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A nonlinear dynamic macro-element for demand assessment of bridge substructures subjected to ship collision*

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Abstract: For the dynamic demand assessment of bridge structures under ship impact loading, it may be prudent to adopt analytical models which permit rapid analysis with reasonable accuracy. Herein, a nonlinear dynamic macro-element is proposed and implemented to quantify the demand of bridge substructures subjected to ship collisions. In the proposed nonlinear macro-element, a combination of an elastic-plastic spring and a dashpot in parallel is employed to describe the mechanical behavior of ship-bows with strain rate effects. Based on the analytical model using the proposed macro-element, a typical substructure under 5000 deadweight tonnage (DWT) ship collision is discussed. Our analyses indicate that the responses of the structure using the nonlinear macro-element agree with the results from the high resolution model, but the efficiency and feasibility of the proposed method increase significantly in practical applications. Furthermore, comparisons between some current design codes (AASHTO, JTGD60-2004, and TB10002.1-2005) and the developed dynamic analysis method suggest that these design codes may be improved, at least to consider the effect of dynamic amplification on structural demand.

Key words: Nonlinear macro-element, Ship-bridge collision, P-a curve, Dynamic demand, Design codes
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1 Introduction

The Sunshine Skyway Bridge Disaster in 1980 was a key turning point in awareness and increased concern about vessel collision design of bridges crossing navigable waterways in the United States (AASHTO, 1991; 2009; Larsen, 1993). The Jiujiang Bridge collapse in Guangdong Province in 2007 again attracted wide attention, particularly from bridge designers and researchers in China.

Guide specifications and commentary for vessel collision design of highway bridges by the American Association of State Highway and Transportation Officials (AASHTO) (2009) pointed out that ship collision design was in its infancy, compared to well-established fields such as earthquake and wind engineering. A static analysis approach was still employed to determine the static demand of an impacted bridge in the Guide Specification (AASHTO, 2009). Similarly, a few static load procedures were studied and developed by Pedersen *et al.* (1993), Fan *et al.* (2008), and Getter *et al.* (2011). Just like the earliest static method used in seismic design (Priestley *et al.*, 1996), most of static analyses and design procedures fail to consider significant dynamic effects, such as inertial forces during a collision event. As a result, the structural demand under ship impact loads may be

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potentially underestimated from these static analysis procedures. Currently, with the rapid development of explicit finite element techniques (ABAQUS, 2005; LS-DYNA, 2007), general-purpose contact-impact nonlinear finite element codes have been widely employed to conduct the analysis of vessel-bridge collision (Consolazio and Cowan, 2003; He *et al.*, 2008; Wang *et al.*, 2008). However, to obtain reliable and realistic results, this approach is not only time-consuming for both building and analyzing model, but also requires supercomputing resource, a great number of input parameters, and significant experience and knowledge (El-Dakhakhni *et al.*, 2010; Fan *et al.*, 2010; 2011). For this reason, Consolazio and Cowan (2005; 2007) proposed some simplified dynamic analysis methods for estimating the response of a bridge structure due to barge collision. However, while similar in many respects, barge vessels and ship vessels differ in some fundamental ways, such as shapes, speeds, and bow structures (Yuan, 2005). Furthermore, Fan *et al.* (2011) pointed out that the dynamic responses of bridge structures may be underestimated since the strain rate effect was not taken into account in (Consolazio and Cowan, 2005).

In this paper, a new macro-model is developed to quantify efficiently the demand of bridge structures subjected to ship collisions. Firstly, the proposed nonlinear dynamic macro-element is introduced in principle. Subsequently, we discuss the parameters and the implementation of the macro-model in detail. The proposed method is verified by the general-purpose nonlinear finite element analyses. Finally, the comparison between the dynamic analyses and current design codes (e.g., AASHTO) is conducted.

2 Analytical model using the proposed nonlinear dynamic macro-element

Analytical models based on macro-element typically employ a single-degree-of-freedom (SDOF) or a multi-degree-of-freedom (MDOF) idealization of the structural element under consideration, which are able to capture the major dynamic behavior of structures under dynamic loads. Macro-models have been extensively used in blast and seismic designs of structures (El-Dakhakhni *et al.*, 2010; Varun, 2010), because they require a limited number of input data and are simple to use. For practical ship collision design of bridges (Fig. 1a), the preferred analytical model should not only consider the dynamic interaction between ship and bridge during a collision event, but also be easy and efficient to use. Thus, in this study, an analytical model based on nonlinear dynamic macro-element is proposed as shown in Fig. 1b.

