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# Seismic behavior of K-shaped eccentrically braced frames with high-strength steel: Shaking table testing and FEM analysis

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ABSTRACT

A shaking table test was carried out on 1:2 scale three-storey K-shaped eccentrically braced frames with high-strength steel (K-HSS-EBFs). The acceleration, displacement, and strain responses of the specimen under different peak acceleration ground motions were measured and analyzed. The natural frequency, acceleration amplification factor, storey drift, and distribution of horizontal seismic actions for the model structure were investigated. Finite element models were established for elastoplastic time history analysis on the model structure. Finite element analysis showed that the links were the weakest part of the structure, especially the webs of the links and welds near the connections between the links and frame beams. The results showed that K-HSS-EBFs may absorb excessive seismic energy, enter the elastoplastic state, and even fail under strong earthquakes owing to shear deformation of the links during vibration. The PBPD method is found to be suitable for use in the design of K-HSS-EBFs. In addition, the K-HSS-EBFs can fulfill the seismic requirements under limiting state. These findings will be helpful for the future design of K-HSS-EBFs.


## 1. Introduction

High-strength steel (HSS; $f_y \geq 460$ MPa) has higher yield and tensile strength than conventional steel ($f_y < 345$ MPa). In recent years, scholars and professionals in the steel structure field of many countries have completed a large number of experiments and a considerable amount of theoretical research on HSS. Research on HSS has focused on the material properties and mechanic behavior of members. Green et al [1]. completed a bearing capacity test for HSS I-beams and discussed the effect of the cross-section, loading form, and material properties on the rotation capacity. Azizinamimi and Barth [2] studied the flexural capacity, tensile ductility, and shear capacity of HSS ($f_y = 485$ MPa) in bridge construction. Some researchers [3–11] have studied the overall buckling behavior and local buckling response of HSS columns with welded box and I-beam cross-sections, the residual stress distribution in the HSS weld section, and the hysteretic behavior of HSS members under cyclic loading. In recent years, the development of steel structures and improvement of production technology have contributed to the use of HSS in bridge structures [12,13]. HSS has been gradually applied in building structures. Under the same stress conditions, the cross-sections of HSS members tend to be smaller than those of conventional members, which increases the available space of the building while decreasing material costs. Therefore, their use has considerable economic benefits [14]. However, the improved strength increases the ratio of the yield strength to tensile strength of HSS, which reduces the plastic deformation capacity. The requirements for steel use in seismic zones are clearly listed in the mandatory provisions of Chinese Code for Seismic Design of Buildings [15]: the ratio of the measured yield strength to the measured tensile strength should not exceed 0.85, and the steel should have an obvious yield plateau with an elongation <20%. Q460 and higher-grade HSS often fail to meet the above seismic requirements. These provisions limit the application of HSS in construction field of China. However, the structures can meet the design concept of seismic codes by using reasonable structural type and structure details design. Eccentrically braced frames (EBFs) with HSS are proposed to solve problem.

These structures can satisfactorily solve the inelastic deformation and energy dissipation problem [16,17], where seismic energy is dissipated through the elasto-plastic deformation of links. Other members (e.g., beams, columns, etc.) need to be connected through links to provide sufficient restraints to maintain elasticity and small deformation. Thus, HSS can be used for these members. EBFs for which the links (bold parts in Fig. 1) are made from conventional steel and the rest of the members are made of HSS are called eccentrically braced frames in combination with high-strength steel (HSS-EBFs) [18].

At present, there have been few studies on the mechanical properties and seismic performance of HSS-EBFs. Dubina et al. [19] performed

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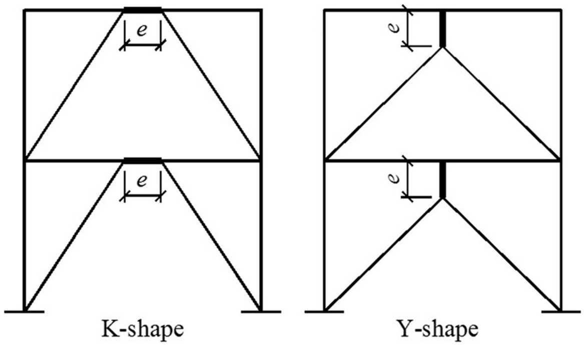


**Fig. 1.** Typical HSS-EBFs.

pseudo-static tests on four one-bay and single-storey K-HSS-EBFs. Their test results showed that, under the effect of cyclic loading, the link made of conventional steel is completely in the plastic stage, and beam-column frames made by HSS are still in the elastic stage. The authors' research group [20–22] performed monotonic loading tests, cyclic loading tests, and finite element analysis on HSS-EBF specimens. The results indicated that HSS-EBFs have good load-carrying, ductility, and energy-dissipation capacities.

