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Ductile crack initiation and propagation in steel bridge piers subjected to random cyclic loading

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ABSTRACT

Results from five cyclic tests of steel bridge piers are presented to examine the extremely low-cycle fatigue (ELCF) behavior of steel bridge piers under random cyclic loading. It is observed that using test results of constant cyclic loading to predict the ELCF behavior under random loading may be not effective. In this study, the random cyclic loading patterns are determined using dynamic analytical results. The effect of various parameters, including axial force ratio, earthquake ground motion type and repeated earthquakes, is investigated. The dynamic analysis suggests that all of these parameters are shown to have a large influence on ELCF behavior of structures. The test data reveal that the sudden increase or decrease displacement amplitude has a significant effect on the ELCF behavior, including the ductile crack initiation, propagation and final failure. Meanwhile, a four staged failure criterion is presented and effectively employed to investigate the ductile fracture of steel bridge piers with thick-walled box section.

1. Introduction

As one of the features of steel bridge structures, the pier is of comparatively thin-walled section, and local buckling occurs in the pier base. On the other hand, for thick-walled steel piers or concrete-filled steel piers, cracks may occur in the welding or the base metal due to the extremely low cycle fatigue (ELCF) before occurrence of local buckling [1–8]. Accordingly, ELCF failure becomes one of important failure modes in steel structures, especially for the thick-walled steel structures, and needs to be investigated deeply.

The interest of researchers in the early days was primarily in the ELCF behavior of steel structures under regular cyclic loading. Previous studies have investigated the ductile crack initiation of steel coupons or steel structures subjected to different regular displacement-based cyclic loading, such as constant amplitude cyclic loading (CC) [9–12] (Fig. 1a), one cycle per each amplitude cyclic loading (C1) [10,11,13,14] (Fig. 1b), three cycles per each amplitude cyclic loading (C3) [9,10,13] (Fig. 1c), and cyclic test under typical far-field ground motions and typical near-fault ground motions [15]. Based on above cyclic tests under regular cyclic loading, many useful findings have been obtained. Previous test results show that the low cycle fatigue (LCF) characteristics under these inerratic cyclic loadings are quite regular and similar. However, the real earthquake ground motions in practical engineering are random and irregular. Liu et al. [16] pointed out that estimating low-cycle bending-fatigue strength based on the results of cyclic loading tests with constant amplitude is inappropriate for random loading histories. Consequently, more experimental investigations about ELCF behavior of steel structures under random cyclic loading should be conducted. Some studies [16,17] have been carried out on seismic behavior of steel welded joints and steel bars under random cyclic loading. Agerskov [17] conducted the fatigue tests and fracture mechanics analyses using load histories, which are realistic in relation to the types of structures studied, i.e., primarily bridges. However, that work is concerned with high cycle fatigue (HCF) behavior and not ELCF performance. Although Liu et al. [16] conducted some LCF experimental investigations of specimens under random cyclic loading, but that study concentrated on steel bars with solid cross section. The ELCF performance of steel bridge piers with box cross section under random cyclic loading still is a puzzle, yet not to be effectively resolved.

Motivated by the scarcity of data about the ELCF performance of steel bridge piers subjected to random cyclic loading, this paper presents the experimental investigation on five steel bridge pier specimens. First of all, dynamic analysis has been conducted to determine the applied loading patterns in cyclic tests. Next, experimental results about ductile crack initiation and propagation are presented. The specimens were subjected to cyclic loading with random displacement amplitude obtained from the dynamic analysis. Lastly, the results of ELCF tests under random cyclic loading are reported and discussed to develop ELCF evaluation method of steel bridge piers under random cyclic loading in a companion study.

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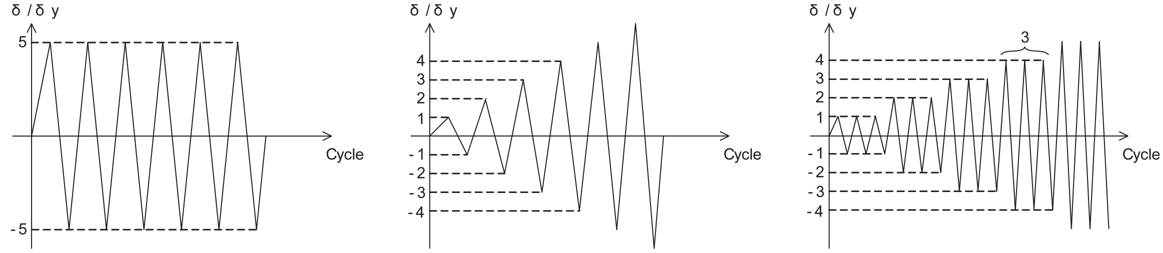


(a) Constant amplitude cyclic loading (CC)

(b) One cycle per each amplitude cyclic loading (C1)

(c) Three cycles per each amplitude cyclic loading (C3)

Fig. 1. Regular cyclic load patterns.