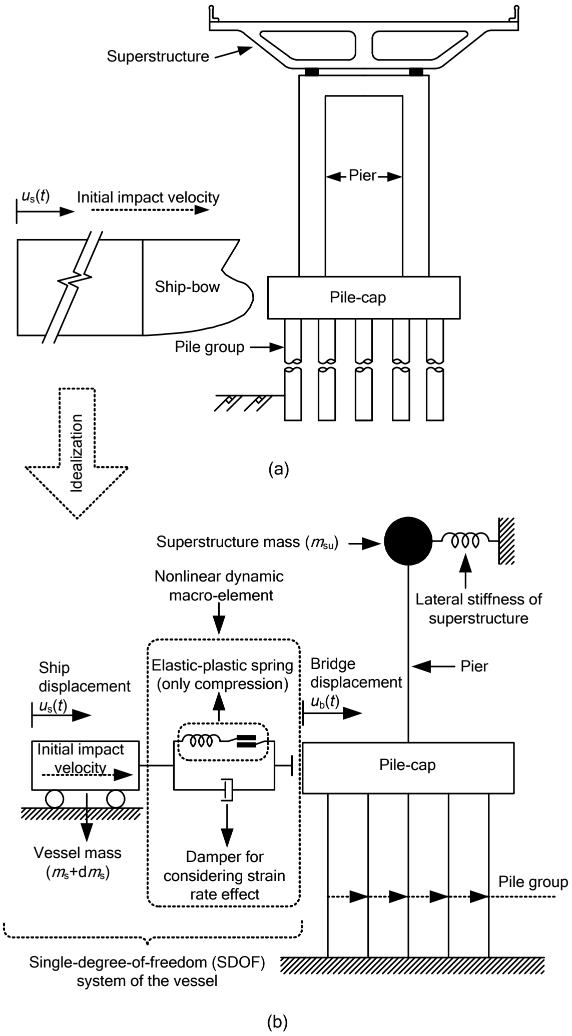


Fig. 1 Analytical model for bridge-ship collisions based on the proposed macro-element

(a) Ship-bridge collision; (b) Analytical (macro) model of ship-bridge collision

As illustrated in Fig. 1b, the proposed nonlinear dynamic macro-element mainly consists of two components: (1) an elastic-plastic spring element; (2) a dashpot element. The elastic-plastic spring element is employed to model the crush static or quasi-static behavior of the ship-bow, which can be defined by a nonlinear static crush relationship of the ship bow as shown in Fig. 2 (P_s-a curve, where P_s is the contact force from static or quasi-static analysis, and a is the crush depth of ship-bow) (Consolazio and Cowan, 2005; Fan *et al.*, 2011). The dynamic strength of ship-bow steel is different from the static one, since it has strain rate sensitivity (Jones, 1989). Hence, the dashpot element is added into the model to consider the influence of strain rate effect on the contact force. It avoids the unnecessary assumptions on the impact velocity for obtaining the dynamic crush curve (P_d-a curve, where P_d is the dynamic contact force) in (Fan *et al.*, 2011). As shown in Fig. 2, the dynamic crush curve can be obtained readily from the parallel combination of the elastic-plastic element and the dashpot.

In the analytical model based on the above macro-element (Fig. 1b), the ship model is reduced to be an SDOF system. It is connected to the MDOF of bridge structures by the proposed macro-element. The dynamic equation for the equivalent SDOF model of ship (Fig. 1b) can be written as

$$(m_s + \mathrm{d}m_s)\ddot{u}_s(t) + P_d(t) = 0, \tag{1}$$

where m_s is the ship mass, $\ddot{u}_s(t)$ is the ship acceleration, $P_d(t)$ is the dynamic contact force between ship and bridge structures, namely ship impact force, and $\mathrm{d}m_s$ is the hydrodynamic added mass, which can be obtained by (Larsen, 1993)

$$\mathrm{d}m_s = \begin{cases} (0.05-0.10)m_s, & \text{if bow impact,} \\ (0.40-0.50)m_s, & \text{if sideways impact.} \end{cases} \tag{2}$$

Before ship rebounds and does not contact with bridge structure, the following equation should be positive:

$$a(t) = u_s(t) - u_b(t), \tag{3}$$

where $u_s(t)$ is the ship displacement and $u_b(t)$ is the bridge displacement in the impacted location.

The equations of motion for the MDOF of bridge structures in Fig. 1 can be written as

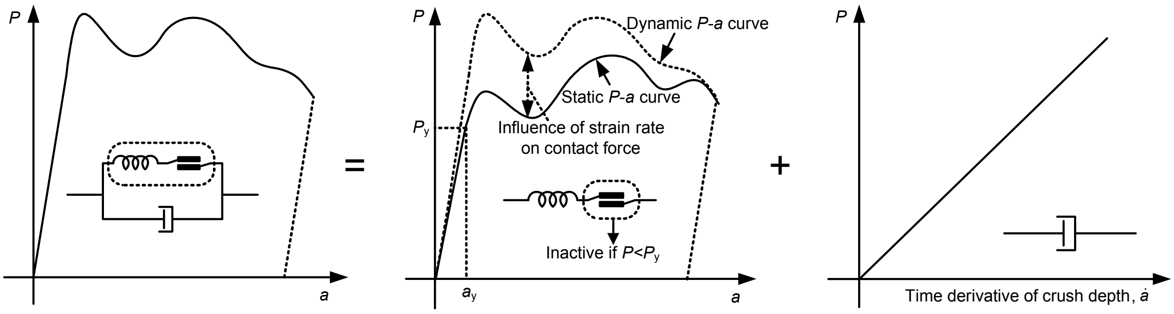
$$\boldsymbol{m}\ddot{\boldsymbol{u}}_b(t) + \boldsymbol{c}\dot{\boldsymbol{u}}_b(t) + \boldsymbol{k}\boldsymbol{u}_b(t) = \boldsymbol{\Gamma}P_d(t), \tag{4}$$

where $\boldsymbol{m}$, $\boldsymbol{c}$, and $\boldsymbol{k}$ are the structural mass, damping, and stiffness matrices, respectively; $\ddot{\boldsymbol{u}}_b(t)$, $\dot{\boldsymbol{u}}_b(t)$, and $\boldsymbol{u}_b(t)$ are the structural acceleration, velocities, and displacements vectors, respectively; and $\boldsymbol{\Gamma}$ is the ship-collision excitation vectors, in which only the vector-element that represents the impacted location is equal to one, and others are zero.

