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Damage characteristics of thin-walled steel arch bridges subjected to in-plane earthquake action

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ABSTRACT

Although steel bridges generally demonstrate good seismic performance, local instabilities within steel plates and ultra-low-cycle fatigue (ULCF) damage at welded joints can cast a important effect on the seismic performance of bridge structures. To study the characteristics of the above-mentioned types of damage in steel arch bridges, a non-hinged half-through steel arch bridge was considered as an example, and a refined finite-element (FE) model, capable of accounting for local deformation within potentially damaged regions, was established. Based on simulation results concerning elastoplastic seismic response of the entire structure and ULCF damage of welded joints at locations with high strain concentrations, seismic damage characteristics of steel arch bridges and influence of steel-plate thickness of arch ribs on them were analysed. Based on FE analysis, the arch springing and beam–arch junctions were identified as locations transmitting longitudinal seismic loads, thereby suffering maximum seismic damage during in-plane earthquakes. Local deformation of steel plates within damaged areas has a remarkable effect on the overall seismic response of structures, and hence, cannot be ignored. The fibre model does not account for local deformation within steel plates; thus, when steel plates undergo local deformations, the results obtained using the fibre model tend to be misleading and dangerous. An increased steel-plate thickness of arch ribs causes significant improvement in local stability of steel arch bridges. However, this method does not guarantee prevention of ULCF failure, which could occur at welded joints within the structure and must be considered during seismic design.

1. Introduction

Compared to concrete structures, seismic performance of steel structures is relatively excellent owing to their light weight and excellent ductility. However, once steel plates suffer local instabilities or ultra-low-cycle fatigue (ULCF) failure under earthquake action, the ductile properties of steel remain underutilized for the most part. Consequently, the seismic performance of the structure sharply declines. During the 1995 Hyogo-ken Nanbu earthquake in Japan, a large number of steel bridges suffered severe damage owing to occurrence of local instabilities within steel plates or ULCF failure of welded joints [1]. Since then, numerous researchers have investigated the seismic performance of steel-bridge piers and proposed methods to verify the above two forms of damage. With regard to the failure caused by local instabilities, Usami et al. [2–4] and Nomura et al. [5] proposed empirical formulae for bearing capacity and ductility of circular and rectangular steel piers whilst accounting for their thickness, slenderness, and axial compression ratios in accordance with experimental and numerical analyses results. They also proposed a criterion for evaluating the ultimate state of steel piers based on strain assessment. Furthermore, Goto et al. [6,7], Dang et al. [8], and Kul et al. [9,10] investigated the local stability of steel piers under bi-directional seismic excitation and proposed evaluation formulae for structural seismic performance. In terms of ULCF damage, Ge et al. [11–13] investigated the fundamental characteristics of fatigue damage in steel piers as well as methods to predict such damage through horizontal cyclic loading tests performed on thick-walled steel piers. Tateishi et al. [14,15] developed a ULCF testing device to investigate ULCF properties of steel and its welded joints under high-strain-loading cycles. An improved ULCF damage-prediction model was proposed based on the Coffin–Manson formula, and a ULCF strength-evaluation technique for steel piers was discussed.

Compared to single-column piers, steel arch bridges belong to the category of complex structures, horizontal and vertical vibration modes of which are coupled. Since forms of seismic damage in such structures manifest more complicated compared to those occurring in single piers, seismic damage characteristics of steel arch bridges have not yet been fully understood. Over the past 15 years, many scholars have investigated seismic damage characteristics of steel arch bridges by establishing full-bridge fibre models. Nonaka et al. [16] studied elastoplastic seismic response characteristics of an upper-deck arch bridge subjected to strong earthquake action and reasonable structural

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anti-seismic system. They also investigated the effects of elastoplastic behaviour of a concrete-deck structure on the seismic response of arch-bridge structures. Liang et al. [17] analysed elastoplastic seismic-response characteristics and structural seismic performance of a steel arch bridge. Usami et al., Lu et al. [18,19], and Cetinkaya et al. [20] verified applicability of the pushover method in the evaluation of seismic response of steel arch bridges. Wang et al. [21] analysed effect of the hysteretic constitutive relation pertaining to steel on simulation results concerning seismic response of steel arch bridges. In addition, to investigate the influence of varying arch-rib axial force on seismic performance of bridge structures, Usami et al. [22] applied the formula for seismic-performance evaluation of steel piers to evaluate corresponding seismic performance of steel arch ribs. This was accomplished using the relationship between real-time axial force and the average ultimate compressive strain. However, use of the fibre model is based on the plane cross-section assumption. When bridge structures are subjected to the action of strong earthquakes causing severe local deformations or instabilities, the fibre-model algorithm tends to overestimate the structural stiffness. Xie et al. [23] and Tang et al. [24,25] verified that fibre model cannot accurately reflect structural damage characteristics. Their investigations were based on simulation results obtained using the fibre model and shell model, fibre model and multi-scale model, respectively.

A typical steel arch bridge was considered in this study to determine seismic damage characteristics of thin-walled steel arch bridges. Seismic performance of the said steel arch bridge was investigated via analysis of localized steel-plate instabilities and ULCF damage suffered by the bridge under the effect of strong in-plane earthquakes. Further, influence of the steel-plate thickness on seismic damage characteristics of the structure has been discussed. Conclusions drawn from this study provide a reference for seismic-damage prediction and corresponding structural design of steel arch bridges.

