Engineering Structures 175 (2018) 617–627

Contents lists available at ScienceDirect

Engineering Structures

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

Development and assessment of efficient models for barge impact processes based on nonlinear dynamic finite element analyses

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ARTICLE INFO

Keywords:
Finite-element simulations
Coupled model
Full barge impact model
Mass-spring model
Linear elastic pier columns

ABSTRACT

The impact of vessels straying out of control poses a serious hazard for bridge piers located in navigation waterways. In order to accurately predict the dynamic responses of the bridge piers subjected to barge impact and to design bridge piers which can resist such impact, the impact forces need to be accurately defined. Empirical formulas such as those provided by AASHTO Guide Specification are currently extensively used for predicting the equivalent static impact forces. Whilst such equivalent static methods cannot accurately reflect the actual dynamic phenomena in a barge impact event, sophisticated finite-element (FE) simulations are computationally expensive. This paper aims to establish a coupled model which can replicate the complex full barge impact model (FBIM) with sufficient accuracy. In this coupled model, the barge model is simplified into a mass-spring model (MSM) whilst the pier is modeled using discrete masses and discrete beam elements. The parameters introduced by MSM are determined using the proposed strategies in this paper. Linear elastic pier columns with fixed bases and cantilevered tops are employed to assess the prediction quality of the proposed coupled model for different impact scenarios.

1. Introduction

A large number of barge impact accidents resulting in great casualties and economic losses occurred in the past [1]. This has raised significant attention to the problem in the context of bridge design, and extensive research into such barge impact events has been carried out. The main focus of most studies is on the impact force time-history as this contact force is critical for the analysis and assessment of structural components such as bridge piers. Empirical formulas such as those provided by AASHTO Guide Specification [2] are widely used for estimating the impact force. However, the equivalent static method ignores the important dynamic effects involved in the impact event. The Eurocode introduced a simplified method to determine the impact force time-history based on initial barge kinetic energy and impact angle [3]. However, the influences of pier shape and pier size upon the impact force are not included in the code whilst several previous studies have indicated that such influences are significant [4,5]. The FE simulation is another strategy that has been extensively used for analyzing the barge impact process [6,7]. However, FE simulation requires enormous computation costs. Several efficient models were thus developed previously to predict the impact force time-history and dynamic responses of bridge pier subjected to barge impact. The Coupled Vessel Impact Analysis (CVIA) technique developed by University of Florida (UF) [8] and the simplified impact model proposed by Yuan [9] are two typical efficient models.

The CVIA technique is implemented by coupling the barge mass with bridge pier at the impact position using a non-linear spring. The barge bow crushing behavior considering the influences of pier shape, pier size and oblique impact angle was studied and a simple procedure for obtaining the force-deformation relationship of the non-linear spring was proposed [7,10]. The CVIA technique has been well calibrated using both experimental results and FE simulation results [11,12]. It is widely used in recent studies [13,14]. The barge crushing model was also employed by Luperi and Pinto [15]. As an alternative to the CVIA technique, the Applied Vessel Impact Load (AVIL) technique was developed for generating the impact force time-history based on a barge bow force-deformation relationship of interest [16]. Yet another alternative, which consists of a frequency-based approach to predict dynamic pier response, and makes use of impact response spectra, was proposed in Ref. [17].

Yuan featured the barge mass as a lumped mass and the barge bow as a group of elastoplastic-collapse elements that become active or inactive in a sequential order. The model allows a physical interpretation of the barge bow force-deformation relationship [5]. A group of model parameters were introduced in Yuan's model. The values of these parameters were determined by the proposed optimization model. The

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https://doi.org/10.1016/j.engstruct.2018.08.086
Received 6 August 2016; Received in revised form 18 May 2018; Accepted 25 August 2018
Available online 31 August 2018

bridge pier was modeled by a cantilever using two concentrated masses representing the superstructure mass and the mass at the impact position. The superstructure constraints were modeled using translational springs and rotational springs. The response spectrum analysis was conducted to estimate the maximum displacements at the impact position and pier top. Yuan's simplified impact model was calibrated against detailed FE barge impact models [9,18].

As the property of the non-linear spring representing the barge crushing behavior is critical for the predictions of impact force time-history and dynamic pier responses, an accurate yet simple description of the spring is essential. The elastic, perfectly plastic spring model proposed by UF takes the yielding force of spring as the peak contact force based on static barge crushing analysis [7,10]. As the peak contact force lasts briefly and soon drops after barge trusses yield, the proposed spring model provides a conservative estimation of barge resistance for engineering designs. The spring model proposed by Yuan using a group of elastoplastic-collapse elements enables an accurate description of barge crushing behavior. However, a large number of model parameters were introduced, leading to inefficiencies for engineering designs. In addition, the force-deformation relationships of the spring models proposed by UF and Yuan are independent on impact velocity, whilst several previous studies have indicated that the barge crushing behavior at the very beginning of impact is significantly influenced by impact velocity [5,19].

