Research on Vulnerability Analysis of Vessel-Bridge Collision

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Abstract: In this paper, the definition and process of vulnerability analysis of vessel-bridge collision are put forward to provide the basis on the design and reinforcement of vessel-bridge collision. The factors that affect the vulnerability of vessel-bridge collision can be described as random variable. The vulnerability of vessel-bridge collision can be expressed as structural reliability problems.The structural reliability theory is introduced to calculate the failure probability of bridge structure under different tonnage of vessel-collision. vulnerability curve can be obtain by curve fitting.

1. Introduction

Vulnerability of engineering structure refers to the degree of damage of the engineering structure which reflects the structural fragility under the specific load[1]. Vulnerability of engineering structure reflects the bearing capacity on the influence of natural disasters or other external factors. It also describes the relationship between the damage of the engineering structure and loading condition.

Vulnerability of vessel-bridge collision refers to the damage probability of bridge structure under collision of different tonnage of vessel which reflects resistant performance under vessel collision. It describes the relationship between degree of damage of the bridge structure and tonnage of vessel from macro perspectives.

The research on vulnerability analysis of vessel-bridge collision can provide the basis on the design and reinforcement of vessel-bridge collision. It also can contribute to the assessment of economic loss and disaster emergency response plan.

2. Analysis method on vulnerability analysis of vessel-bridge

2.1 Research status

In terms of vulnerability analysis of vessel-bridge collision, the Guide Specification and Commentary for Vessel Collision Design of Highway Bridges (AASHTO specification) gives a figure which describes the relationship between equivalent collapse probability and ratio of capacity and load which can be considered as a kind of vulnerability curve of vessel-bridge collision, as shown in figure 1[2].

In addition, Proske and Curbach calculated the failure probability of the bridge under vessel-bridge collision by the methods of FORM and SORM [3]. In 2006, Prof. Manuel L in university of Texas at Austin did research on failure probability of bridge under vessel-bridge collision with the support of transportation department of Texas[4]. In 2010, Prof. Consolazio in the university of Florida calculated the failure probability of the bridge under vessel-bridge collision with Monte Carlo Method[5] .
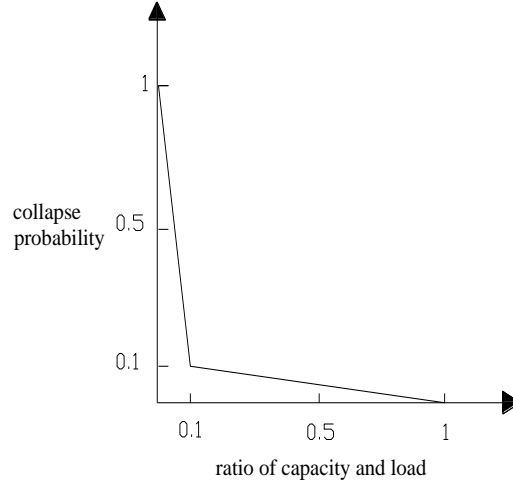
Figure 1. equivalent collapse probability （AASHTO 2009）

2.2 Definition on vulnerability of vessel-bridge collision

The vulnerability of vessel-bridge collision can be described as vulnerability curve which can be shown as figure 2. The abscissa denotes the tonnage of vessel and the ordinate denotes the failure probability of bridge under vessel collision. The vulnerability analysis of vessel-bridge collision involves three parameters: the bridge structure response on behalf of the structural performance , the threshold value of limit state for failure as well as the tonnage of vessel.
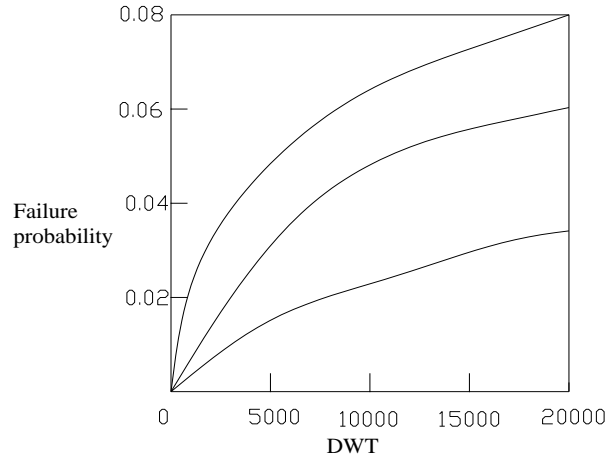

Figure 2. vulnerability curve of vessel-bridge collision

The uncertainty factors that affect the vulnerability of vessel-bridge collision can be described as random variable X. The structural damage state i can be expressed as limit state function $G_i(\mathbf{X})$. The vulnerability of vessel-bridge collision can be expressed as structural reliability problems:

$$F(a_j) = P[G_i(\mathbf{X}) | DWT = a_j] = \int_{G_i(\mathbf{X})|DWT=a_j \leq 0} f(\mathbf{X})d\mathbf{X} \qquad （1）$$

$P[G_i(\mathbf{X}) | DWT = a_j]$ denotes failure probability of limit state function $G_i(\mathbf{X})$ when tonnage of vessel equals to a_j. $f(\mathbf{X})$ denotes probability density function of random variable X.

The vulnerability of vessel-bridge collision can be expressed as:

$$F(a_j) = \Phi^{-1}(-\beta_i | DWT = a_j) \qquad （2）$$

Φ^{-1} denotes the inverse function of standard normal distribution function. β_i denotes reliability index of limit state function $G_i(\mathbf{X})$.

2.3 The process for vulnerability of vessel-bridge collision

The process for vulnerability of vessel-bridge collision can be shown as figure 3.

