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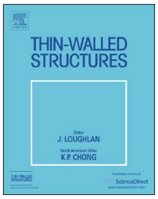

Full length article

Performance-based seismic design of staggered truss frames with friction dampers

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ABSTRACT

In this study performance-based seismic design procedure for staggered truss frames with friction dampers in the vierendeel panels was developed and their seismic performance was evaluated. To this end 6- and 12-story analysis model structures with friction dampers were designed using the capacity design procedure. For comparison the same structures without dampers were designed following the strength based approach specified in the ASCE 7–13, and the seismic performances of all model structures were compared. Fragility analyses were carried out to evaluate the seismic safety of the model structures and to validate the response modification factor used for seismic design. Analysis results showed that the capacity design method leaded to the formation of plastic hinges concentrated at vierendeel panels. It was also observed that the substitution of rotational friction dampers at the location of plastic hinges resulted in enhanced ductility and reduced probability of failure when the structures were subjected to design level seismic load.

1. Introduction

The staggered-truss frames (STF) consist of a series of story-high trusses spanning the total width between exterior columns on the opposite sides of the building and arranged in a staggered pattern on adjacent column lines. The STF has the advantage that large clear span and open areas are possible because columns are located only on the exterior faces of the building. As story-high staggered trusses function as floor beams as well as partition walls, story height can be minimized and significant advantage in economy can be achieved. It is also reported that the structural costs per unit building area is relatively low in staggered-truss framed structures [1]. Staggered truss systems have been successfully applied to many large-scale building projects and their efficiency and economy are reported [2]. Kim et al. [3] conducted nonlinear static analyses of staggered truss system buildings and identified failure modes under seismic loads. Zhou et al. [4] conducted a series of experimental and numerical analysis on the seismic behavior of staggered truss systems, and investigated the influence of the typical design parameters. Chen and Zhang [5] and Chen et al. [6] carried out experimental research to study the failure mode and joint capacity of a steel staggered truss system model exposed to pool fire. Kim et al. [7] proposed various seismic retrofit schemes for STF without and with vierendeel panels, and showed their validity through fragility analysis. Recently similar design concept utilizing vertically staggered wall panels was applied to design of reinforced concrete structures [8].

The staggered truss frames, however, have not been considered as one of the basic seismic-force-resisting systems in design codes, which implies that further research is still necessary for the system to be accepted as a standard structure system for seismic load. It is specified in the FEMA-450 [9] that a seismic-force-resisting systems that are not listed as the basic seismic-force-resisting systems can be permitted if analytical and test data are submitted to demonstrate the lateral force resistance and energy dissipation capacity. To facilitate the application of the STF, AISC (American Institute of Steel Construction) published the Design Guide 14: Staggered Truss Framing Systems [10], in which some recommendations and examples for structural design are provided.

These days various energy dissipation devices are widely used in order to improve the seismic behavior of structures. Morgen and Kurama [11] carried out a seismic response evaluation tests of unbonded posttensioned precast concrete moment frames with friction dampers at selected beam ends. Chung et al. [12] proposed a friction damper that is applied between coupled shear walls in order to reduce the deformation of the structure induced by earthquake loads. Mualla et al. [13] developed a rotational friction damper which can produce maximum friction force as high as 5000 kN, which was later applied to the Abeno Harukas Building in Japan [14,15]. Dai et al. [16] developed electromagnetic friction dampers for seismic energy dissipation of building structures. Currently in Korea rotational friction dampers are

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used in link beams connecting coupled shear walls as an alternative of deep link beams congested with diagonal and transverse rebars.

This study is focused on the validation of the effectiveness of rotational friction dampers for seismic design of staggered truss frames. The performance based seismic design is applied on steel staggered truss systems with friction dampers installed in the chord members of vierendeel panels, and their seismic performance and fragility are evaluated. To this end, 6- and 12-story structures with friction dampers are designed based on the capacity design procedures. The same structures without dampers are designed following the conventional strength-based procedure specified in the ASCE 7–13 [17], and the seismic performances of all model structures are compared. Fragility analyses are carried out using 44 earthquake ground records to evaluate the seismic safety of the model structures and to validate the response modification factor used for seismic design of staggered truss systems.