3 Development of the nonlinear dynamic macro-element

3.1 Static *P-a* curve of ship bow

To develop the proposed macro-element, firstly the static crush curve of ship-bow should be obtained. Generally, static crush curve from the quasi-static or static crush tests are the best choice. Few tests, however, were available until now. Alternatively, Consolazio and Cowan (2005) pointed out that a quasi-static crush analysis using finite element method could be employed to obtain the P_s-a curve of the barge bow. This method presented by Consolazio and and Cowan (2005) will be adopted in our study.



(a) (b) (c)

Fig. 2 Schematic description of the nonlinear dynamic macro-element

(a) Dynamic *P-a* curve; (b) Static *P-a* curve; (c) Dashpot curve for including strain rate effect

Although the nonlinear finite element analysis is time-consuming, it is conducted only once and the crush curve can be saved and subsequently retrieved for use in the analytical model (Consolazio and Cowan, 2005; Cowan, 2007; Fan *et al.*, 2011). For a typical 5000 DWT ship (Fig. 3a) on the Yangtze River, the P_s-a curve (Fig. 4) is determined by the quasi-static crush analysis using the finite element model as shown in Fig. 3b and Table 1.

If the strain rate effect is included in the dynamic analysis, the Cowper-Symonds strain rate model is employed as follows (Jones, 1989):

$$\frac{\sigma_0^{\mathrm{d}}}{\sigma_0}=1+\left(\frac{\dot{\varepsilon}}{C}\right)^{1/D}, \tag{5}$$

where σ_0^{d} is the dynamic flow stress, σ_0 is the static flow stress, C and D are constants in the strain rate hardening law. For mild steel, the dynamic flow stress can be estimated reasonably as C=40.4 s^{-1} and D=5 (Jones, 1989).

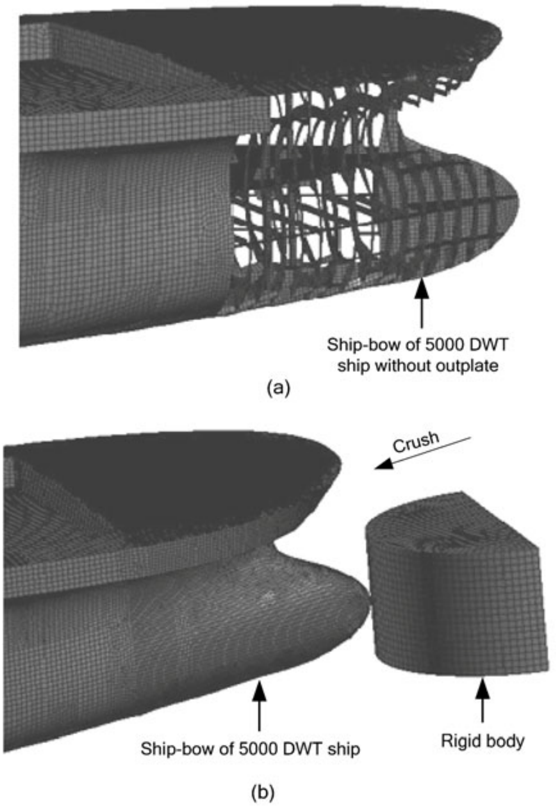


Fig. 3 Finite element model of 5000 DWT ship (a) and quasi-static crush analysis (b)

3.2 Parameters for the proposed element

For the elastic-plastic spring component, the above static crush curve can be used to describe the force-deformation relationship. Then the behavior of the dashpot component is discussed. According to the principle of the nonlinear dynamic macro-element (Fig. 2), $P_{\mathrm{d}}(t)$ in Eqs. (1) and (4) can be given by

$$P_{\mathrm{d}}(t)=P_{\mathrm{s}}(t)+P_{\mathrm{v}}(t), \tag{6}$$

where $P_{\mathrm{s}}(t)$ is the elastic-plastic spring force and $P_{\mathrm{v}}(t)$ is the damper force in the dashpot. Using Eqs. (5) and (6), the relationship between $P_{\mathrm{d}}(t)$ and $P_{\mathrm{s}}(t)$ can be expressed as

$$\frac{P_{\mathrm{d}}(t)}{P_{\mathrm{s}}(t)}=\frac{\sigma_{\mathrm{d}}}{\sigma_0}=1+\left(\frac{\dot{\varepsilon}}{C}\right)^{1/D}, \tag{7}$$

$$\dot{\varepsilon}=\frac{\partial\varepsilon}{\partial t}=\frac{1}{l_0}\frac{\mathrm{d}l}{\mathrm{d}t}\approx\frac{\dot{a}(t)}{l_0}, \tag{8}$$

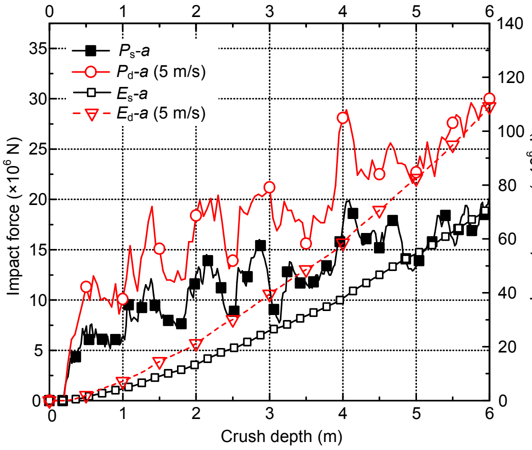


Fig. 4 Static and dynamic crush curves and the impact energy curves for 5000 DWT ship

