



## SEISMIC PERFORMANCE OF HYBRID STEEL STAGGERED TRUSS FRAME

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### Abstract

In this study, steel staggered truss frame (SSTF) with hybrid steel in the vierendeel panels is developed. In particular, the concept of a hybrid SSTF can be realised by a wise combination of steel members with various yield strengths to trigger early yielding of chords in the vierendeel panels under seismic attacks. Thus, the seismic energy is allowed to be dissipated at the special region of the SSTF (i.e. the vierendeel panels) for a wide deformation range. The seismic performance of a hybrid SSTF is studied by examining a 6-storey prototype structure. For comparison, a conventional SSTF structure without hybrid steel technology is also studied. Two 3-dimensional models of the SSTF systems are studied, and the numerical models are developed using beam elements. Based on numerical models of prototype structures verified by the test results, seismic response quantities including initial stiffness, energy dissipation, ultimate strength, and rigidity degeneration are analysed. Seismic performance of the prototype systems is evaluated using nonlinear static (pushover) analysis and incremental dynamic analyses (IDA). Pushover analysis with the invariant lateral load distribution corresponding to the first mode is adopted in this study. The pushover curves show that a hybrid SSTF exhibits a wide damage-control stage and significant post-yielding stiffness ratio. The plastic hinges are formed in the vierendeel panels and column bases. No plastic hinges are formed in the chord and the diagonal members outside the vierendeel panels. The yielding sequences make the hybrid SSTF shows multi-stage performance. Subsequently, a total of ten (10) ground motion records are used in the dynamic analysis according to the FEMA P695 recommendations. Record scaling includes two steps. In the first step, individual records in each set are “normalised” by their respective peak ground velocities (PGV). In the second step, “normalised” records are amplified to a specific seismic magnitude and used as input excitations to examine the response of the structures. It can be observed from the nonlinear dynamic analysis results that the residual displacement of the hybrid SSTF is less than the conventional SSTF structure. Nonlinear incremental dynamic analyses is used to compute the collapse margin ratio for both structures under the amplified levels of earthquake, and the results have been compared with the recommended values by the FEMA P695. The collapse margin ratio for evaluation of seismic safety of the hybrid SSTF is larger than that of the conventional SSTF structure. The conventional SSTF has higher values than the hybrid SSTF in the maximum and residual interstorey drift. In general, the observations drawn from this work show that the hybrid SSTF has more encouraging seismic performance compared with the conventional SSTF structure.

*Keywords: hybrid steel staggered truss frame, pushover analysis, incremental dynamic analyses, residual deformation*



## 1. Introduction

The steel staggered truss frame (SSTF) was developed in Massachusetts Institute of Technology in the 1960s [1]. A series of storey-high trusses are spanned the overall width between exterior columns and arranged in a staggered pattern [2]. Because of its effective load transferring mechanism and reasonable cost, the SSTF is known to be appropriate for use in a few hotels, apartments, office, and hospital buildings. Zhou [2] conducted a large-scale experiment on a SSTF structure and examined the influence of the parameters by the verified finite element model. The elastic and inelastic response of the SSTF structure under earthquake ground motions were first analysed by Gupta [3]. Kim [4] adopted performance-based design methodologies to design the SSTF with friction damper in the vierendeel panels.

The SSTF applies to non-seismic regions or seismic design with a fortification intensity of 6 to 8 [5]. In recent years, researchers took various measures to improve the seismic performance of structures. Basha [6] proposed a vierendeel middle segment in special truss moment frame (STMF). Kim [7] introduced various strategies for the SSTF and showed their validity through fragility analysis. In seismically active areas, Simasathien [8] took three steps to achieve the goal of the SSTF showing stable response under severe ground motions. On the other hand, the concept of “hybrid-steel-based” technology [9] may improve the seismic performance of a structure, which offer a promising alternative for further advances of the SSTF systems.

The purpose of this study is to verify the effectiveness of hybrid steel technology in the vierendeel panels of the SSTF. The concept of a hybrid SSTF can be realised by a wise combination of high strength steel members and mild carbon steel members with reduced strength to trigger early yielding of chords in the vierendeel panels during ground motions. Thus, the vierendeel panels may dissipate the input seismic energy to protect the remaining structure. To verify the feasibility of hybrid SSTF, the seismic response of a 6-storey conventional SSTF and a hybrid SSTF are examined in the current study.

