Engineering Structures 41 (2012) 63–76

Contents lists available at SciVerse ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Nonlinear finite element analysis of barge collision with a single bridge pier

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ARTICLE INFO

Article history:
Received 23 February 2011
Revised 12 March 2012
Accepted 12 March 2012
Available online 22 April 2012

Keywords:
Barge–pier collision
Impact force
Crush depth
Nonlinear analysis

ABSTRACT

Vessel collisions with bridge piers are one of the most frequent accidents that may lead to bridge failure. To reliably assess bridge response and damage due to barge impact, and design the bridge piers to resist such impact, the impact force should be accurately defined. In most of the previous works of numerical simulation of barge collision with bridge piers for defining the barge impact force, the pier was assumed to be rigid or elastic and the interaction between the barge and the pier was neglected. As pier plastic deformation and damage will absorb impact energy and also prolong the interaction time, the impact force acting on the bridge pier might not be accurately predicted with rigid and elastic pier assumption. In this paper, a detailed numerical model of barge–pier impact is developed in LS-DYNA. The bridge pier is modelled with nonlinear materials to more realistically generate the bridge pier characteristics. Barge–pier impact force time history, barge crush depth and pier displacements are calculated in this paper. The reliability of the numerical model is calibrated with some results available in the literature. Based on numerical results simplified formulae are derived to predict the impact force time history with respect to the collision conditions. Numerical results are compared with the previous works. The adequacy of current code specifications is also discussed.

1. Introduction

Bridge structures over navigable waterways are usually designed to resist wind load, vehicle load and seismic excitation. However, in addition to such loads, bridges, especially piers, are susceptible to accidental vessel collisions and should be capable of resisting the vessel collision loads. According to Manen and Frandsen [1] and Larsen [2], at least one serious vessel collision occurs worldwide each year and many such collisions lead to serious consequences. It is reported that during the period of 1960–2007, there were 34 major bridge collapses worldwide due to vessel (ship or barge) collision, with a total loss of 346 lives. For example, an empty 35,000 DWT bulk carrier collided with one of the support piers of the Sunshine Skyway Bridge in the USA in 1980. The bridge collapsed after the collision and 35 people lost their lives in this accident [3]. A recent example of the catastrophic accident occurred in 2007, a cargo vessel ploughed into the Jiujiang cable-stayed bridge in Guangdong, China, causing the collapse of two side spans [4] (see Fig. 1). In addition to the loss of nine lives, the accident also caused significant economic losses and long legal battles. Therefore, it is important to protect piers of bridges crossing the waterways. To do that, it is essential to reliably predict the possible vessel impact loads on bridge piers.

In order to quantify the impact load during vessel–pier collision, Minorsky [5] conducted 26 ship–ship collision experiments. Based on the experiment results he proposed an empirical relationship between the resistance of penetration and the energy absorbed in the collisions. A linear relationship was found between the deformed steel volume and the absorbed impact energy. From 1967 to 1976, Woisin [6] conducted a number of high energy ship collision tests for the purpose of protecting the nuclear powered ships in Germany, he modified Minorsky's method and proposed a new empirical formula for ship-bridge collision. To evaluate the barge–pier impact force, both static and dynamic pendulum hammer testing of reduced-scale European hopper barges were conducted by Meir-Dornberg [7], and an equivalent static method was developed to calculate the impact force. According to this research, The American Association of State Highway and Transportation Officials (AASHTO) published the Guide Specification and Commentary for Vessel Collision Design of Highway Bridge in 1991 [8]. Only minor modifications were made in the expressions in AASHTO to reflect the size difference between US Jumbo Hopper (JH) barge and European barge. The peak impact load generated during the collision is a function of impacting barge mass, velocity and bridge structure configuration. Although the AASHTO specification, which uses equivalent static method to compute the impact force, provides a simple mean to determine the impact force for pier design to resist barge impact, the barge–pier collision process is dynamic in nature. Simply quantify impact with static loads may lead to unrealistic predictions of barge–pier collision responses.

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0141-0296/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.engstruct.2012.03.026

Fig. 1. Example of bridge collapse after barge collision.

For example, in 2004, a group of full-scale barge impact tests were conducted between a barge and a real bridge, the St. George Island Causeway Bridge in Florida, USA [9]. The tests revealed that at small levels of barge bow deformation, the AASHTO specification gives smaller impact load predictions than those obtained in the tests. However, at larger levels of deformation, those impact loads predicted by AASHTO specification are substantially larger than the test results, indicating the current AASHTO specifications which neglected the dynamic effects may give inaccurate predictions of barge impact loads on bridge piers.