To the authors' knowledge, no relevant information about shaking table tests on K-HSS-EBFs has been reported. Systematic experimental research and numerical analysis of the K-HSS-EBFs has theoretical and practical significance for the application of HSS in the construction field [23–25]. In order to further investigate dynamic characteristics and seismic performance of K-HSS-EBFs, the shaking table test and numerical analysis were performed on K-HSS-EBFs. Results of this analysis reveal that K-HSS-EBFs are capable of fulfilling seismic requirements under the limiting state and are more economical when compared against traditional EBFs. In addition, the finite-element model established in this paper is valid for analyzing K-HSS-EBFs, and the PBPD method is found to be suitable for use in the design of K-HSS-EBFs.

**Table 1**
Typical scaling factors and similarity relationships of the test model.

| Physical parameters | Similarity relation | Ratio of similarity |
|---|---|---|
| Length | $S_l$ | 0.5 |
| Stress | $S_\sigma$ | 1.0 |
| Acceleration | $S_a$ | 1.2 |
| Elastic modulus | $S_E = S_\sigma$ | 1.0 |
| Density | $S_\rho = S_\sigma/(S_a \cdot S_l)$ | 1.6667 |
| Mass | $S_m = S_\sigma \cdot S_l^2/S_a$ | 0.2083 |
| Period | $S_T = S_l^{1/2} \cdot S_a^{-1/2}$ | 0.6455 |
| Force | $S_F = S_\sigma \cdot S_l^2$ | 0.25 |

## 2. Test overview

The prototype structure was designed according to Chinese current design codes [14,26,27]: it is a three-storey HSS-EBF structure with shear links. The plan size of the structure is 5.65 m × 5.65 m, and the height of the structure is 3.6 m.

### 2.1. Similarity relationship

One of the key tasks of model testing is to design a specimen according to the requirements of the similarity theory so that the working conditions are similar to the prototype structure. Based on the lifting capacity of the shaking table and experimental site conditions of the Key Lab of Structure and Earthquake Resistance of Xi'an University of Architecture and Technology, the length scaling factor $S_l$ was set to 1/2. The stress scaling factor $S_\sigma$ was set as 1 because the specimen and prototype structure were made of the same material. The acceleration scaling factor was determined to be 1.2 according to the peak ground acceleration (PGA) at the maximum level and laboratory conditions. Other typical scaling factors were calculated according to similarity theory [28], as listed in Table 1.

### 2.2. Model design

As shown in Fig. 2, the total height of the model was 5.4 m, and the plan of the model was 2.85 m × 2.85 m. The thickness of the two-way reinforced concrete slab was 80 mm. The grade, diameter, and spacing of the reinforcement were HRB335, 8 mm and 200 mm, respectively. To ensure a reliable connection between the cast-in-place concrete slab and beams, shear studs (Fig. 2(a)) were arranged every 100 mm at the center of the top flange of the beams. However, no shear studs were provided between the link and storey. The links and beams were welded together to ensure that the connection had superior force-bearing performance. According to the density similarity relationship,

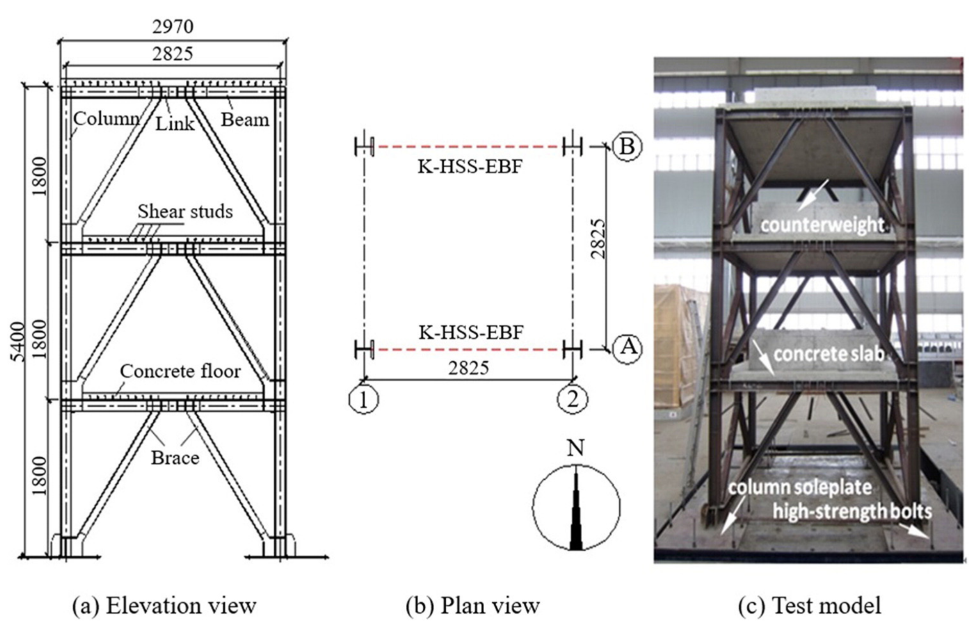


**Fig. 2.** Test model (unit: mm).