## 2. Verification of computational modelling

Zhou et al. [2] conducted a quasi-static experiment on the behaviour of an 8-storey SSTF, and the test arrangement is reproduced in Fig. 1. The vertical, chord, web members, longitudinal beams were constructed using square steel tubes with various sizes. The steel sheet stiffened by angles was used to simulate the effect of floor slabs. More detailed information can be found in [2].

A three-dimensional finite element model of the test specimen is modelled in ABAQUS [10]. The shell element S4R and the beam element B31 are adopted to simulate the floor slabs and structural members, respectively. The connection between the shell element and beam element is realised by “kinematic coupling constraint”. The bilinear behaviour with a 2% hardening ratio is assumed for all members. The finite element model of the subassembly is shown in Fig. 2.



Fig. 1 – Assemblage of the test setup [2]

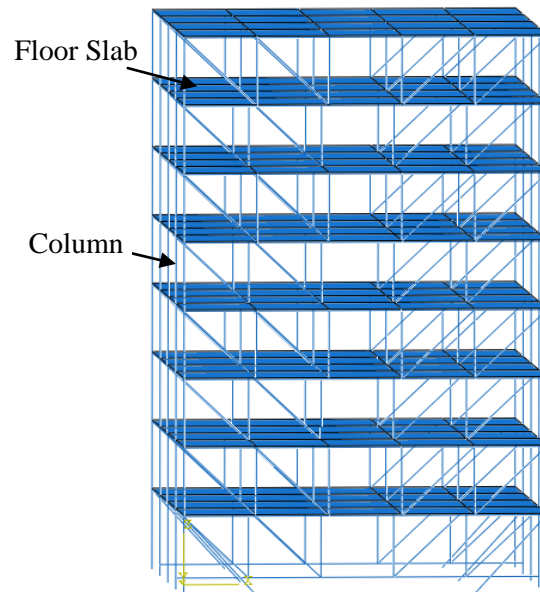


Fig. 2 – The FE model of SSTF

The comparisons of the experimental data and numerical simulations are displayed in Fig. 3 in terms of base shear versus roof displacement response. As can be seen from the comparison, hysteretic behaviour and skeleton curves are captured well together with acceptable accuracy. It can be verified that the seismic response quantities including initial stiffness and energy dissipation of numerical model are consistent with the test results.

