



Dynamic Response of Steel Frame Structures under Horizontal Earthquake

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Abstract. To investigate the seismic performance of steel frame structures, this study focuses on horizontal seismic actions. A three-dimensional finite element numerical model is developed. Box columns and I-beams are employed as structural components. Material parameters and boundary constraints are specified. The El Centro seismic wave is selected as the dynamic input. Horizontal loads are applied along the X-direction for elastic time-history analysis. The mechanical characteristics and dynamic response laws of the structure under horizontal earthquakes are systematically examined. This research provides theoretical support and practical references for the seismic design and engineering application of steel frame structures.

Keywords: Steel frame; Earthquake; Dynamic response; Numerical simulation

1 Introduction

Earthquakes feature strong suddenness and high destructive capacity, and are one of the major threats to the safe service of building structures. Steel frame structures are widely adopted in modern construction engineering owing to their merits of high strength, good ductility, and high construction efficiency^[1]. Existing research has shown that horizontal seismic action is the main cause of structural damage^[2]. Therefore, studying the dynamic response of steel frame structures under horizontal earthquakes and clarifying their deformation and mechanical evolution laws is of great theoretical significance and engineering application value for improving structural seismic safety and guiding engineering seismic design.

Scholars worldwide have carried out extensive studies on the seismic performance of steel frame structures, established a theoretical system for structural dynamic analysis, and deeply investigated the influence of ground motion characteristics on steel frame responses. Alejandro and Edgar^[3] studied the seismic performance of steel frame joints consisting of I-beams and box columns with different diaphragm details, and clarified the effects of diaphragm configurations on the mechanical properties and failure modes of joints. Li et al.^[4] proposed a deep feature learning network model integrating a cross-attention mechanism and graph neural network, which can provide a high-precision and low-energy solution for seismic analysis of complex steel struc-

tures. Zhang et al.^[5] improved the seismic performance of steel frames while reducing material usage through optimal design, and verified the effectiveness of the method using a 25-story rigid steel frame and a 20-story eccentrically braced steel frame as examples. Liu et al.^[6] established structural models with different truss layouts and analyzed their seismic performance under strong earthquakes using the elastoplastic dynamic time-history method. Overall, existing results have fully verified the reliability of the time-history analysis method in structural seismic calculation. However, refined analysis on the elastic response of regular multi-story steel frames under frequent horizontal earthquakes still requires further supplementation.

To systematically reveal the dynamic response characteristics of multi-story steel frames under horizontal earthquakes, this paper establishes a three-dimensional finite element model of a steel frame. Section dimensions of box columns and I-beams and mechanical parameters of steel are defined. Boundary conditions of rigid joints and fixed column bases are adopted. The El Centro seismic wave is selected as the input load, and horizontal seismic action with a peak acceleration of $0.15g$ is applied along the X-direction of the structure for dynamic time-history analysis. Through comprehensive analysis of structural acceleration, displacement, strain and stress responses, the overall working performance and seismic safety reserve of the structure are evaluated. This study provides a reference for the seismic design and optimization of similar steel frame structures.

2 Numerical Model

To study the dynamic response of steel frames under horizontal earthquakes, a 3D numerical model of a regular multi-story steel frame is established via ABAQUS (see Fig. 1). Beam-column joints are rigidly connected, and column bases are fully fixed to simulate practical foundation constraints. Frame columns use $400\text{mm} \times 400\text{mm}$ box sections with 15mm uniform wall thickness. Vertically, the first storey is 4000mm high, and upper standard storeys are 3300mm high. Frame beams (longitudinal and transverse) are 400mm-high I-shaped sections, with 150mm-wide top/bottom flanges and 20mm-thick flanges/web. Both beam types have a 6000mm calculated span, and the structure has a regular, symmetric planar layout.

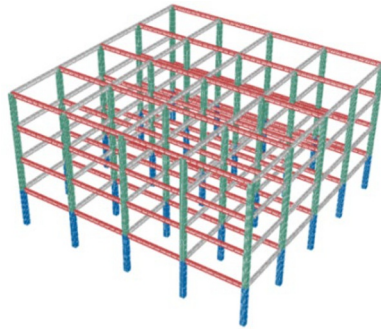


Fig. 1. Three-dimensional numerical model

All components in the model are made of steel. Material parameters are determined in accordance with finite element modeling specifications: the mass density of steel is $7.8 \times 10^{-9} \text{ t/mm}^3$; an isotropic linear elastic model is used for the elastic constitutive relation, with an elastic modulus of 206000 MPa and a Poisson's ratio of 0.3; an isotropic hardening model is adopted for the plastic constitutive relation. The yield strength of steel is 345 MPa, the ultimate strength is 450 MPa, and the corresponding plastic strain is 0.01.

