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Review Article

A Comprehensive Review of Simulation Software and Experimental Modeling on Exploring Marine Collision Analysis

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Keywords

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Abstract

Understanding the intricacies of marine collisions holds the key to implementing cutting-edge collision avoidance strategies for offshore structures. Central to this exploration are downscaled models and powerful computational tools like LS-DYNA and USFOS, instrumental in probing collision dynamics. This paper strides forward, aiming to propel this domain into new frontiers. It conducts an exhaustive review of collision research within simulation software and modeling experiments, delves into a comprehensive discourse on the challenges and constraints within the discipline, and navigates prospective trajectories for its evolution.

1. Introduction

Over the past few years, marine equipment and cross-sea bridges have contributed to the improvement of transportation, economic development, and energy in coastal areas. Due to the increasing number of navigable ships and various complex environmental factors, there has been an increase in the risk of ship-bridge collisions and ship-marine equipment collisions [1-2]. As shown in Figure 1, such issues are receiving increasing attention.

The major studies about collisions have involved crash tests with simplified structural models. According to relevant studies, the application of the downscaling method and mathematical modeling can enhance efficiency, reduce costs, and enhance safety. Unfortunately, the complexity of a ship's hull makes it difficult to study collisions between ships and bridges. It is a challenging task [3].

There has been rapid development in information and computer technology over the past few years. As a result of technological innovations such as cloud computing, high-performance processors, and big data analysis, computing power is being developed at a rapid rate. An improvement has been made to the task. Due to the advancement of digital technology in ocean engineering, it is now possible to model the hull of a ship. As shown in Figure 2. Using highly advanced modeling and simulation systems, fluid-structure interaction analysis techniques, and the hydrographic code LS-DYNA, full-scale simulations of marine structures were conducted. The collision state was successfully simulated. The results of the model and simulation analysis were analyzed, and several collision prevention suggestions and schemes were submitted [4].

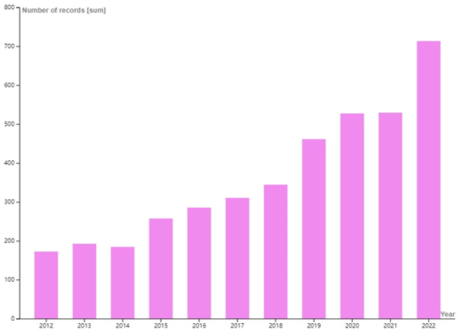

Figure 1. The number of published results about marine*collision in the Web of Science, from 2012 to 2022.

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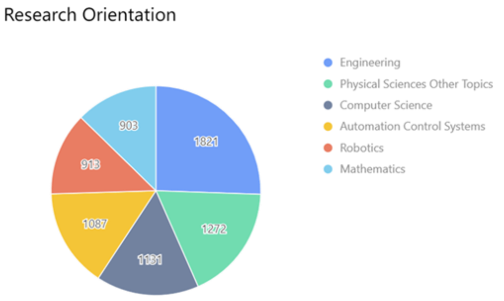

Figure 2. The main research orientation and corresponding number of publications about marine*collision in the Web of Science

The investigation into the dynamics governing collisions holds paramount significance in the formulation and enhancement of robust collision avoidance protocols. This scholarly contribution endeavors to fortify the existing discourse on collision research. The focal intent of this paper lies in furnishing a comprehensive elucidation, encapsulating an exhaustive scrutiny of simulation methodologies germane to the emulation of maritime collision scenarios, juxtaposed with an appraisal of model experimentation techniques. By means of a meticulous comparative analysis, this study discerns the prevailing constraints within the domain, thereby illuminating avenues for prospective development and advancing the frontier of collision research.

2. The Study of Collisions

2.1. Computer Simulation

The use of computer-based simulation techniques to obtain relevant data is one of the most important tools in the study of collisions. In this chapter, several mainstream simulation software products are reviewed, and some simulation cases are discussed. Analyses are discussed in terms of cost, data accuracy, and operability.