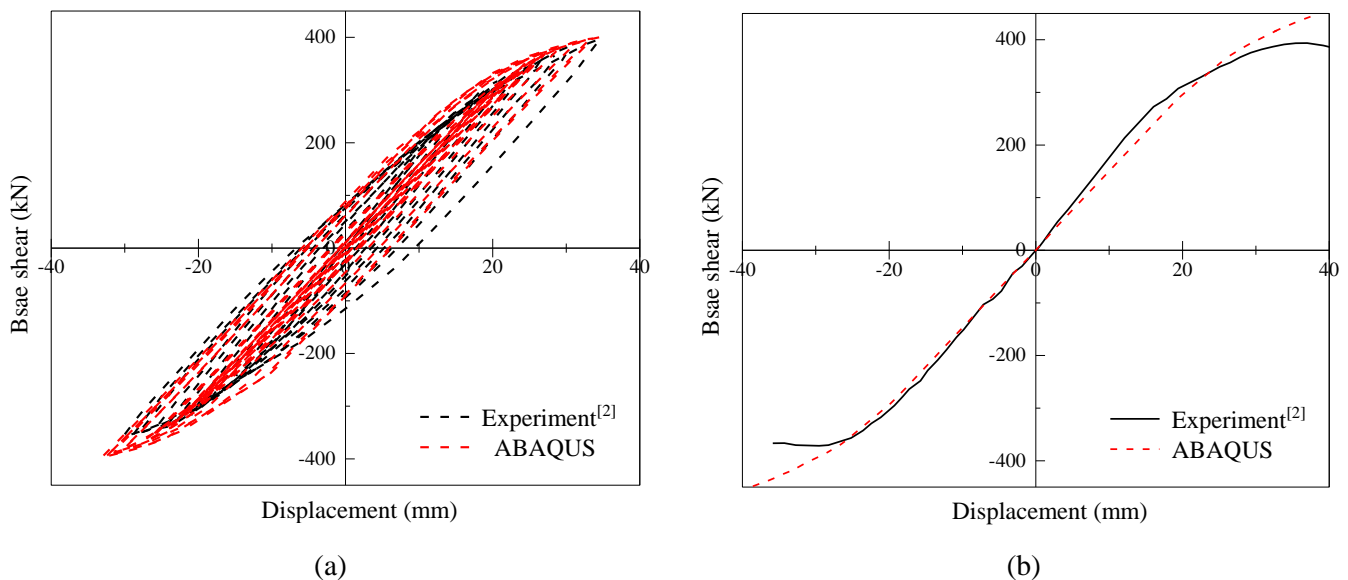


Fig. 3 – Comparison of the results: (a) hysteretic loops, (b) skeleton curves [2]

### 3. Design of model structures

To explore the philosophy of the hybrid SSTF, a proof-of-concept study is carried out and presented in the conference paper. As a case study, a six-storey prototype structure is designed according to the seismic spectra specified in Chinese seismic design provisions [11]. The structure is originally designed as buildings



located on a stiff soil site (Site Class D). The building plan and elevation of the applied SSTF can be seen in Fig. 4. The building has a plan dimension of 36 m by 20 m. The height of the first storey and others are 4.0 m and 3.0 m, respectively. The design strategy of the model is shown in Table 1.

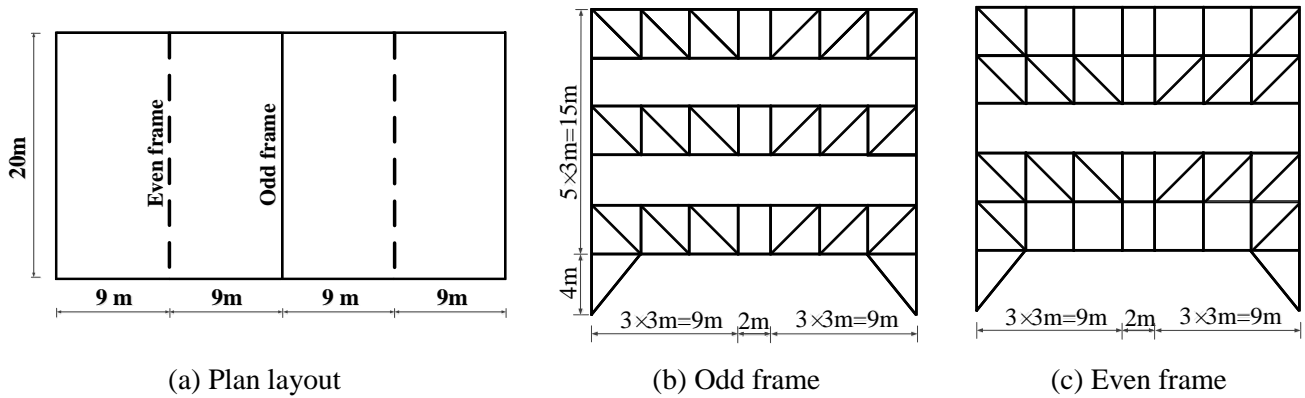


Fig. 4 – Arrangement and dimension of the SSTF

Table 1 – Parameters of the case study model. □, box section

Members	Cross sections	
	The conventional SSTF	The hybrid SSTF
Column	□300×300×20	□300×300×20
Chord	H400×250×16×22	H400×250×16×22, H300×150×14×18, H230×130×12×18
Web	H300×150×14×18	H300×150×14×18
Longitudinal beam	□400×400×30	□400×400×30

