Engineering Structures 102 (2015) 93–107

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Seismic retrofit schemes for staggered truss structures

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ARTICLE INFO

Article history:
Received 5 January 2014
Revised 3 August 2015
Accepted 4 August 2015

Keywords:
Staggered truss systems
Seismic performance
Fragility analysis
Ductility
Overstrength

ABSTRACT

In this study the seismic performances of staggered truss system (STS) structures with and without vierendeel panels were evaluated. The force–displacement relationship and seismic fragility of basic type STS were compared with those of the structures retrofitted with additional members such as interior columns, vertical cables, end braces, and buckling-restrained braces (BRB). The analysis results showed that the seismic performance of the STS with vierendeel panels could be greatly enhanced by installing interior columns. The use of end bracing and vertical cable also turned out to be somewhat effective in enhancing strength and ductility and decreasing inter-story drifts and residual displacements. Similar results were obtained in the STS structure without vierendeel panels retrofitted with end bracing or designed with some of the diagonal members replaced with BRB.

1. Introduction

The staggered-truss systems (STS) consists of a series of story-high trusses spanning the total width between two rows of exterior columns and arranged in a staggered pattern on adjacent column lines. The system is known to be appropriate for use in residential buildings such as apartments, condominiums, dormitories, and hotels [1]. As columns are located only on the exterior faces of the building, large clear span and open areas can be created. Compared with conventional reinforced concrete residential buildings' plan layouts which are divided into many small spaces by vertical shear walls, the residential buildings with staggered trusses placed at alternate levels have enhanced spatial flexibility with the economy and constructability. 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. Other benefits include minimum deflection and greater stiffness in the structure [2]. The reduced weight of the superstructure results in reduced seismic loads and substantial cost savings in foundation work. It was reported that the structural costs per unit building area turned out to be relatively low in STS [3]. Kim et al. [4] conducted nonlinear static analyses of staggered truss system buildings to identify failure modes under seismic loads. Zhou et al. [5] 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 [6] carried out experimental research to study the failure mode and joint capacity of a steel staggered truss system model exposed to pool fire. Staggered truss systems have been successfully applied to many large-scale building projects and their efficiency and economy were reported [7–9].

To facilitate the application of the STS, AISC (American Institute of Steel Construction) published the Design Guide 14: Staggered Truss System Framing Systems [10], in which recommendations and examples for structural design are provided. The STS, however, has not been considered as one of the basic seismic-force-resisting systems in most of design codes, which implies that further research is still necessary for the system to be accepted as a standard structure system for seismic load. FEMA-450 [11] requires that seismic-force-resisting systems that are not listed as the basic seismic-force-resisting systems shall be permitted if analytical and test data are submitted to demonstrate the lateral force resistance and energy dissipation capacity. In this sense it is worthwhile to note that the special truss moment frames, which have similarity with STS in structural configuration and failure mechanism, is included in ASCE 7-13 with high response modification factor based on the extensive research on the seismic performance of the system [12–14].

In this study 6-, 12-, and 18-story staggered truss structures with vierendeel panels (Type A structures) and a 12-story structure without vierendeel panels (Type B structure) were designed, and their seismic behaviors were compared through nonlinear analysis. Fragility analyses were carried out using 44 earthquake ground records to estimate the probability of reaching specified limit states for a given earthquake intensity. Based on the analysis

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http://dx.doi.org/10.1016/j.engstruct.2015.08.006
0141-0296/

results, seismic reinforcing schemes were derived and their effects on enhancing lateral load-resisting capacity were evaluated.

2. Design and analysis modeling of example structures

In this study total of ten STS analysis model structures were designed per current design code: 6-, 12-, and 18-story STS structures with 2 m, 2.5 m, and 3 m long vierendeel panels in the middle of the staggered trusses (Type A) and, for comparison, a 12-story STS structure without vierendeel panels (Type B). In the Type B structure it was assumed that the corridor was located outside of the structure along the longitudinal direction, which was pin-connected to the main structure and was neglected in the analysis modeling. Fig. 1 depicts the structural plan of the Type A model structures with vierendeel panel and the side view of the 6-story analysis model structure. Fig. 2 shows the elevation of the 12-story Type B model structure without vierendeel panel. The staggered trusses were located along the transverse direction, and the moment-resisting frames were placed along the longitudinal direction. No truss was placed in the first story to accommodate large open space; instead diagonal members were installed at both ends of the span along the transverse direction as was done in the example structure of the AISC Steel Design Guide [10]. Exterior columns were located in such a way that their strong axes were in parallel with longitudinal direction of the structures as recommended in the Design Guide [10]. The height of the typical stories is 3.75 m and the height of the first-story is 4.0 m.