Table 1 Parameters of material model

Parameter	Ship-bow (Mat_003)	Rigid body (Mat_020)
Material density (kg/m^3)	7.85×10^3	3.00×10^3
Young's modulus (MPa)	2.06×10^5	3.00×10^4
Poisson's ratio	0.3	0.2
Tangent modulus (MPa)	885	
Yield stress (MPa)	235	
C (s^{-1})	40.4	
D	5	
Failure strain	0.3	

where l_0 is the original length of the deformational object, dl is the change in length, and $\dot{a}(t)$ is the velocity in the macro-element. Due to the elastic-plastic spring and the dashpot in parallel, the total displacement is equal to the displacement of elastic-plastic element ($a_s(t)$) and dashpot ($a_v(t)$). Thus, the corresponding time derivative can be written as

$$\dot{a}(t)=\dot{a}_{\mathrm{v}}(t)=\dot{a}_{\mathrm{s}}(t). \tag{9}$$

Substituting Eqs. (7)–(9) into Eq. (6) and rearranging, and then

$$P_{\mathrm{v}}(\dot{a})=P_{\mathrm{s}}\left(\frac{\dot{a}}{l_0 C}\right)^{1/D}. \tag{10}$$

Obviously, it is necessary to determine l_0 in Eq. (10) for different DWT ships before the use of the proposed macro-element. In this study, the least square method (LSM) will be employed to estimate l_0 for a 5000 DWT ship. Based on Eqs. (7) and (10), we can obtain

$$\ln(\beta-1)=\frac{\ln\dot{a}}{D}-\frac{\ln(Cl_0)}{D}, \tag{11}$$

where the dynamic increase factor β=$P_{\mathrm{d}}/P_{\mathrm{s}}$, and β−1=$P_{\mathrm{v}}/P_{\mathrm{s}}$. Letting $\tilde{\beta}=\ln(\beta-1)$, $A=\ln(Cl_0)/D$, $\tilde{\dot{a}}=\ln\dot{a}$, and then

$$\tilde{\beta}=\frac{\tilde{\dot{a}}}{D}-A. \tag{12}$$

Note that the nonlinear equation (Eq. (11)) has been transformed to the corresponding linear equation (Eq. (12)). Based on the linear LSM and Eq. (12), the estimation equation of parameter A is

$$\frac{\partial}{\partial A}\sum_{i=1}^{N}\left[\tilde{\beta}_i-\left(\frac{\tilde{\dot{a}}_i}{D}-A\right)\right]^2\Bigg|_{A=\hat{A}}=0, \tag{13}$$

where $\hat{A}$ is the estimator of A, and N is the number of (β_i, $\dot{a}_i$). The solution of Eq. (13) is

$$\hat{A}=\left(\frac{1}{D}\sum_{i=1}^{N}\tilde{\dot{a}}_i-\sum_{i=1}^{N}\tilde{\beta}_i\right)\Big/N. \tag{14}$$

Based on Eqs. (11), (12), and (14), the estimator can be given by

$$\hat{l}_0=\frac{\mathrm{e}^{D\hat{A}}}{C}. \tag{15}$$

A critical step of the determination of $\hat{l}_0$ using Eqs. (14) and (15) is to obtain the reasonable data of (β_i, $\dot{a}_i$). For this purpose, the bow of a 5000 DWT ship with strain rate effect was crushed by rigid bodies at different constant velocities ranging from 0.5 to 5 m/s. For example, the dynamic crush curve of a 5000 DWT ship-bow at the constant velocity of 5 m/s is shown in Fig. 4.

As shown in Figs. 4 and 5, it may be difficult to determine β_i directly from the comparison of P_{d}-a and P_{s}-a curves, since the factor β varies greatly with different crush depths. Consequently, the static and dynamic impact energy curves (E_{s}-a and E_{d}-a curves as plotted in Fig. 4) were calculated from the numerical integrations via the static and dynamic crush curves, respectively. The ratio of E_{d} to E_{s} is given by

$$\frac{E_{\mathrm{d}}}{E_{\mathrm{s}}}=\frac{\int_0^a P_{\mathrm{d}}(a)\mathrm{d}a}{\int_0^a P_{\mathrm{s}}(a)\mathrm{d}a}=\beta=1+\left(\frac{\dot{a}}{l_0 C}\right)^{1/D}. \tag{16}$$

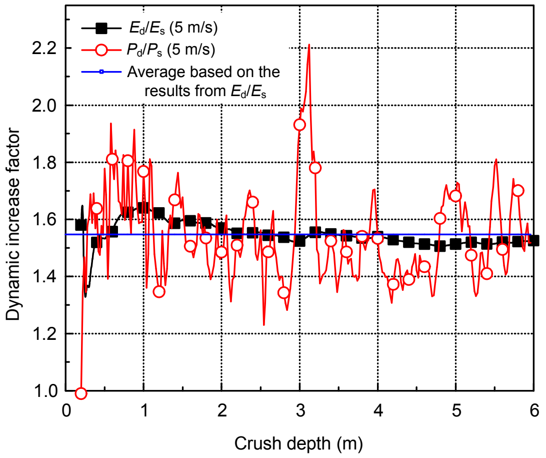


Fig. 5 Dynamic increase factors obtained from P_d/P_s and E_d/E_s

Using Eq. (16) and the results as shown in Fig. 4, the data pairs of β_i and $\dot{a}$ were determined and used to estimate l_0. Although different β_i are still given at different crush depths ($a\in$(0 m, 6 m)), the differences decrease significantly compared to the ratio from P_d/P_s as illustrated in Fig. 5. In this study, the average dynamic increase factor ($\beta=E_d/E_s$) is adopted to obtain the above required data pairs, as shown in Fig. 5. Using Eqs. (14)–(16) and the corresponding data pairs in Fig. 6, l_0 is equal to 2.92 m for 5000 DWT ship. To assess reliability of the estimate of l_0, the correlative analysis was conducted using

