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Experimental study on constitutive relation of the high performance marine structural steel under extreme cyclic loads

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ABSTRACT

Jacket offshore platform serving in the marine environment is often subjected to severe dynamic loads such as winds, waves, currents and earthquakes. The alternating stress state of jacket offshore platform will lead to the degradation of mechanical properties of the structural steel, which results in the decline of the overall bearing capacity. In this paper, eighteen types of cyclic loading program designed according to the characteristics of the steel and extreme cyclic loads are presented for the first time. The hysteresis behavior of structural steel NV-D36 under various cyclic loading program is studied. The changing process of energy dissipation capacity of the steel under different loading program is compared. The hysteresis skeleton curve of steel under variable amplitude cyclic loading is fitted based on the basis of the classical Ramberg-Osgood model. The parameters of combined hardening of the steel based on Chaboche constitutive model are calibrated. The results of the cyclic loading are numerically simulated with the obtained hysteresis skeleton curves and parameters. The combined hardening criterion can be used to analyze the responses of the steel under cyclic loading, and the parameters can be applied to study the dynamic properties of the jacket offshore platform of structural steel NV-D36.

1. Introduction

1Jacket offshore platforms are majorly located in a severe environment and usually subjected to crucial dynamic loads caused by winds, waves and currents. Occasionally, there are hurricanes, earthquakes or other extreme cyclic loads (Wang et al., 2006). Extreme cyclic loads such as earthquakes can result in the positive and negative change alternately of structural internal forces. Under those extreme cyclic loads, structural members, particularly those acting as dissipative elements, will experience small numbers of large plastic deformation cycles in a short time. This process that lead to structural members' damage or failure caused by small numbers of cyclic loading can be seen as low-cycle fatigue (Kuroda, 2002; Nip et al., 2010). Once low-cycle fatigue loads such as earthquakes and hurricanes occur, jacket offshore platforms maybe destroyed seriously or even collapse (Health and Safety Executive (HSE), 1999). In the last two decades, earthquakes and hurricanes have caused serious damage to several jacket offshore platforms in service (Panthaki, 1992; Ajamy et al., 2014).

The study on fatigue of jacket offshore platform mainly concentrated on the high-cycle fatigue life caused by waves, currents and other common cyclic loads, but rarely focused on the features of material or structure mechanical properties caused by hurricanes, earthquakes and other extreme cyclic loads (ABS, 2014; DNVGL-RP-C203, 2016). Besides, steel engineering stress-strain relation is commonly defined as bilinear or multi-linear simplified models in the current engineering calculation (Kuroda, 2002; Xue, 2008; Nip et al., 2010). However, due to cyclic hardening or softening and Bauschinger effect of steel, those simplified models have a great difference from the real stress-strain relation, which are shown in Fig. 1 (Shi et al., 2011). Those simplified methods cannot provide a very accurate simulation on steel mechanical behavior under cyclic loading. Therefore, it is significant to obtain engineering stress-strain relation accurately under cyclic loading to evaluate the ultimate state of structure and safety of overall structure.

Many scholars have put forward some simplified cyclic constitutive models such as bilinear model, three-linear model, skeleton model and non-linear model to simulate the material in structure under cyclic loading. Ramberg and Osgood (1943) proposed a widely used three-parameter model to describe the hysteresis skeleton curve of metal materials. Jhansale (1977) proposed an inelastic computation model of

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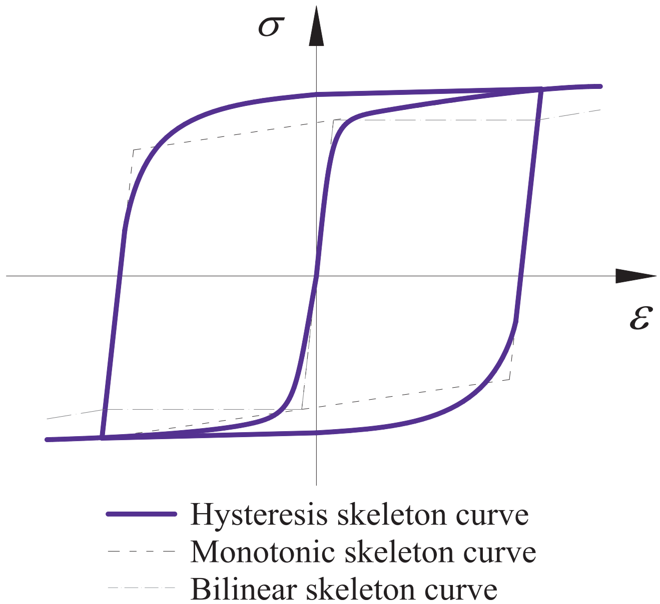

Fig. 1. Constitutive model of structural steel used (Shi et al., 2011).