The design loads for the model structures were determined based on the ASCE 7-10 [15] and structural member design was carried out based on the Load and the Resistance Factor Design (LRFD) of AISC 360-10 [16]. The dead load of 5.0 kN/m^2 and live load of 2.0 kN/m^2 were used as gravity loads. Along the transverse

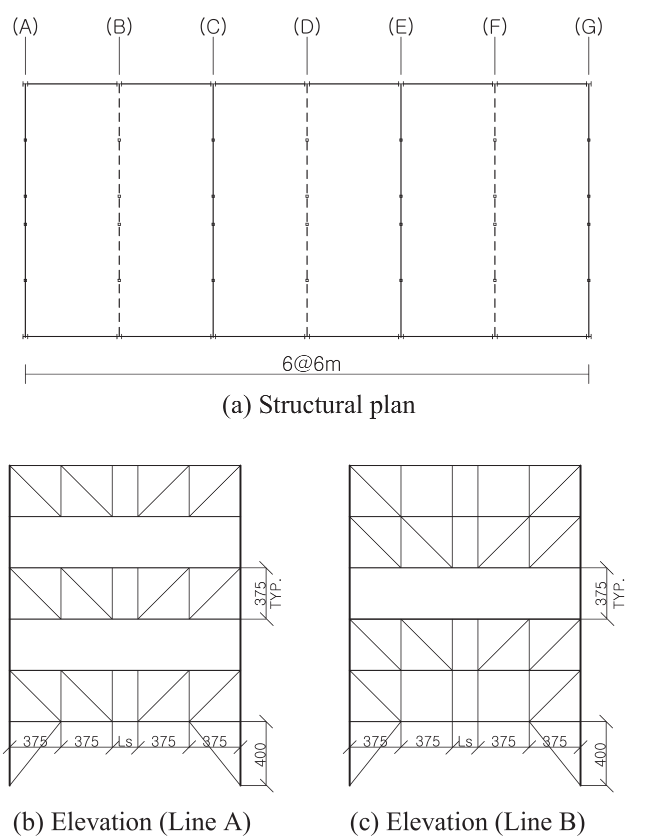

Fig. 1. Six-story staggered truss model structure with a central corridor (Type A) (mm).

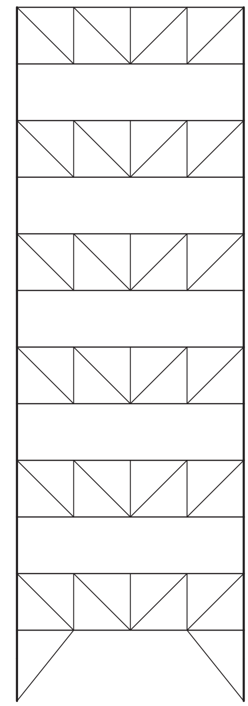

Fig. 2. 12-story staggered truss model structure without a central corridor (Type B).

direction, where staggered trusses are located, the response modification factor of 3.0 was applied in the computation of the design base shear, which is generally applied in structures not defined as one of the seismic load-resisting systems; along the longitudinal direction, where the seismic load-resisting system is the ordinary moment-resisting frames, the response modification factor of 3.5 was used. The design spectral acceleration parameters for short period (S_{DS}) and at 1.0 s (S_{D1}) are 0.5 and 0.2, respectively, and the short- and the long-period site coefficients F_a and F_v are 1.36 and 2.28, respectively. The design spectral acceleration parameters correspond to the seismic design category C_{max} and D_{min} in the ASCE 7-10 [15]. The site class was assumed to be *D*.

In all model structures, columns and upper and lower chords of the staggered truss were designed with A572 steel (F_y = 345 MPa, F_u = 450 MPa) and the other members were made of A500 steel (F_y = 250 MPa, F_u = 400 MPa). The columns were designed in such a way that the strength ratio P/P_{CL} is about 0.5 as was done in the design of the example structures in the AISC Steel Design Guide 14 [10], and those of the members of the staggered trusses were maintained around 0.8–0.9. The floor slabs were assumed to be rigid diaphragm in the structural analysis. Table 1 shows the fundamental natural periods of the model structures, where it can be observed that the natural period increases as the length of the vierendeel panel increases, and that the natural period of the 12-story STS without vierendeel panels is significantly smaller than that of the 12-story structure with vierendeel panels. The Type A structure is similar to the coupled shear walls connected by beams. In this case the overall stiffness depends mainly on

Table 1
Fundamental natural periods of the model structures.

		2 m	2.5 m	3 m
Type A	6F	1.07	1.27	1.49
	12F	1.85	2.10	2.40
	18F	2.49	2.77	3.08
Type B	12F	0.90		