$$\begin{cases} R^2=1-\dfrac{\text{SSE}}{\text{SST}}, \\ \text{SST}=\sum_{i=1}^{N}(\beta_i-\bar{\beta})^2, \\ \text{SSE}=\sum_{i=1}^{N}(\beta_i-\hat{\beta}_i)^2, \end{cases} \tag{17}$$

where R^2 is the coefficient indicating fitness of the prediction, β_i is the original data from E_d/E_s averaged on the crush depth, $\hat{\beta}_i$ is the estimated value from the regression, and $\bar{\beta}$ is the mean of β_i. R^2=0.941 shows that the results from the predicted curve are in good agreement with the original data (Fig. 6).

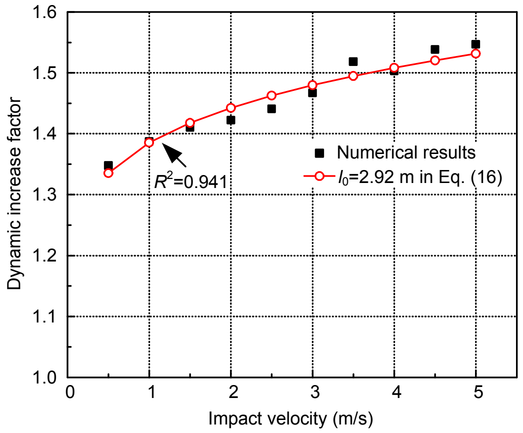


Fig. 6 Determination of parameter l_0 for the 5000 DWT ship-bow

3.3 Implementation of the developed analytical model

Since the damper force (P_v) in the damper element depends on the elastic-plastic spring force (P_s) for each time step using Eq. (10), the required nonlinear macro-element was not found in some general-purpose finite element codes (ABAQUS, 2005; LS-DYNA, 2007). Thus, the finite element codes for the proposed macro-model should be developed based on the couple dynamic equations from Eqs. (1) to (4). The flowchart for the detailed algorithm of the nonlinear macro-element model is illustrated in Fig. 7. The program mainly consists of two modules, namely structure and ship modules. For the structural linear analysis, the Newmark-β constant average acceleration method is used for the solution of Eq. (4) in the structure module. For the ship module, the central difference method is adopted to solve Eq. (1). In addition, it may be necessary to employ an iteration to solve the structural response, since the ship impact load and the structural displacement are coupled according to Eqs. (3) and (4). Two state variables (flag and flag2) are chosen to judge the states of ship motion, because the developed spring is only compression. Fig. 7 summarizes the above described procedure as it is implemented using MATLAB software in this study.

4 Validation and discussion

4.1 Finite element model and parameters

To assess the accuracy of the proposed nonlinear macro-element for structural demand under ship impact loads, both the high resolution model and the proposed macro-element model were built as shown in Figs. 8 and 9. In the high resolution model using general purpose nonlinear finite element techniques (Fig. 8), a typical bridge substructure in China was modeled by solid finite element with constant stress in LS-DYNA, which was in collision with the above inland 5000 DWT ship with initial velocities of 2 and 5 m/s, respectively. The elastic material model (concrete density $\rho=2.5\times10^3$ kg/m^3, Young's modulus $E=3.0\times10^{10}$ Pa, and Poisson's ratio $\upsilon=0.2$) was used for the bridge substructure. The detailed design information about this bridge is referenced in (Yuan *et al.*, 2009). In the analytical model based on the proposed macro-element (Fig. 9), the pier and piles were modeled by beam element, and the pile-cap was defined as a rigid body.