Although experimental tests are straightforward and give good impact load measurements, they are usually costly, time consuming and often not possible to be performed. Finite element (FE) method is an alternative way to study the vessel–pier impact problem. Pedersen et al. [10] reviewed and summarised the merits of numerical simulations and found that FE simulation is efficient and produces reasonable results. Consolazio and Cowan [11] developed FE models to analyse a single barge impacting against several piers. In their study, FE code ADINA was adopted to study the effects of pier size and shape to the impact forces. Jin et al. [12] studied platform damage due to barge collision. Using FE method, Yuan and Harik [13] also studied flotillas impact against bridge piers. They built numerical models to study the multi-barge flotilla impacting on bridge piers in the software package LS-DYNA. In these studies, although special care was taken in the modelling of barge structure, the pier was assumed to be rigid or elastic in the model owing to difficulty in modelling nonlinear response and damage of reinforced concrete structures. Since both bridge pier and barge deform and suffer impact damage under collision, and bridge pier plastic deformation and damage affect the collision process, to accurately predict the interaction between barge and pier during a barge collision, and hence derive more accurate impact forces on the bridge pier, nonlinear responses and damage of both barge and pier should be considered in the numerical simulation.

In this paper, nonlinear FE models of barge and reinforced concrete bridge pier are developed in the dynamic FE code LS-DYNA [14]. A barge-rigid pier impact model is also built first for comparison purpose. The simulated impact force is compared to those available in the literature to calibrate the numerical model. Then the bridge pier is modelled with nonlinear concrete and steel materials to generate more realistic bridge pier characteristics. The influences of nonlinear bridge pier responses on the impact forces are discussed. The objective of this paper is to study the effect of nonlinear inelastic response and damage of pier and barge on impact forces, and to develop the more accurate predictions of barge impact forces on bridge piers under different collision conditions. Parametric study is also carried out to study the effects of the barge mass and barge velocity on impact forces.

2. Numerical model of barge–pier impact

2.1. Barge and pier configurations

According to AASHTO, the JH barge is the most widely used barge type in the US waterways, therefore, without losing generality, it is employed as the baseline model in the present study. A typical JH barge used in inland waterways in the United States is shown in Fig. 2 [15]. The corresponding parameters are given in Table 1.

In this study, a square pier of cross section dimension 3.1×3.1 m and 15 m in height is considered. The pier is modelled as a reinforced concrete column with a lumped mass on its top to simulate the weight a bridge pier supports. The pier is positioned along the longitudinal axis of the barge and a distance of 0.49 m between the front surface of the barge and the pier is defined to avoid the initial penetration. It should be noted that the analysis in the present study does not include the soil–structure interaction effect. The bridge pier is assumed to be fixed in all directions at the foundation. The whole barge–pier collision model is shown in Fig. 3.

2.2. Elements

A FE barge model is built in the software package ANSYS (see Fig. 3). Since in the crushing stage, a large proportion of the kinetic energy is dissipated through the deformation of barge bow structure, the barge bow is carefully modelled in detail to represent the actual stiffness of the contact area. The front part of barge bow is modelled using high density finite element meshes and the rear part of the barge bow is modelled with a relatively coarse mesh as a relatively smaller deformation is expected to occur in the region. The hopper section of the barge is modelled by large solid elements with elastic material property for computational efficiency because no plastic deformation is expected in the rear part of the barge.

Four-node shell elements are utilised to model steel outer plates while internal trusses are modelled by 3-node beam elements. The internal trusses are welded to the outer plates, and are modelled using CONSTRAINED_SPOTWELD in LS-DYNA. Eight-node brick element is used in the hopper section. Eight-node solid element and 3-node beam element are used to model concrete and reinforcement of the bridge pier. In numerical simulations, the pier is modelled with either rigid or elastic or detailed concrete and steel material properties capable of simulating plastic deformation and damage. A supported mass of 130 ton on pier top which represents the mass from the bridge superstructure is modelled by element Mass166 in LS-DYNA. After mesh convergence test, which will be discussed in more detail in Section 3, the numerical model of a JH barge and a pier consists of 11,709 shell, 10,760 beam and 154,952 solid elements. The element types for each structure component in the model are listed in Table 2.

2.3. Material model and contact interface

The elastic–plastic material model *MAT_PLASTIC_KINEMATIC is employed to model the outer shell and internal truss of the barge bow. It is a cost effective model to represent isotropic and kinematic hardening plasticity including strain rate effects. The material fails when failure strain reaches 0.35 [16]. The well-known Cowper–Symonds equation (1) is used to describe the elastic visco-plastic behaviour of the structural steel.