3 Calculation Cases

To analyze the dynamic response characteristics of steel frame structures under horizontal earthquakes, the El Centro seismic wave, which is widely adopted in engineering practice, is selected as the dynamic input load to perform elastic dynamic time-history analysis. The acceleration time-history curve and Fourier spectrum characteristics of the seismic wave are presented in Fig. 2.

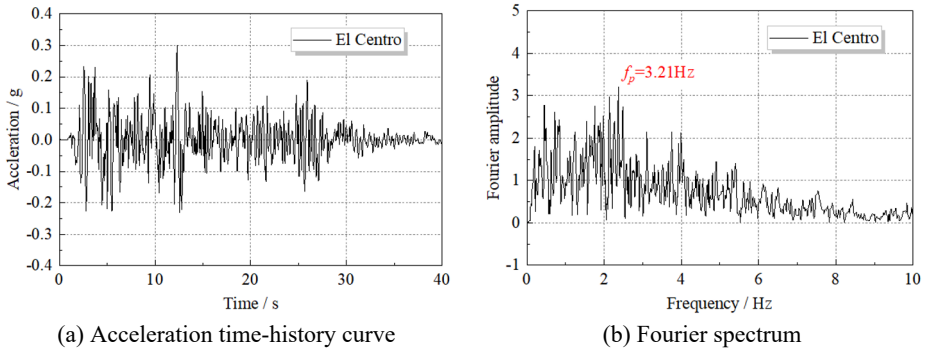


Fig. 2. Ground motion

In accordance with the fortification requirements for frequent earthquakes, the ground motion amplitude is adjusted, and the peak ground acceleration is set to 0.15 g. Results of the spectral analysis indicate that the predominant frequency of the El Centro wave is 3.21 Hz, and its energy is mainly concentrated in the low-frequency band. It can effectively excite the main vibration modes of multi-story steel frame structures, thus satisfying the load input requirements for structural dynamic response analysis.

4 Results Analysis

(1) Acceleration

To study the acceleration response characteristics of the steel frame structure under horizontal excitation of the El Centro wave, acceleration nephograms of the structure are extracted for quantitative analysis, with the results shown in Fig. 3.

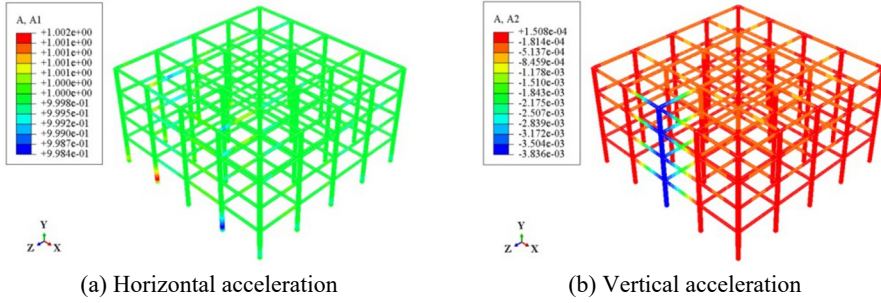


Fig. 3. Acceleration response

It can be observed from Fig. 3(a) that under X-direction horizontal seismic input, the horizontal acceleration distribution of the structure is highly uniform. Most nodal accelerations range from 0.998 g to 1.001 g, with a peak value of 1.002 g. The numerical deviation is only 0.018 g and negligible, indicating uniform lateral stiffness along the structural plan and height, no obvious stiffness mutation or weak story, and excellent cooperative performance under seismic action.

As shown in Fig. 3(b), the vertical acceleration response is extremely weak, with a peak value of 3.836×10^{-3} g, accounting for only 0.38% of the horizontal peak and far below the threshold specified in the current seismic design code. It presents a “large at the bottom and small at the top” gradient, and the response of columns is significantly higher than that of beams, which is caused by coupled bending-shear deformation at column bases.

(2) Displacement

To quantify the deformation characteristics of the steel frame structure under the horizontal action of the El Centro wave, displacement nephograms of the structure are extracted for analysis, and the results are shown in Fig. 4.