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                    ┌─────────────────────────┐
                    │     Tonnage of vessel    │
                    └─────────────────────────┘
                       │                   │
                       ▼                   ▼
        ┌──────────────────────┐  ┌──────────────────────┐
        │  Probabilistic model │  │  Probabilistic model │
        │    of impact angle   │  │   of impact velocity │
        └──────────────────────┘  └──────────────────────┘
                       │                   │
                       └─────────┬─────────┘
                                 ▼
        ┌───────────────────────────────────────────────┐
        │   Dynamic loading model of vessel-bridge       │
        │                  collision                     │
        └───────────────────────────────────────────────┘
                                 ▼
        ┌───────────────────────────────────────────────┐
        │      Finite element model of bridge structure  │
        └───────────────────────────────────────────────┘
                                 ▼
        ┌───────────────────────────────────────────────┐
        │  Dynamic response analysis of bridge under     │
        │              vessel collision                  │
        └───────────────────────────────────────────────┘
                                 ▼
        ┌───────────────────────────────────────────────┐
        │  Divide performance level according to         │
        │           performance index                    │
        └───────────────────────────────────────────────┘
                                 ▼
        ┌───────────────────────────────────────────────┐
        │  Structural failure probability calculation    │
        │         based on reliability theory            │
        └───────────────────────────────────────────────┘
                                 ▼
        ┌───────────────────────────────────────────────┐
        │  Failure probability calculation of each       │
        │    performance level under vessel collision    │
        └───────────────────────────────────────────────┘
                                 ▼
        ┌───────────────────────────────────────────────┐
        │  Curve fitting according to value of failure   │
        │               probability                      │
        └───────────────────────────────────────────────┘
                                 ▼
        ┌───────────────────────────────────────────────┐
        │  Vulnerability curve of vessel-bridge collision│
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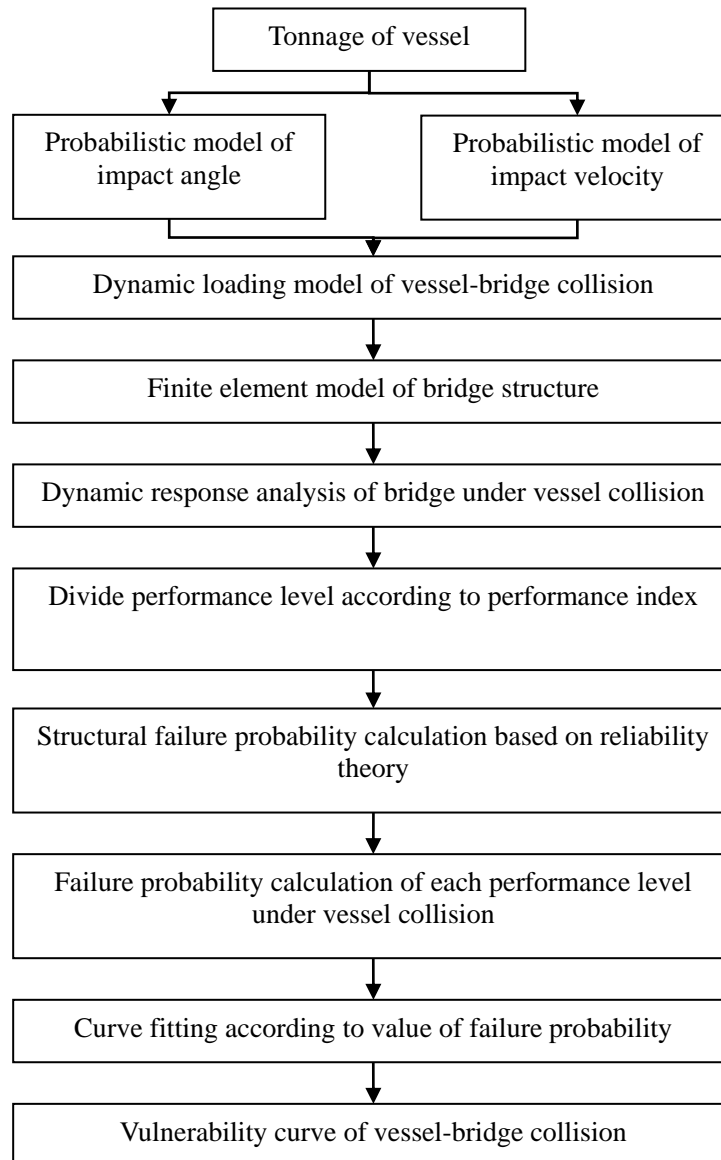
Figure 3 The process for vulnerability of vessel-bridge collision

The steps of vulnerability analysis of vessel-bridge collision are as follows:

(1) According to the tonnage of vessel, considering the impact Angle and the impact velocity of randomness, the random time history curve of collision force is generated considering randomness of impact angle and the impact velocity.

(2) The nonlinear finite element model of bridge is established.

(3) The nonlinear time history analysis is carried on to calculate the response of bridge structure under vessel collision. Forced vibration method and finite element method can be used to carry on nonlinear time history analysis.

(4) Calculate the performance index under different performance levels of bridge structure.

(5) According to structural reliability theory, the failure probability of bridge structure under different tonnage of vessel-collision can be calculated by the method of FORM ,SORM as well as Monte Carlo Method.

(6) According to the failure probability of bridge structure under different tonnage of vessel-collision, vulnerability curve can be obtain by curve fitting.

In order to achieve vulnerability analysis of vessel-bridge collision, the core problems are the calculation method for response of bridge structure under vessel collision and failure probability analysis.

3. Conclusions

In this paper, the definition and process of vulnerability analysis of vessel-bridge collision are given. The vulnerability analysis of vessel-bridge is transformed into the problem of failure probability of bridge structure under vessel-collision that can be solved based on structural reliability theory.

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