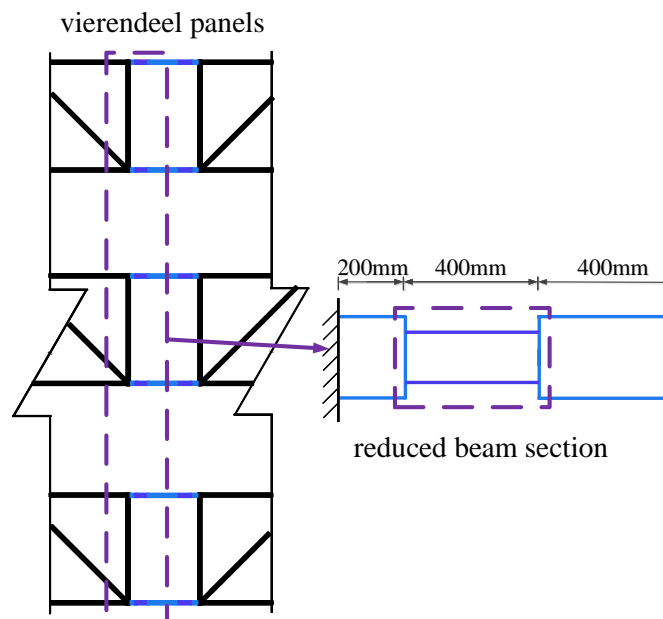


Fig. 5 – The typical layout of the Hybrid SSTF



The structure can be realised by incorporating two techniques. On the one hand, in the vierendeel panels, reduced beam section is introduced in the chord. The typical detail of the vierendeel panels in the hybrid SSTF is illustrated in Fig. 5. On the other hand, hybrid steel is employed in the structure, and chord members of the vierendeel panels are made of steel grades with lower-yielding strengths than other members. In particular, mild carbon steel with a yield strength of 235 MPa is used for the vierendeel panels chord members, and the surrounding frame members are designed with high strength steel a nominal yield strength of 460 MPa. For comparison, all members of the conventional SSTF are designed with mild carbon steel of a yield strength of 345 MPa. Because the SSTF has typical spatial performance under external excitation, the three-dimensional models are carried out to simulate the SSTF. Along the longitudinal direction, the web members are connected by pin joints to simulate the constraint provided by the floor slab. The Young's modulus is assumed as 206 GPa. The bilinear kinematic hysteretic is used to model all members [12].

## 4. Analytical study

### 4.1 Modal analysis

The dead load and live load are designed with  $5.0 \text{ kN/m}^2$  and  $2.5 \text{ kN/m}^2$ , respectively. The combined load is converted to mass properties. Total mass at each floor is assumed to distribute at the panel points of the trusses. The Modal analysis adopts Lanczos method. Because this study is concerned with seismic behaviour of the SSTF structures in the transversion direction, out-of-plane displacement is constrained. Based on the analysis, the period of the first two vibration modes of the conventional SSTF are 0.65 s, 0.22 s, respectively. Meanwhile, the corresponding periods of the hybrid SSTF are 0.66 s and 0.23 s, respectively. Two types of the SSTF generally have the identical elastic vibration characteristics. Thus, it is confirmed that a reduced beam section has little influence on structure stiffness. The rayleigh damping ratio of 0.05 is assumed for the first two vibration modes.

### 4.2 Pushover analysis

Pushover analysis is conducted for both conventional SSTF and hybrid SSTF under the invariant lateral load distribution corresponding to the fundamental mode of the vibration.

Fig. 6 shows the base shear versus roof drift curves of two SSTF structures, and the maximum interstorey drift ratio (IDR) of 2% and 3% are also indicated in the figure. As shown in the graph, they have almost the same ultimate strength, however, the hybrid SSTF developed inelastic action at much lower lateral deformation. Therefore, a hybrid SSTF exhibits a wide damage-control stage with inelastic actions concentrated in the vierendeel panels. There is sufficient yield deformation tolerance between the main structural member and the vierendeel panels. In the hybrid SSTF, the plastic hinges are formed in the vierendeel panels and column bases.