2. Proposed structural calculation model and seismic ground motion

2.1. Overview of half-through steel arch bridge

Fig. 1 depicts the profile of a half-through non-hinged steel arch bridge measuring 130 m in span and 50 m in width of the deck. The height of the main arch rib is 32.5 m. To enhance the overall structural stability, a pair of secondary arch ribs measuring 34.08 m in height are set on both sides of the main arch ribs. The main and secondary arch ribs are connected by means of braces. Springing points of the main arch and sub-arch ribs are fixed to the ground. The main arch ribs are set vertically while secondary ribs are inclined inwards at an angle of 17.5°. The main girder, main and secondary arch ribs, and columns are comprised of thin-walled steel-box sections, wherein the longitudinal rigid stiffeners and rigid diaphragms are set. The transverse beams are comprised of I-shaped cross sections while the deck is constructed of orthotropic steel plates. An asphalt concrete pavement is set on the bridge deck. The entire bridge structure is made of Q345qC steel, and hangers are made of high-strength steel parallel cables having an elastic modulus of 2.0×10^5 MPa and ultimate bearing capacity of 1670 MPa.

Fig. 2 depicts cross sections of the main components of the half-through arch bridge. As seen, the heights of the main arch rib cross section vary along the cross-sectional axis. The cross-sectional heights from the main arch springing to the arch crown vary from 3.5 m to 2.0 m while the rib plates are 10-mm thick. To investigate the influence of the local buckling stiffness of main arch ribs on seismic damage characteristics of steel arch bridges, thicknesses of the rib steel plates were varied to perform parametric analyses. Three thicknesses of steel plates—10 mm, 20 mm, and 30 mm—were considered. Structural parameters of steel components corresponding to different plate thicknesses are listed in Table 1. The parameter values listed in Table 1 satisfy the necessary requirements of Chinese design specifications for steel bridges [26] as follow.

$$\begin{cases} \dfrac{h_s}{t_s} \le 12\sqrt{\dfrac{345}{\sigma_y}} \\ \gamma/\gamma^* \ge 1.0 \\ \gamma_t \ge \dfrac{1+n\gamma}{4(a/B)^3} \end{cases} \tag{1}$$

In the above equation, h_s denotes cross-sectional height of the plate ribs while t_s denotes thickness of the plate ribs. For longitudinal stiffeners and diaphragms, t_s refers to values of t_1 and t_2, respectively. γ^* denotes the optimal relative stiffness of stiffeners; γ and γ_t represent relative stiffnesses of longitudinal stiffeners and diaphragms, respectively, which can be expressed as

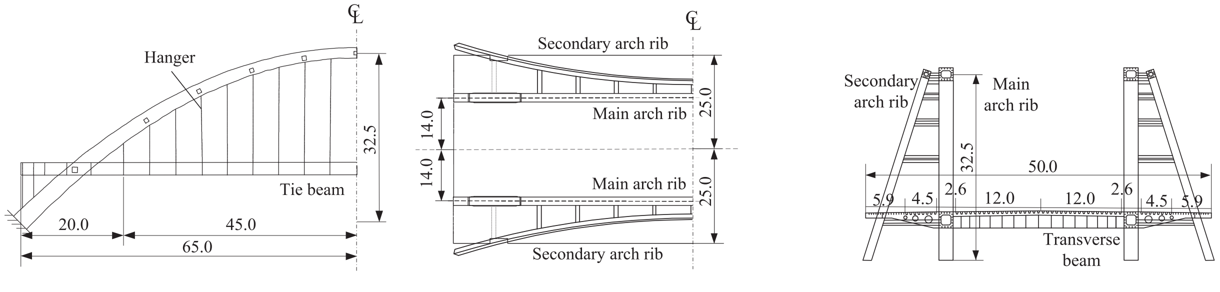
$$\begin{cases} \gamma = \dfrac{I_\lambda}{Bt_1{}^3/[12(1-\mu^2)]} \approx \dfrac{I_\lambda}{Bt_1{}^3/11} \\ \gamma_t = \dfrac{I_t}{Bt_2{}^3/[12(1-\mu^2)]} \approx \dfrac{I_t}{Bt_2{}^3/11} \end{cases} \tag{2}$$

In the above equation, B denotes the section width, I_λ and I_t represent bending moments of inertia concerning the single longitudinal stiffener and diaphragm, respectively, against mother plates, and μ denotes Poisson's ratio.

Secondary arch ribs are also comprised of cross-sections with heights varying in the range of 2.0–1.2 m, and thicknesses of the flange and web measure 8 mm each. Widths of both the main arch ribs and tie beam are 2.2 m, and width of the secondary ribs is 1.2 m.

2.2. Structural model for seismic response analysis

Although both, instabilities within steel plates and ULCF damage at welded joints qualify as local mechanical behaviours, instabilities in steel plates within regions affected by seismic damage cast a major influence on mechanical properties of the entire structure, and the effect must be accounted for during elastoplastic seismic response evaluation



(a) Facade and plane (b) Cross-section

Fig. 1. Overview of half-through steel arch bridge (unit: m). (a) Facade and plane, (b) Cross-section.