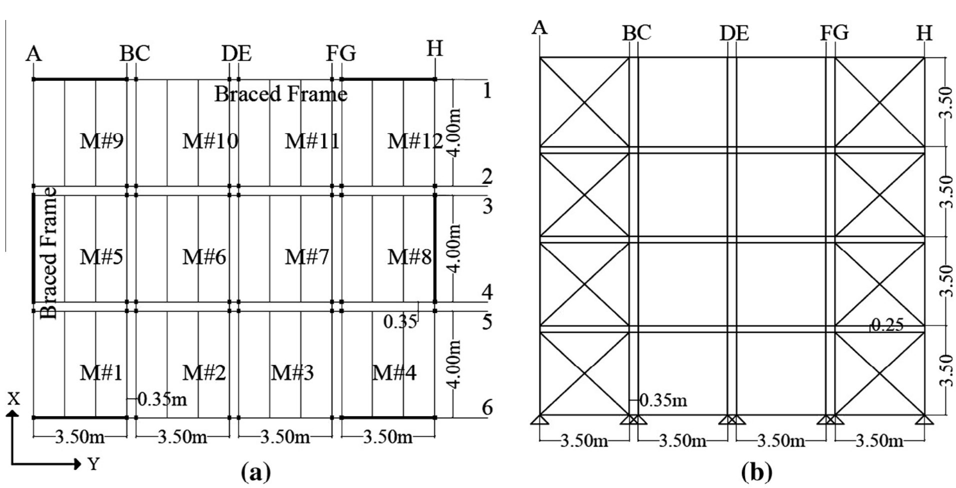

Fig. 1. 4-story MSB braced frame (a) floor plan and (b) elevation of frame 1 or 6.