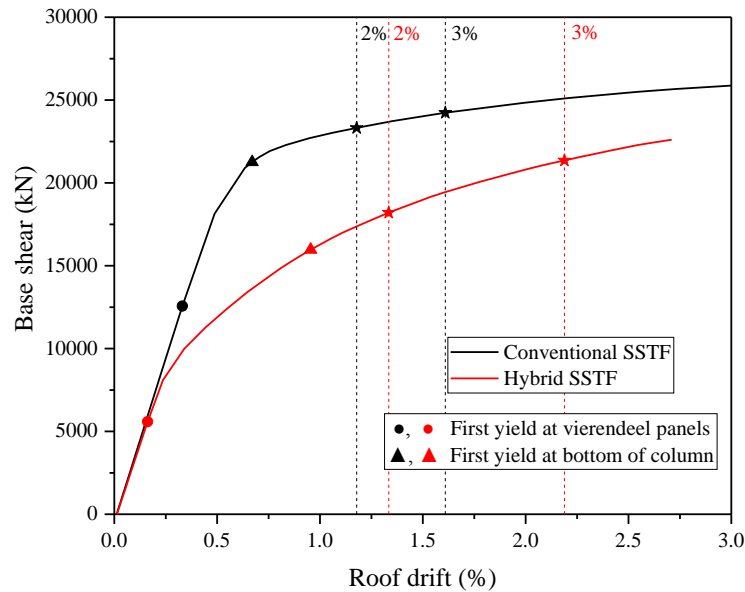


Fig. 6 – Pushover curves of SSTF

#### 4.3 Nonlinear dynamic analysis

Incremental dynamic analysis (IDA) is widely used seismic performance assessment, and the response from the linear state to yielding even at collapse [13] can be examined using IDA. In this study, the collapse resistance of both types of the case study have been evaluated in the IDA according to the FEMA P695 [14] guidelines.

A set of ground motion records were selected by Gada [15] to take nonlinear dynamic analysis. A summary of ground motion database are shown in Table 2. Record scaling involves two steps. Firstly, individual records are “normalised”, and the normalisation factor is used to remove unwarranted variabilities. Secondly, “normalised” records are scaled to a specific ground motion intensity. Fig. 7 illustrates 5% damped elastic response spectra of the records, and the median response spectrum is also indicated.

Table 2 – Summary of Ground motion characteristic for IDA [14, 15]

Record	Earthquake	Recording	PGA(g)	PGV(cm/s)	Normalization Factor
120111	Northridge, USA	Beverly-Mulhol	0.52	63	0.65
120411	Duzce, Turkey, Japan	Bolu	0.82	62	0.63
120521	Hector Mine, USA	Hector	0.34	42	1.09
120611	Imperial Valley	Delta	0.35	33	1.31
120711	Kobe, Japan	Nishi-Akashi	0.51	37	1.03
120721	Kobe, Japan	Shin-Osaka	0.24	38	1.10
120821	Kocaeli, Turkey	Arcelik	0.22	40	1.36
121011	Loma Prieta, USA	Capitola	0.53	35	1.09
121111	Manjil, Iran	Abbar	0.51	54	0.79
121711	Friuli, Italy	Tolmezzo	0.35	31	1.44

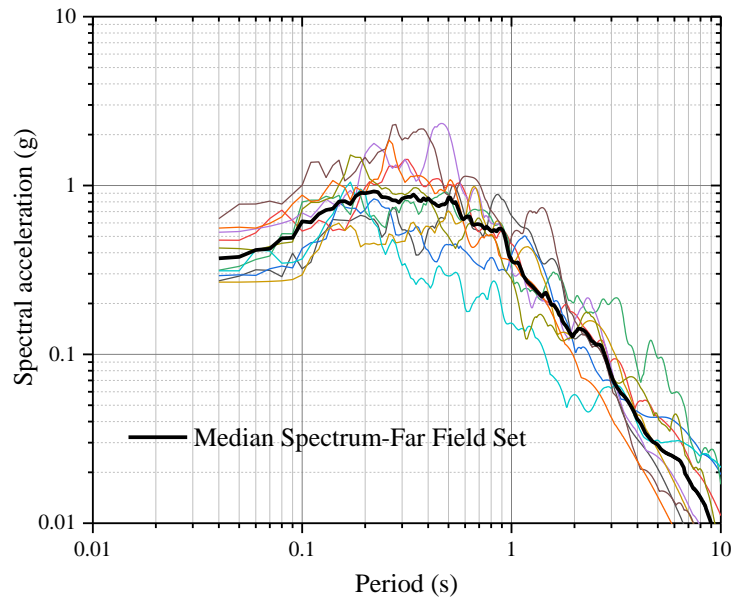


Fig. 7 – The selected earthquake records response spectra ( $\zeta=0.05$ )

Fig. 8 depicts roof drift of structures subjected to the “Northridge” earthquake with 1.5 g spectral acceleration at the fundamental period of the structures. It can be seen that hybrid SSTF experience smaller maximum displacement and residual displacement compared with the conventional SSTF.

