Fundamental Study for Improving Structural Planning, Design and Maintenance of Steel Arch Bridges

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Steel arch bridge was firstly constructed in the USA (Eads Bridge, completed in 1874). Its success promoted the booming development of steel arch bridges worldwide. A number of steel arch bridges, such as the Hell Gate Bridge built in the USA in 1916 (main span: 298m), the Sydney Harbor Bridge constructed in Australia in 1932 (main span: 503m), the Bayonne Bridge and the New River Gorge Bridge, with main spans of 504m and 518.3m, respectively, in the USA, were built successively. In 2003, the completion of Lupu Bridge (main span: 550m) in China broke the world record of steel arch span. Four years later, Chaotianmen Bridge in China with the main span of 552m was completed. Its main span length is the present world record of steel arch span. It is expectable that the upper limit of the span of steel arch bridge is far from being reached. The steel arch is aesthetically beautiful, highly stiff, efficient in cost, and can be in multiple structural forms, hence it has been widely accepted. Improved materials, products and design capabilities contribute to make the steel arch bridge one of the main bridge types in the world, even though many bridge types have become available in recent years. It still has prosperous future especially in this era of large scale transportation infrastructure construction in developing counties. However, some issues to be improved still remain in structural planning, design and maintenance of steel arch bridges as follows.

(1) The rapid development of steel arch bridge calls for a higher requirement of the bridge planning. A good structural planning contributes a suitable appearance for surroundings as well as favourable mechanical characteristics to the bridge. However, so far, there is no comprehensive statistical data on main structural parameters of steel arch bridges available for planning reference.

(2) Although extensive works on the theory and numerical methods to prevent out-of-plane instability have been conducted in the past few decades, design code updates lag behind these rapid developments in research works.

(3) In order to satisfy architectural aesthetics as well as the mechanical requirements of steel box arch bridges with long spans, some irregular-shaped box sections are sometimes adopted for arch ribs. These types of irregular sections have rarely been employed for a steel box arch bridge anywhere in the world, so there is no established engineering experience for reference. In fact, there are no provisions for the design of such irregular-shaped steel box sections anywhere in the world.

(4) Stiffness and strength of existing steel arch bridges decline inevitably due to overloads, fatigue damages, corrosions and insufficient maintenance etc. The fault of steel arch bridge occurred frequently while we review the great achievement of steel arch bridges acquired in 20 century. As of now, the issues we should clearly recognize are that the potential risk and the multiplying fault probability of steel arch bridges may lead to the collapse of bridge if there is no sufficient maintenance. Therefore, maintenance of existing steel arch bridges become imperative.

In this dissertation, the author tries to solve these problems aiming at improving structural planning, design and maintenance of steel arch bridges. It is composed of seven chapters.

Chapter 1 gives the background and objectives of the research with a discussion of major previous works conducted in the related field.

Chapter 2 collects a large amount of data and literature about steel arch bridges in China and Japan constructed before December of 2011 and 2008, respectively. The data are then analyzed in terms of their history, main span length, structural form, construction method and aesthetics. In addition, the design vehicle loads for steel arch bridges are outlined. It is expected to provide base data and a reference for its future research, design and construction.

In Chapter 3, provisions relating to the out-of-plane stability of steel arch bridges in the Chinese design code Fundamental code for design on railway bridge and culvert, the Japanese code Specifications for Highway Bridges and Eurocode 3 Design of Steel Structures are outlined first. The influences of the main structural parameters on out-of-plane critical axial forces are then studied by carrying out FE analysis for the cases of through-type, half-through type and deck-type steel arch bridges, focusing on the influence of the ratio of stiffness between the arch ribs and the lateral bracing, the bridge type, the rise-to-span ratio, the range of lateral bracing arrangements and the arch rib spacing. By comparing the critical axial forces of arch ribs given by the codes and evaluated by FE analysis, the applicability and accuracy of provisions in the codes are revealed. Finally, a method to improve accuracy of the code calculations is proposed.

Chapter 4 focuses on the mechanical behaviour of one of irregular-shaped steel box sections, convex sections. Extensive parametric analyses considering local buckling, residual stress and initial deflections of the stiffened plates in the section were carried out to examine the differences in critical stress among the stiffened plates as well as the effects of width ratio η, stiffened plate width-thickness ratio R_R and γ/γ^* value on the normalized stress-strain relation of the section. The width ratio is the ratio of top plate width to middle plate width and is used to investigate the influence of the shape of convex box section. The normalized stress-strain relations of convex sections and conventional rectangular sections are compared. Then a formula for obtaining the normalized stress-strain relation of convex sections is developed. These normalized stress-strain relations can be employed as constitutive material relationships in an overall FE model of a large-scale structure with a convex box section using beam-column elements in order to take into account local buckling and initial imperfections.

In Chapter 5, the present condition of an existing CFST arch bridge is evaluated by comparing the results of tests and measurements with those of FE analysis according to a Chinese code, specifications for old highway bridge load capacity identification. The outline of the specifications and the result of reliability assessment of the bridge, i.e. the static loading test on the arch ribs, cross girders, deck and hangers, ambient vibration measurement and forced vibration test. The results of test and analysis are compared to evaluate the reliability of the bridge according to the code.

Chapter 6 presents a simple and efficient approach for detecting the damage of steel arch bridges. The FE models of steel arch bridge with intact hangers, one or two ruptured hangers at $L/4$ and $L/2$ are established, and eigenvalue analyses of the models are conducted to estimate the changes in dynamic characteristics by the hanger rupture. Then the ambient vibrations of bridge with intact and ruptured hanger are simulated by applying the independent white noise on nodes except supporting points in vertical and transverse directions. By using the velocity response, natural frequencies of the bridge models with intact and ruptured hanger are identified with eigensystem realization algorithm (ERA) method. The identified natural frequencies of the model with intact hangers are compared with those of models with ruptured hanger to verify the feasibility of damage detection for the bridge with ERA method.

In Chapter 7, the main findings of each chapter are summarized. The points that need to be studied in the further work are also indicated.