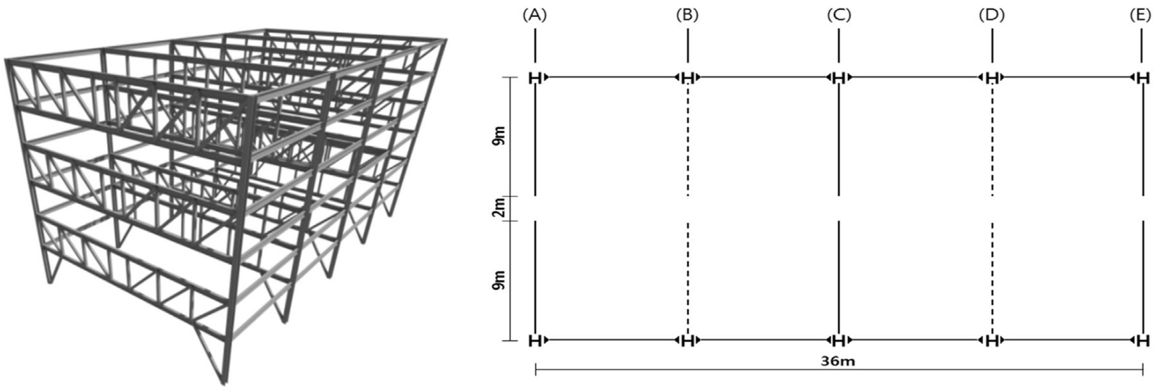
2. Design of model structures

2.1. Design of conventional staggered truss systems

As conventional STF analysis model structures, 6- and 12-story buildings are designed using the design loads specified in the ASCE 7-13. The staggered trusses are located along the transverse direction, and the moment-resisting frames are placed along the longitudinal direction. Along the transverse direction, the staggered trusses and the perimeter columns are connected by pin joints, and columns and perimeter beams are rigidly connected along the longitudinal direction. No truss is placed in the first story to accommodate large open space; instead diagonal members are installed at both ends of the span along the transverse direction as is done in the example structure of the AISC Steel Design Guide [10]. Along the transverse direction a 2 m long vierendeel panel without a diagonal member is located in the middle of two staggered trusses, which is generally used as a corridor. In each staggered truss, story-high vertical elements are located in the interval of 3 m, and a diagonal member is placed between two vertical members. Fig. 1 depicts the three dimensional view and structural plan of the 6-story analysis model structure. The staggered arrangement of the floor-deep trusses placed at alternate levels on adjacent column lines allows an interior floor space of twice the column spacing to be available for freedom of floor arrangements. The floor system spans from the top chord of one truss to the bottom chord of the adjacent truss, serving as a diaphragm transferring the lateral shears from one column line to another. This enables the structure to perform as a single braced frame, even though the trusses lie in two parallel planes. With the columns only on the exterior walls of the building, the usual interior columns are omitted, thus providing a full width of column-free area on the first floor. Exterior columns are located in such a way that their strong axes are in parallel with longitudinal direction of the structures as recommended in the Design Guide. The columns and beams are rigidly connected along the longitudinal direction, and the staggered trusses and the columns are pin connected as shown in Fig. 1(b). The height of the typical stories is 3 m and the height of the first-story is set to be 4 m. The column spacing along the longitudinal direction is 9 m.

The design loads for the model structures are determined based on the ASCE 7–13 and structural member design is carried out based on the Load and the Resistance Factor Design (LRFD) of AISC [18]. The dead load is estimated to be 5.0 kN/m^2 and live load of 2.0 kN/m^2 is used assuming that the structures are used as residential buildings. Along the transverse direction, where staggered trusses are located, the response modification factor of 3.0 is applied in the computation of the seismic design base shear, which is generally applied in structural steel systems not specifically detailed for seismic resistance; along the longitudinal direction, where the seismic force-resisting system is the ordinary moment-resisting frames, the response modification factor of 3.5 is used as recommended in the design code. The design spectral acceleration parameters for short period (S_{DS}) and at 1.0 s (S_{D1}) are assumed to be 1.0 and 0.6, respectively, and the short- and the long-period site coefficients F_a and F_v are 1.0 and 1.5, respectively, in the ASCE 7-13 format. The site class is assumed to be D, and the design spectral acceleration parameters correspond to the seismic design category D. These assumptions lead to seismic design loads similar to those for structures located in San Francisco area with the same site class.

Structural analysis and design of the model structure is carried out using the general purpose software MIDAS-Gen [27]. In all model structures, columns and upper and lower chords of the staggered truss are designed with A572M steel ($F_y = 345$ MPa, $F_u = 450$ MPa) and the other members are made of A500M steel ($F_y = 250$ MPa, $F_u = 400$ MPa). The columns are designed in such a way that the demand/strength ratio is about 0.8 and the other members around 0.9. The 20 cm thick floor slabs, which is designed to resist gravity load as well as the inplane shear force transmitted from the staggered truss located above, are assumed to be a rigid diaphragm in structural analysis. According to the modal analysis, the fundamental natural period of the 6-story model structure is 1.50 and 0.56 s for the longitudinal (moment frame) and the transverse (staggered truss) directions, respectively. Those of the 12-story structure turned out to be 1.81 and 0.78 s, respectively. It can be noticed that the natural periods along the transverse direction, where staggered trusses are located, are significantly smaller than those along the longitudinal direction. The fundamental vibration mode shapes of the structures are depicted in Fig. 2, where the mode shapes of the structures along the transverse direction are similar to those of a typical moment resisting frame, due to the flexural deformation of the vierendeel panel.



(a) 3D view

(b) Structural plan

Fig. 1. Analysis model structure (6-story). (a) 3D view (b) Structural plan.