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# Experimental and constitutive model study of structural steel under cyclic loading

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ABSTRACT

In order to study extremely low cycle fatigue performance of structural steel and find a suitable constitutive relationship under cyclic loading, a total of fifty Q235B and Q345B steel extremely low cycle fatigue experiments have been carried out. The mechanical behavior of Q235B and Q345B structural steel including monotonic loading behavior, hysteresis loading behavior and hysteresis criterion are discussed. With fully recognized cyclic behavior of structural steel, a uniaxial and simplified constitutive relationship of structural steel under cyclic loading is proposed. Then the uniaxial steel constitutive relationship is developed as user-defined material based on the user subroutine interfaces UMAT provided by Finite Element Software ABAQUS. By introducing the fiber beam element method, the steel uniaxial constitutive model can be used for steel structural analysis. With comparison of Q235B and Q345B tests data under various loading systems, the model proposed in this paper is proved correct and can be applied in nonlinear time history analysis of steel frame. Both tests and analysis results show that the response of Q235B and Q345B steel under cyclic loading and monotonic loading are quite different, and the skeleton curve under cycle loading is much higher than monotonic loading after steel yielding. Both cyclic loops and amplitudes seriously affect the fracture ductility of steel material. While the structural steel bearing cyclic loading, the necking and the fracture behavior will occur ahead of time, it means that the cumulative damage makes the ductility of steel reduced.



## 1. Introduction

In severe earthquake, the structural steel members usually have to resist enormous cyclic forces and fewer hysteresis loops which show a short load duration with large plastic deformation. It mainly depends on the mechanical properties of materials themselves to resist such loads, which is described as the reaction of large strain extremely low cycle fatigue in material level [1–4]. In seismic design and analysis of steel structure, due to high cost of the tests, numerical simulation is widely used currently. However, three-dimensional finite element model is too time consuming and quite inconvenient to extract internal forces. By introducing fiber beam method, "line" finite element model is often used in seismic analysis (Fig. 1), so uniaxial constitutive model of structure steel under cyclic loading plays a quite important role in structural seismic design and analysis. Currently, steel stress–strain relationship is commonly defined as bilinear or multi-linear models [5,6]. However, those methods cannot give a very accurate simulation on steel mechanical behavior under cyclic loading, which are shown in Fig. 2.

In order to meet the practical and convenient requirements for engineering applications, many researchers have put forward some simplified calculation models to simulate the material in structure under cyclic loading. Ramberg and Osgood [7] proposed a three-parameter stress–strain relationship which has been widely used in metal material as skeleton curve. Krawinkler and Nathaniel [8,9] developed a mathematical model for uniaxial cyclic stress–strain behavior of steel assuming the existence of stress bounds which is controlled by hardening, softening and mean stress relaxation. Chaboche [10,11] proposed a cyclic constitutive model to describe the cyclic behavior based on elastic–plasticity theory. Atkan et al. [12] and Wang et al. [13] gave a mathematical model for reinforced steel rebar under reverse loading according to test results. Dong and Zhang [14] summarized cyclic stress–strain relationship of structural steel including both uniaxial and three-dimensional behavior. And also some other researchers have conducted great work on cyclic constitutive models of concrete [15–18]. All of them have conducted outstanding works on steel constitutive relationship, but their expressions of the models are quite complicated for description. Due to limited calculation conditions, they preferred to focus on material constitutive relationship and the models were not widely used in the calculation of structural system.

In this paper, two series of total 50 Q235B and Q345B steel specimens are imposed on a variety of loading systems. Their

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**Nomenclature**

*The following symbols are used in this paper.*

| | |
|---|---|
| $R_{el}$ | Lower yield strength |
| $R_m$ | Tensile strength |
| $A$ | Elongation after fracture |
| $J_k$ | Impact energy |
| $E_s$ | Young's modulus |
| $\sigma_y/f_y$ | Yield stress |
| $\varepsilon_y$ | Yield strain |
| $f_u$ | Ultimate stress |
| $f_{u2}$ | Fracture stress |
| $\varepsilon_l$ | Strain as ultimate stress $f_u$ |
| $\varepsilon_u$ | Fracture strain as fracture stress $f_{u2}$ |
| $f_{u3}$ | 15% of $f_u$ |
| $\varepsilon_{u3}$ | Strain when stress is 15% of $f_u$ |
| $E_n$ | Hysteretic energy when gauge is 20 mm |
| $N_p$ | Plastic hysteresis loops |
| $\Delta\varepsilon$ | Total strain amplitude |
| $\Delta\varepsilon_e$ | Elastic strain amplitude |
| $\Delta\varepsilon_p$ | Plastic strain amplitude |
| $\Delta\sigma$ | Stable stress amplitude |
| $K'$ | Cyclic hardening factor |
| $n'$ | Cyclic hardening index |
| $\tilde{\sigma}$ | $\sigma/\sigma_y$ stress of regularization |
| $\tilde{\varepsilon}$ | $\varepsilon/\varepsilon_y$ strain of regularization |
| $\tilde{K}$ | Cyclic hardening factor of regularization |
| $\tilde{n}$ | Cyclic hardening index of regularization |
| $k_1, k_2, k_3$ | Control the shape of monotonic loading curve |
| $a, b_0, b_1, b_2$ | Control the shape of hysteresis skeleton curve |
| $E_k$ | Tangent stiffness |
| $\varepsilon_0$ | Strain of start point on $\varepsilon$-axis |
| $\sigma_0$ | Stress of start point on $\varepsilon$-axis |
| $\varepsilon_p$ | Strain of end point on hysteresis skeleton curve |
| $\sigma_p$ | Stress of end point on hysteresis skeleton curve |
| $\eta$ | Proportional coefficient |
| $[K_e]$ | Element stiffness matrix |
| $[K]$ | Global stiffness matrix |
| $[D]$ | Jacobian matrix |
| $\Delta P$ | Load increment |