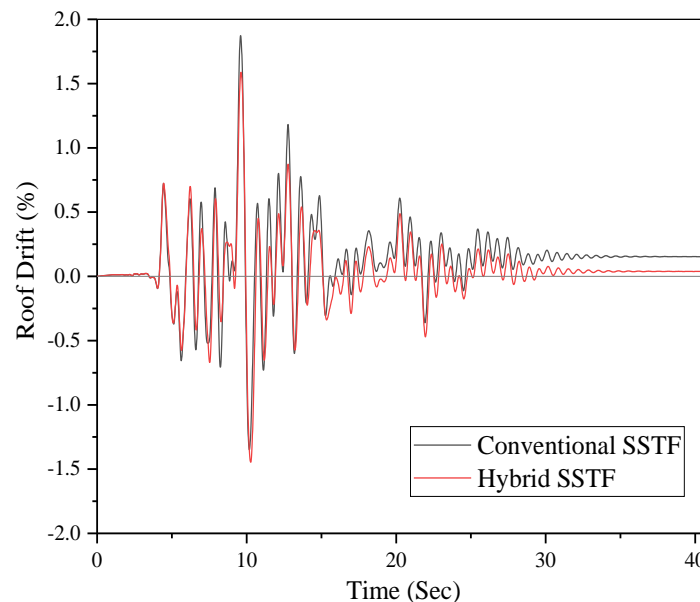


Fig. 8 – Roof drift of structures subjected to the “Northridge” earthquake

Fig. 9 illustrates the results of IDA. In Fig. 9, the horizontal axis is maximum interstorey drift ratio (IDR) and the vertical axis is ground motion intensity  $S_a(T_1, 5\%)$ , which is defined as the 5%-damped spectral acceleration of the selected earthquake records at the fundamental period of the structures. In the IDA, the spectral accelerations corresponding to fundamental period varied from 0.5g to 3.0g with an increment of 0.5g.

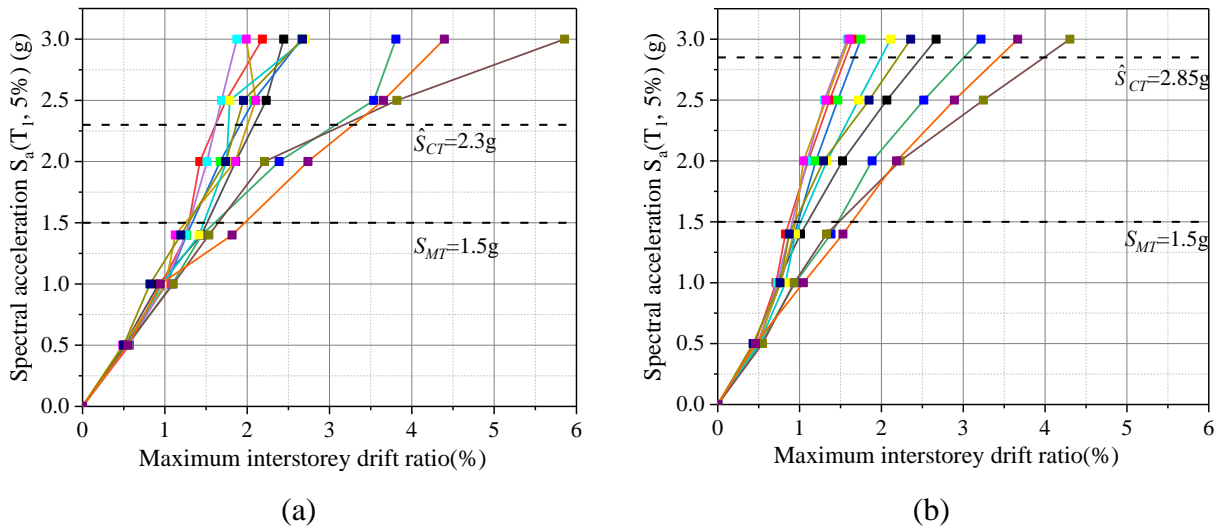


Fig. 9 – IDA curves for (a) Conventional SSTF and (b) Hybrid SSTF

As defined in Equation (1) [14], the collapse margin ratio (CMR) is the ratio of the collapse level ground motions to the MCE ground motions.