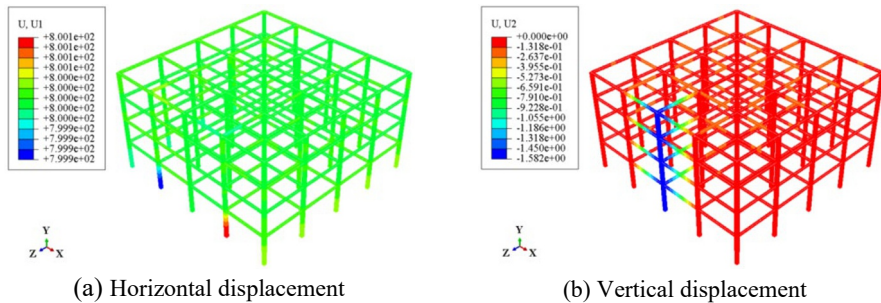


Fig. 4. Displacement response

Fig. 4(a) shows that the horizontal displacement distribution of the structure is highly uniform. Most nodal peak horizontal displacements range from 799.9 mm to 800.1 mm, with a maximum of 800.1 mm. The deviation is merely 0.2 mm and negligible. This distribution agrees well with the acceleration response, verifying uniform

lateral stiffness, no stiffness mutation or weak stories. The structure is dominated by translational deformation with negligible torsion and good cooperative performance.

As illustrated in Fig. 4(b), the vertical displacement response is very weak, with a peak of 1.582 mm (only 0.20% of the horizontal peak) and negligible contribution to global deformation. It shows a “large at the bottom and small at the top” gradient and concentrates in bottom columns, caused by coupled bending-shear deformation at column bases, which is local secondary deformation with no adverse effect on structural safety.

(3) Strain

To further investigate the local mechanical characteristics of the steel frame structure under the X-direction excitation of the El Centro wave, peak strain nephograms of all elements in the structure are extracted for analysis. Among them, Fig. 5 (a) shows the X-direction normal strain response, and Fig. 5(b) shows the shear strain response in the X-Y plane.

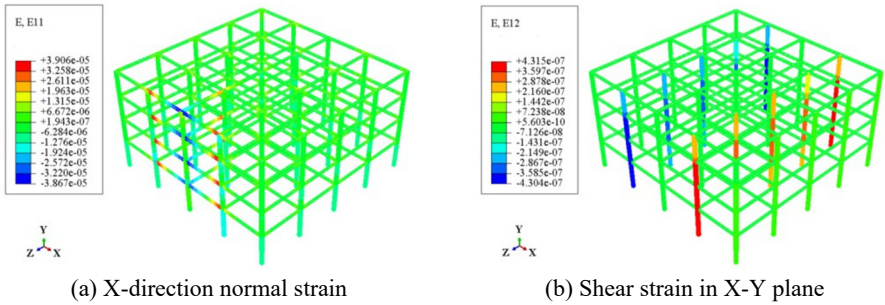


Fig. 5. Strain response

Fig. 5(a) shows that the overall X-direction normal strain of the structure is extremely low, with most elements at the order of 10^{-6} , a peak tensile strain of 3.906×10^{-5} and a peak compressive strain of 3.867×10^{-5} . Spatially, it is “concentrated at the bottom and uniform in the upper part”, mainly focusing on bottom column bases and partial beam-column joints. Notably, all peak strains are far lower than the yield strain of Q235 steel, indicating the structure is completely in an elastic state without plastic deformation.

As presented in Fig. 5(b), the X-Y plane shear strain is much lower than normal strain, with a peak of 4.304×10^{-7} (only $\sim 1.1\%$ of the peak normal strain) and negligible contribution to overall mechanics. It mainly concentrates in bottom columns, showing a “maximum at column base, gradual decrease upward” gradient, caused by horizontal shear force accumulation at bottom column bases.

5 Conclusions and Discussion

(1) Under horizontal earthquakes, the dynamic response of the steel frame is dominated by horizontal components. The magnitudes of vertical acceleration, displacement and

strain responses are less than 0.5% of the horizontal ones, with negligible contributions to the structure's overall mechanical behavior and deformation.

(2) The distributions of structural acceleration and horizontal displacement are uniform with small discreteness. The lateral stiffness has no obvious mutation, and there are no seismic weak stories. The structure is dominated by overall translational deformation under seismic action, with negligible torsional effect and excellent cooperative performance of each frame.

(3) The strain concentration regions of the structure are mainly distributed at the bottom column bases and beam-column joints, showing an obvious gradient characteristic of "large at the bottom and small at the top", which is consistent with the distribution law of shear force and overturning moment under horizontal earthquakes.

(4) This study has limitations: it only uses a single El Centro seismic wave, without fully considering the randomness and spectral differences of ground motions; it only involves unidirectional horizontal earthquakes, ignoring the multi-directional seismic coupling effect; and it does not conduct systematic analysis on the influences of key design parameters. Future research can address these shortcomings to improve the seismic performance evaluation system of steel frame structures.

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