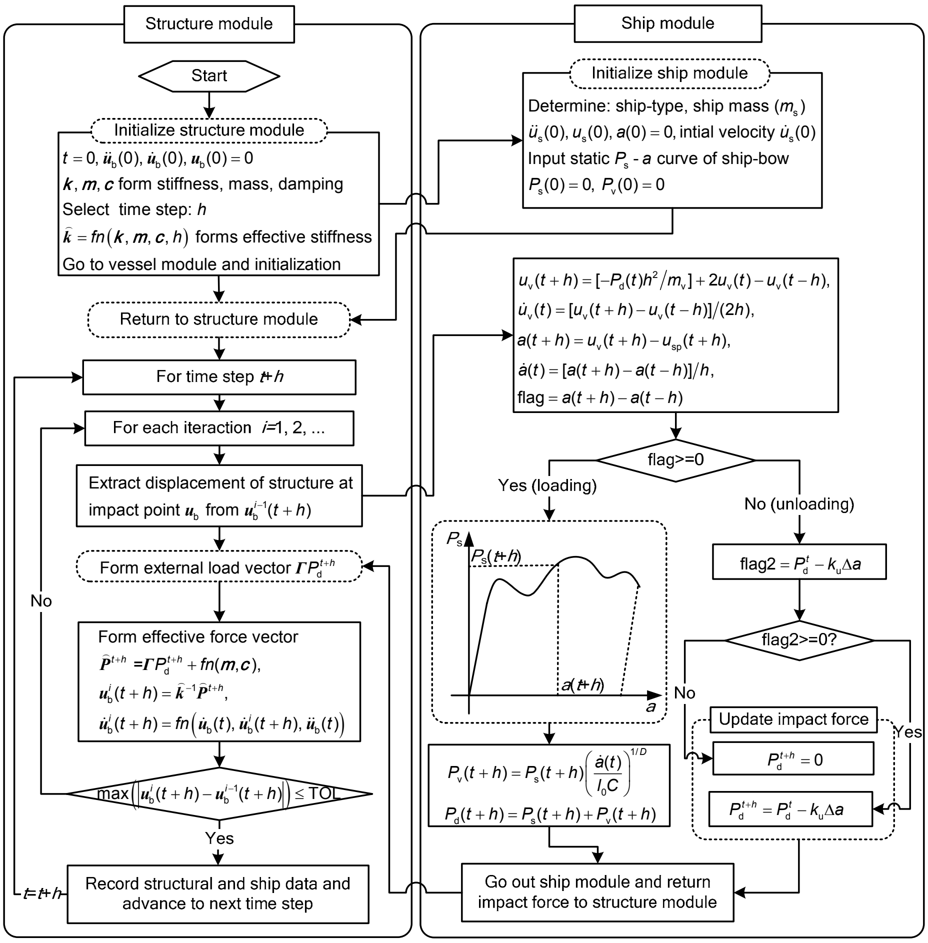


Fig. 7 Flowchart for the implementation of the analytical model using the nonlinear dynamic macro-element (modified from Consolazio and Cowan, 2005)

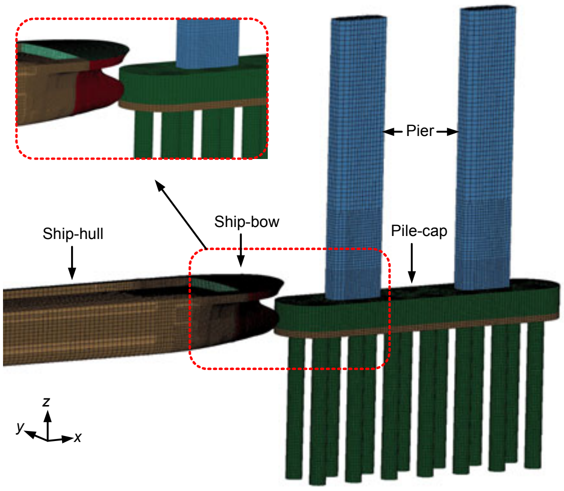


Fig. 8 High resolution model of ship-bridge collision

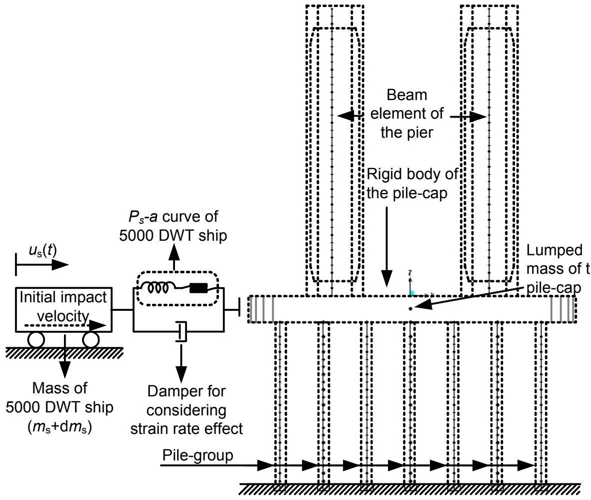


Fig. 9 Proposed macro-element model of ship-bridge collision

4.2 Results and discussion

Based on the above two models and the corresponding parameters, the dynamic responses of the structure under 5000 DWT ship collisions were obtained using LS-DYNA (2007) and MATLAB, as shown in Figs. 10–13. It is observed that the total energy in the high resolution model is almost constant in Fig. 10, which provides a reliable basis for the high resolution model to validate the accuracy of the developed analytical model.

Our results show that both the contact force (Fig. 11) and the displacement of the pile-cap (Fig. 12) using the developed macro-element model almost agree with those of the high resolution model for the initial velocities of 2 and 5 m/s. Fig. 12 also shows that the displacements of the pile-cap from the proposed model are generally but not always, slightly less than the results of the high resolution model. A major reason is that the pile-cap in the proposed model (Fig. 9) is taken as a rigid body connected to the pile-group and piers, so that the lateral stiffness is different from that of the high resolution model (Fig. 10). Fig. 13 also indicates that the mechanical behavior of the pile-cap in the high resolution model is different from the rigid body to some extents, particularly when the depth of pile-cap is small.