$$CMR = \frac{\hat{S}_{CT}}{S_{MT}} \tag{1}$$

The values of  $S_{MT}$  and  $\hat{S}_{CT}$  for the conventional SSTF are noted as 1.5g and 2.3g, the corresponding values for the hybrid SSTF are 1.5g and 2.85g. The CMR values are computed as 1.53 and 1.9 respectively, it indicates that the hybrid SSTF has relatively higher ratio against its collapse.

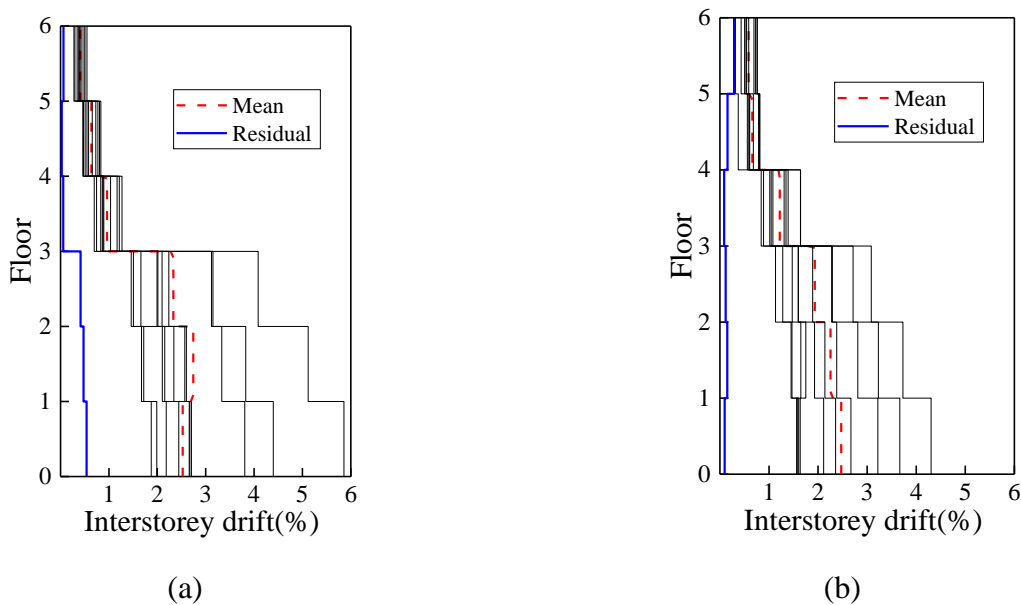


Fig. 10 – Comparison of interstorey drift ratios under rare earthquake: (a) Conventional SSTF, (b) Hybrid SSTF

The maximum interstorey drift is shown in Fig. 10, and each gray line represents the response under a ground motion with a 3.0 g spectral acceleration at the fundamental period of the structure. For comparison,



the mean values of maximum and residual interstorey drift are computed, as shown in Fig. 10 by red dash line and blue line, respectively. Therefore, the more encouraging seismic performance of a hybrid SSTF is seen.

## 5. Conclusions

The hybrid-steel technology is applied to SSTF to improve the seismic response of the structures. Finite element models of SSTF are developed and the adequacy of the modelling techniques is verified by the previous test results. Then, seismic performance of two prototype structures, i.e. a conventional SSTF and a hybrid SSTF are compared based on a numerical study. Pushover analysis shows that the hybrid SSTF has a wider inelastic deformation range, which help forming a more encouraging damage evolution mode under seismic actions. Based on nonlinear dynamic analysis, the seismic performance quantities (i.e. maximum interstorey drift ratio and residual interstorey drift ratio) of the prototype structures are acquired under a series of ground motions. In general, this case study shows that the hybrid SSTF has more encouraging seismic performance compared with the conventional SSTF structure.

However, the current conference paper focuses on the feasibility study of the hybrid SSTF. The design procedure is not studied, and a more comprehensive research is under way.

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