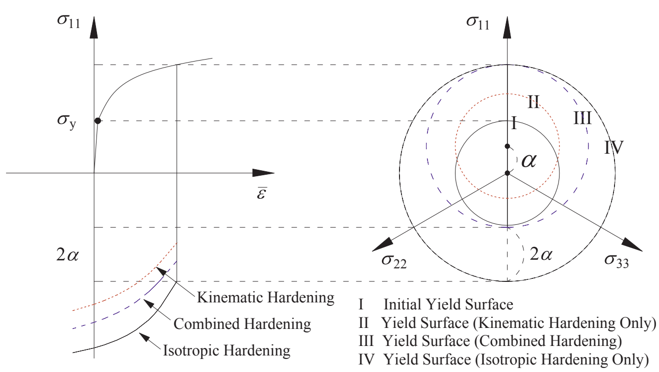

Fig. 2. Combined isotropic and kinematic hardening under uni-axial loading (Myers, 2009).

structural material under complex cyclic loading and described the hysteresis skeleton curve by piecewise polyline. Krawinkler et al. (1983, 1985) develop 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 (1986, 1991) proposed a cyclic constitutive model considering the characteristics of isotropic hardening and kinematic hardening to describe the hysteretic behavior based on elastic-plasticity theory. The initial yield condition and the flow law have been basically agreed based on the classical plastic theory of the unified system under the Drucker (1951) postulate. Therefore, the main difference among the above constitutive models is how to define the evolution law of the initial yield surface (hardening criterion). Generally, the hardening criterion can be divided into linear hardening criterion and nonlinear hardening criterion. The form of linear hardening criterion is simple and easy to apply, but its simulation of the real yield surface is poor. The form of nonlinear hardening criterion is more complex, but its simulation is closer to the evolution law of the real yield surface (Lee et al., 2009). Take the hardening criterion of the nonlinear cyclic constitutive model as an example (Myers, 2009), as shown in Fig. 2. The hardening criterion can be equivalent to isotropic hardening criterion, kinematic hardening criterion or combined hardening criterion. The isotropic hardening criterion means that the initial yield surface expands along each stress direction uniformly under cyclic loading. The kinematic hardening criterion is that the subsequent yield surface only move without shape change under cyclic loading. The combined hardening criterion is the combination of isotropic hardening and kinematic hardening. Therefore, it is crucial to obtain the reliable control parameters of hardening criterion for constructing the constitutive relation of steel under cyclic loading accurately.

Because of the cyclic constitutive model is related to the material properties and processing technology of the steel, the control parameters of hardening criterion of the specific steel are usually calibrated by the cyclic loading test. Generally, the test types are divided into shaking table test, pseudo dynamic test and pseudo static test (low-cycle cyclic loading test). Shaking table test and pseudo dynamic test are the closest to the real loading condition, but its strict full size test conditions and high test costs result in such tests are difficult to implement. However, low-cycle cyclic loading test can be easily conducted to obtain the strength, stiffness and energy dissipation and other important information. It becomes most economically effective method to acquire the hardening parameters and establish the cyclic constitutive relation (Robert, 1996). Some scholars have carried on low-cycle cyclic loading test to various metal materials, and obtained suitable cyclic constitutive relation (Dusicka et al., 2007; Nip, 2010; Shi et al., 2011; Shi et al., 2012). The cyclic loading program of the above test is triangular waveforms, but the loading amplitude, loading history and the number of loading program are different. The cyclic constitutive relation of material is not only dependent on the properties of the material but also the characteristics of cyclic loads. Therefore, it is very important to determine the loading amplitude, loading history and the number of loading program. Extreme cyclic loads, such as earthquakes, have strong randomness. Superstition Hills-02 seismic spectrum was measured by El Centro Imp. Co. Cent in 1987 and the acceleration time history are shown in Fig. 3 (Yang et al., 2017). Part A is the typical stage of load amplitude increasing and the amplitude is symmetry. Part B is a reverse loading stage with large amplitude. Part C, cyclic loading in the tensile direction, is a one-way loading stage. The A, B and C section is only part of the extreme cyclic loads. Therefore, a rich and accurate cyclic loading program should be designed to reflect the characteristics of the material itself and the seismic loads.

In the current paper, various types of cyclic loading program are designed according to the characteristics of the steel and extreme cyclic loads. Then, we choose the high performance marine structural steel (HPMS) NV-D36 to carry out the experimental study under different cyclic loading program for analyzing the monotonic behavior, hysteretic behavior and energy dissipation capacity of the steel. Further, Ramberg-Osgood (1943) model is used to fit the hysteresis skeleton curves and Chaboche (1986) model is applied to calibrate the combined hardening parameters. After the calibration, finite element software ABAQUS is used to simulate and verify the test hysteresis curves. The experimental basis is provided for the response analysis of HPMS NV-D36 steel in the overall jacket offshore platform.

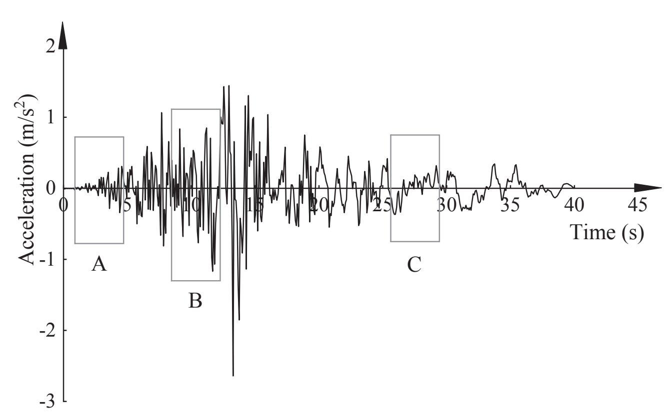

Fig. 3. Acceleration time history of superstition Hills-02 El centro.