The quasi-static and static analyses were conducted by the solid finite element model and the beam element model, respectively, to obtain the lateral stiffness of the bridge substructure. The lateral stiffness of the beam element model is clearly larger than the value from high resolution model as shown in

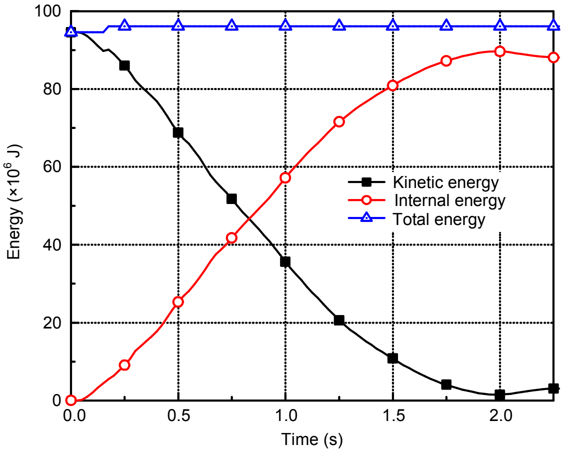


Fig. 10 Energy in the high resolution model ($\dot{u}_s(0)$ =5.0 m/s)

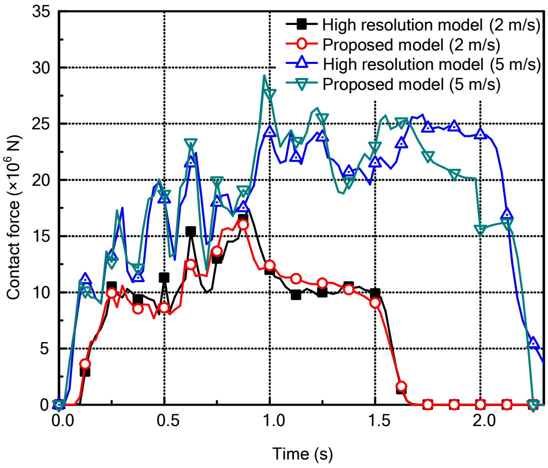


Fig. 11 Comparison of contact impact forces

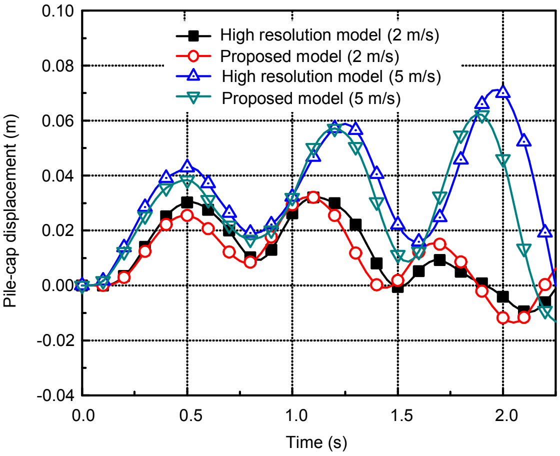


Fig. 12 Comparison of the pile-cap displacement

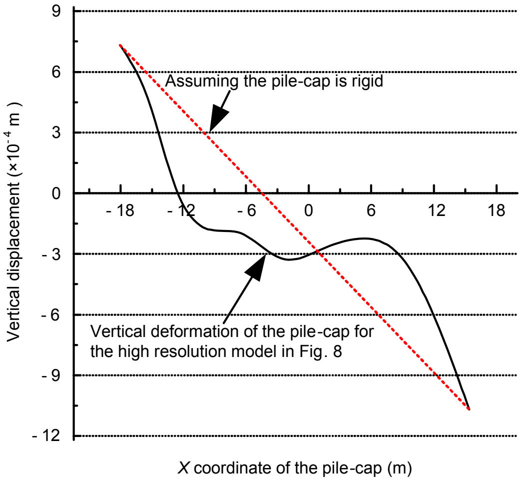


Fig. 13 Vertical deformations of the pile-cap in Fig. 8 ($\dot{u}_s(0)$ =5.0 m/s and t=2.0 s)

Fig. 14. These results further indicate that the use of rigid body may result in the larger lateral stiffness of the pile-cap. Additionally, the equivalent shear forces of the side pile at the top (Fig. 15) generated by lateral stiffness from the two models are in good agreement. Therefore, the proposed macro-element model would be applicable, particularly for the dynamic demand determination of bridge structures subjected to ship collisions. Meanwhile, comparisons of other performances are shown in Table 2. Obviously, there are several advantages of the proposed model compared with the high resolution model, such as high efficiency, without hourglass control and contact definition. In other words, the developed macro-element model is a computationally efficient alternative to general contact-impact nonlinear finite element analysis, and is feasible to be utilized in practical applications.

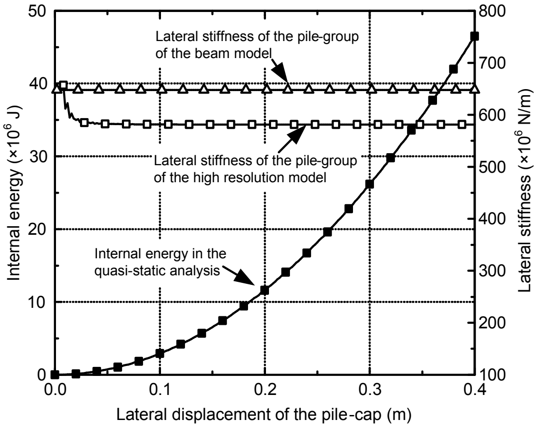


Fig. 14 Lateral stiffness of the structure in the high resolution model and beam model