Sha proposed the simplified single degree-of-freedom (SDOF) model for predicting the dynamic responses of the bridge pier subjected to barge impact [20]. In this model, the pier column is simplified into an SDOF model whilst the barge impact load is represented by a simplified triangular impact load time-history described in details in Refs. [6,20]. The dynamic responses of the pier column is predicted by imposing the proposed triangular impact load time-history at the impact position on the pier column. Sha's simplified SDOF model can well consider the dynamic effects involved in the barge impact process with high calculation efficiency. However, the prediction accuracy of the model is not highly sufficient for several impact scenarios investigated considering material non-linearity of the pier members, as presented in the previous studies conducted by Sha [20].

Cao proposed the strategy to describe the barge crushing curves with regression formulas [19]. However, the barge crushing behavior is dependent on many factors such as pier shape, pier size, impact velocity and oblique impact angle. Using a large number of regression formulas to describe each crushing curve is inconvenient for engineering designs. Fan's simplified model [21] for ship impact analysis introduced the velocity influence factor to modify the dynamic ship crushing curve. The velocity influence factor is calculated either by the average factor method or the variable factor method. However, the average factor method ignores the ship velocity change during the impact process. The variable factor method assumes that all the impact energy is dissipated by the ship bow deformations, which is inadequate for flexible piers as the pier material also absorbs a portion of the impact energy. In addition, the iterations required by the variable factor method would increase the computation cost.

The idea of adopting a dashpot which acts in parallel with the non-linear spring was developed by Fan [22,23] along with fast evaluation procedures for peak structure deflection and peak impact force. However, the barges and ships share fundamental differences in shapes and inner structures, the crushing behaviors of two vessel types are thus different. The relevant studies by Fan [21–23] cannot be directly used for barge impact analysis.

This paper proposes a simplified mass-spring model to replicate the complex finite-element barge model using a limited number of model parameters. The influence of impact velocity upon the barge crushing behavior is considered by the proposed non-linear spring model. A coupled model is developed herein by coupling MSM with the multi-degree-of-freedom (MDOF) pier column model at the impact position. The coupled model can be used to predict the impact force time-history and dynamic responses of the pier column subjected to barge impact. The prediction quality of the proposed simplified models is assessed for different impact scenarios using linear elastic pier columns with fixed bases and cantilevered tops.

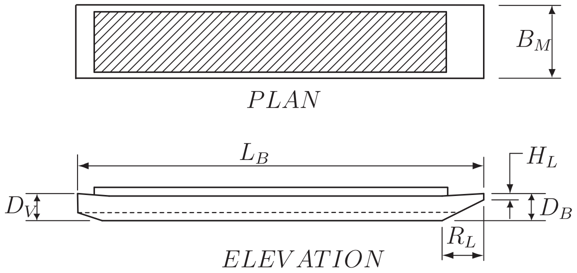

Fig. 1. Configuration of the JH barge [2].

2. Non-linear FE simulation of barge impact process

The barge impact on bridge pier is a highly dynamic process. The actual deformation process, including the pier deformation and resulting time-history of contact forces, depends on the specific material, geometric and mass distribution properties of barge and pier and on the barge impact velocity. A realistic FE simulation thus needs to account for these effects accurately. In current studies, the barge is modeled in detail, with non-linear material models as described below.

2.1. Barge configurations

A typical Jumbo Hopper (JH) barge is used in the AASHTO Guide Specification and also employed for current studies. Fig. 1 shows the configuration of the JH barge and Table 1 provides the values of the corresponding geometric parameters. The empty mass and fully loaded mass of the JH barge are 181.4 ton and 1723.7 ton, respectively.

The outskin of the JH barge is made from steel plates of thicknesses varying from 0.010 m to 0.013 m [5]. In current studies, the thickness of the barge outskin is taken to be 0.012 m. Shell elements are used to model the barge outskin. The barge bow is comprised of a group of inner trusses located at equal spaces. The inner trusses are modeled using beam elements with non-linear material and are welded to the barge outskin using CONSTRAINED _SPOTWELD in LS-DYNA [5–7]. The barge model is divided into two zones: the front 6.10 m is included in Zone1 and the rear 53.38 m is included in Zone2, as shown in Fig. 2.

2.2. Material models

During the impact process, relatively large deformation occurs in Zone1 whilst Zone2 does not experience the same level of deformation. Zone1 is thus finely modeled using piecewise linear plasticity material (MAT_PIECEWISE_LINEAR_PLASTICITY) whilst Zone2 is modeled using rigid material (MAT_RIGID). The stress-strain curve of the barge steel is shown in Fig. 3 [4,24]. Other property parameters are tabulated in Table 2 [5].

In order to keep the mass of the barge model same as the real barge mass, the density of the material in Zone2 should be modified using the

Table 1
Geometric dimensions of the JH barge.

Symbols	AASHTO [ft] [2]	This study [m]
L_B = Length	195.0	59.48
B_M = Width	35.0	10.68
D_B = Depth of bow	13.0	3.97
H_L = Head log height	2.0–3.0	0.76
D_V = Depth of vessel	12.0	3.66
R_L = Bow rake length	20.0	6.10