2. Experimental program

2.1. Test specimens

Due to the limited capacity of available equipment and also to economic reasons, the quasi-static tests were performed on scaled models rather than full-scale structures, as the same as the previous study reported [18]. As shown in Fig. 2, the test specimens consisted of five steel bridge pier specimens with unstiffened box section, which were supported on a rigid steel foundation plate, loaded vertically by one hydraulic actuator and loaded transversely by another two actuators. Special attentions were placed on making the specimens representative of practical engineering and fabrication practices. Summarized in Table 1 were the test parameters of the five specimens, including geometric dimensions and structural parameters. The structural parameters R_f and $\bar{\lambda}$ are calculated by the following equations [13]:

$$R_f = \frac{b}{t}\sqrt{\frac{12(1-\nu^2)}{4\pi^2 n^2}}\sqrt{\frac{\sigma_y}{E}} \tag{1}$$

$$\bar{\lambda} = \frac{2h}{r}\frac{1}{\pi}\sqrt{\frac{\sigma_y}{E}} \tag{2}$$

where b = plate width, t = plate thickness, σ_y = yield stress, E = Young's modulus, υ = Poisson's ratio, n = number of sub-panels (for unstiffened section, n = 1), h = height of steel bridge pier and r = radius of gyration, respectively. Besides, 9 mm thick diaphragms were arranged in equidistance of flange width in the longitudinal direction of bridge pier.

All of the tested specimens were made of SM490 (equivalent to ASTM A242). Table 2 summarized the material parameters attained from averages of five coupon tension tests. The column flanges were welded to the column webs with one-sided groove welds, and the column flanges and webs were welded to the base plate with two-sided groove welds. Mechanical properties and chemical compositions of weld electrode were listed in Table 3.

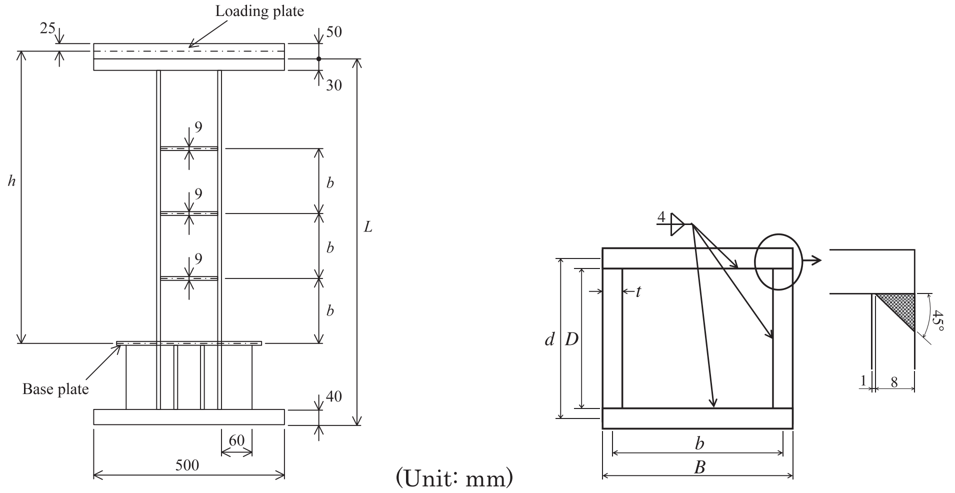
2.2. Test setup

As shown in Fig. 3, the test setup provided a fixed-sliding boundary condition, where one end of the steel bridge pier specimen was bolted directly to a large fixed base plate and the other end was attached to a moving device. The constant vertical load was applied through one vertical servo-hydraulic actuator before cyclic horizontal loading. The cyclic horizontal load was applied through two servo-hydraulic actuators, each with a ±350 kN force capacity. Determination of cyclic horizontal loading patterns is stated in one later section. Cyclic lateral load tests were performed in displacement control with actuators set in a loading plate to minimize end rotations and maintain a sliding boundary condition at the translating end.

3. Determination of loading patterns for cyclic tests

3.1. Dynamic analytical model

To determine the loading patterns for cyclic tests, an extensive dynamic analysis was firstly carried out, as shown in Fig. 4. The



(a) Test specimen

(b) Cross section

Fig. 2. Test specimen and cross section.