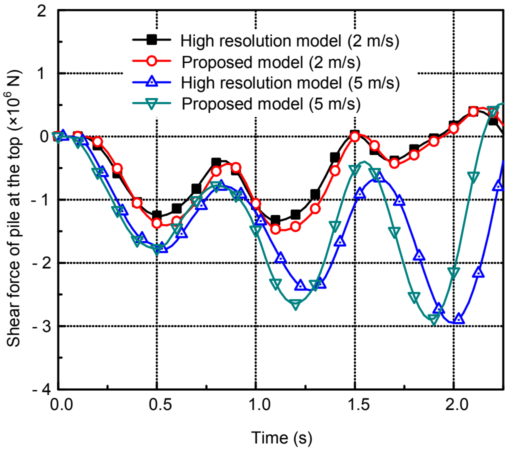


Fig. 15 Shear force of the side-pile at the top

Table 2 Performance comparisons between the proposed macro-element model and high-resolution model

Item	High resolution model	Proposed model
Computing efficiency	~7 h/case	~2 min/case
Numerical algorithm	Only explicit	Both implicit and explicit
Contact definition	Need	Not need
Hourglass control	Need	Not need
Nonlinear macro-element	Not need	Need

Comparisons between the results from the above dynamic analyses and several current design codes (including AASHTO (2009), JTG D60-2004, and TB10002.1-2005) were carried out as shown in Figs.16 and 17. As can be seen from Fig. 16, ship impact forces calculated by various design codes are significantly different from each other, which will result in various demands (e.g., shear forces of pile in Fig. 17) of the bridge structure. For TB10002.1-2005 in China, the results are always less than the results from the dynamic analyses; although the impact force using JTG D60-2004 approximates the maximum values of the proposed model at the initial impact velocity of 5 m/s, the ship impact velocity is not considered in this design code. Furthermore, since the AASHTO's equation was developed for bulk carriers larger than 40000 DWT from the Woisin's data (AASHTO, 2009), using the AASHTO's equation to estimate ship impact forces of the inland 5000 DWT ship in China may be not warranted, as depicted in Fig. 16. Conversely, although the ship impact forces from current design codes may be the same as the maximum value of the dynamic analyses (e.g., JTG D60-2004 as $\dot{u}(0)=5$ m/s and AASHTO as $\dot{u}(0)=2$ m/s), the shear forces of the pile are underestimated as shown in Fig. 17. This is because all of the above design codes employ a simple and static analysis procedure, without including the dynamic amplification of structural responses under ship impact loading, such as the influence of inertial forces associated with bridge structures. But, a major aspect of the proposed method herein is the ability to quantify important dynamic effects inherently present in a ship collision event, compared to these design codes.

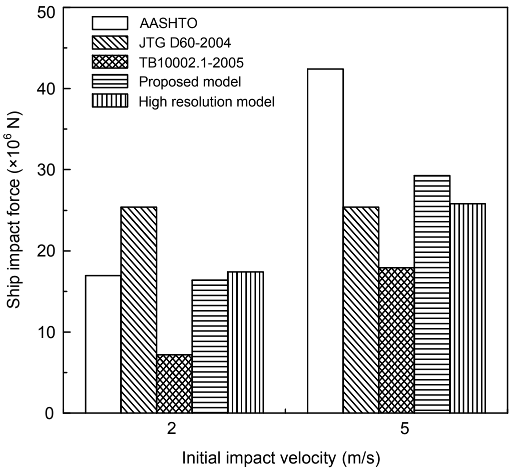


Fig. 16 Comparison of the peak impact forces from current design codes and dynamic analyses

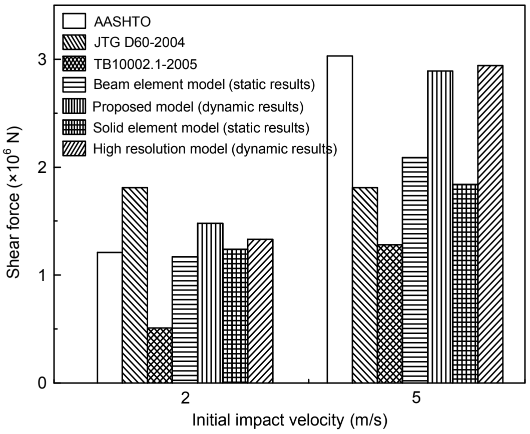


Fig. 17 Comparison of the peak shear forces from current design codes and dynamic analyses

5 Conclusions

For ship collision design of bridges, the nonlinear dynamic macro-element is developed and implemented to permit the rapid analysis of the demand of bridge structures with reasonable accuracy. The following conclusions were drawn:

1. The nonlinear dynamic macro-element consists of an elastic-plastic spring element and a dashpot element. The elastic-plastic spring element can be defined by the static or quasi-static crush curve (P_s-a curve); the dashpot component can be used to consider the strain rate effect of ship-bow steels and the corresponding parameters were discussed in detail.

2. The implementation procedure for the analytical model based on the proposed macro-element was presented. Based on the procedure and model, the results show that the responses of the macro-model is in agreement with that of the high resolution model using solid finite elements. However, other performances of the proposed method far outweigh the general contact-impact nonlinear finite element techniques, particularly for calculation efficiency. Thus, it would be more feasible to be utilized in practical applications, particularly for the dynamic demand assessment of bridge structures subjected to ship collisions.

3. Large variations of the ship impact forces and structural demands between various design codes and the dynamic analyses demonstrate that AASHTO, JTG D60-2004, and TB10002.1-2005 should be improved in future. Meanwhile, although ship impact forces from these design codes may be approximately the same as the maximum value of the dynamic analyses, ignoring dynamic amplification effect can potentially lead to underestimate the design forces.

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