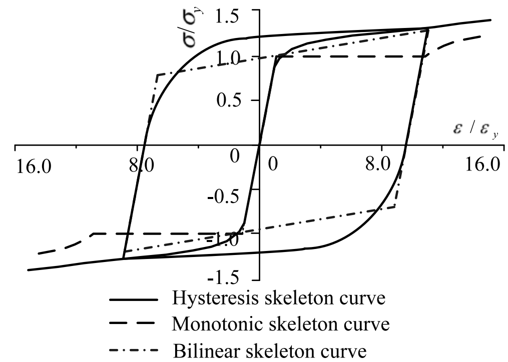


**Fig. 2.** Constitutive model of structural steel usually used.

monotonic behavior, hysteretic behavior, macro- and micro-failure modes, ductility characteristics and cumulative damage degradation are discussed. Differences of mechanical behavior under cyclic loading and monotonic loading are studied deeply. The effect on steel ductility and failure modes under various loadings are summarized. Based on the advantages of constitutive models mentioned above, a uniaxial and simplified constitutive model of Q235B and Q345B structural steel under cyclic loading is proposed including: monotonic loading curve, hysteresis skeleton curve and hysteresis criteria. It is also embedded into finite element software ABAQUS by user subroutine prefaces UMAT. The model proposed in this paper is proved correct and applicable through comparing with the test data under various loading systems, and it can be used for nonlinear time history analysis of steel structure.

## 2. Experimental study

### 2.1. Experimental details

The whole paper fixes on both Q235B and Q345B which are widely used. Total 50 specimens of Q235B and Q345B structural steel are designed. As steel plates are widely used in engineering structures, the plate specimens not cylinder are adopted in the experimental study. The specific sizes are shown in Fig. 3. Loading device is the INSTRON Model 1343 which is a universal tension, compression and torsion fatigue testing machine (Fig. 4). Strain is measured by tension and compression extensometer whose gauge is 20 mm. Pull range mechanical properties and the chemical

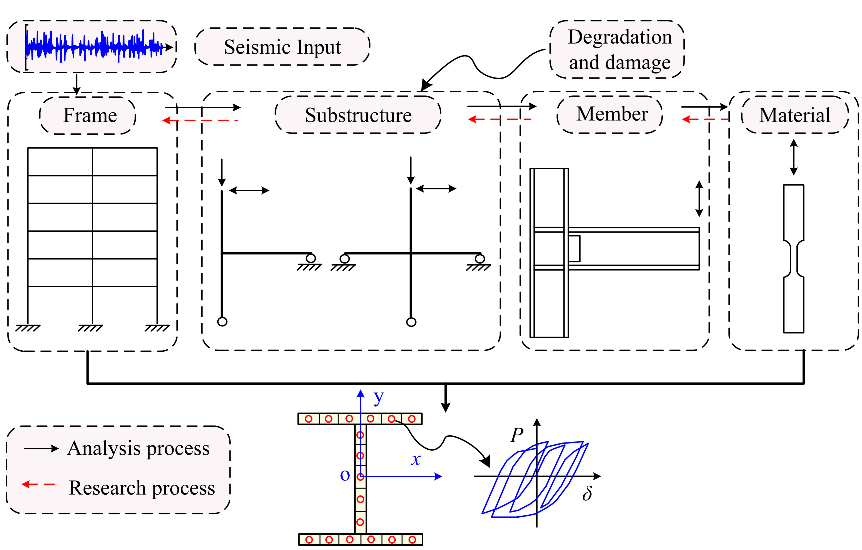


**Fig. 1.** The process of seismic behavior of fine member model.