2.1.1. USFOS

A dynamic analysis software called USFOS is based on the theory of elastic wave transmission and is used for analyzing the response of large structures during earthquakes. USFOS is capable of considering multiple complex boundary conditions, non-linear material models, and multi-mode excitations. The pricing of USFOS is high, and there is a relatively small amount of documentation and manuals related to USFOS, which requires some learning on the part of the user [5-6].

In the Norwegian Public Roads Authority's Bjørnafjorden fjord crossing project, a pontoon bridge is one of the proposed solutions. One of the key issues in bridge design is ensuring that the bridge is safe from accidental collisions with ships. SHA et al. developed a numerical model of the bridge collision system using the dynamic analysis software USFOS. The impact position may have a significant impact on the structural response.

Figure 3 shows the maximum bridge responses for different impact locations. The maximum bridge displacement, force, and bending moment are independent of the collision position for collisions away from the bridgehead. It is expected that due to the fixed boundary conditions, a collision near the bridge end will result in severe local structural deformation and failure [7]. In addition, the project proposes introducing the concept of cable-stayed bridges. Among its challenges are harsh natural conditions and ship shocks. In order to study the effects of wind and waves as well as ship collisions, AALBERG et al. constructed a bridge model. Based on the results presented in this thesis, the bridge girder lacks the capacity to withstand weak axis moments. Also, some suggestions have been made to improve the design of the bridge [8].

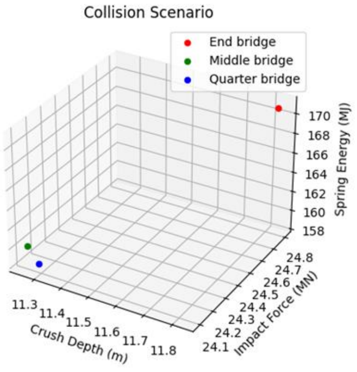

Figure 3. Maximum bridge responses for different impact locations, from [7].

2.1.2. ANSYS/LS-DYNA

ANSYS/LS-DYNA is an advanced nonlinear dynamics analysis software that uses explicit finite element methods to solve complex nonlinear problems, such as elasticity, plasticity, damage, and so forth. Because of this, the simulation results of this software are relatively accurate and can be used for most engineering simulations. The corresponding threshold of use is relatively high, and proficiency re-quires training and practice [9].

Lin and Hong et al. tested the dynamic and compressive properties of the honeycomb reinforced structure under the collisions by using ANSYS/LS-DYNA. Based on influencing factors such as impact velocity and impact direction, the dynamic performance of the honeycomb reinforced pipe leg was examined. As a result of the study, both hexagonal honeycomb structures and arrow honeycomb structures can reduce damages caused by ship collisions to inclined pipe legs. The hexagonal honeycomb structure provides better collision resistance, reduces offset sliding, and better protects pipe legs from ship collisions [10].

To investigate the fluid-structure coupling (FSI) behavior during ship-bridge collisions at different impact angles, YE et al. developed a physics-based high-fidelity finite element (FE) model. A potential flow solver, WADAM, was used to examine and verify the FSI modeling method based on LS-DYNA code [11].

An analysis of the Bjørnafjorden pontoon concept is presented by SHA et al. There are two possible collision scenarios, namely ship-pontoon collision and ship-beam collision. To numerically investigate local deformations and damage to the structure, a detailed finite element model is developed using LS-DYNA [12].

The interaction between wind turbines and ships is complex. A commercial finite element tool, ANSYS LS-DYNA, was used to simulate the impact of a ship on the substructure of a tripod-type offshore wind turbine. Additionally, an equivalent beam model was used to generate the FE model of the blade. The method was validated by static and dynamic analysis results between the full 3D blade model and the equivalent beam model [13].

GHOLIPOUR et al. Numerical evaluation of girder bridge superstructures on pier impact responses and shear forces transmitted in LS-DYNA for moder-ate-energy barge collisions [14].

Based on numerical simulations in LS-DYNA, GHOLIPOUR et al. evaluated the effect of axial loads on the dynamic response and failure behavior of reinforced concrete columns subjected to transverse impact loads [15].

The response of offshore tubular members under the bow and stern impacts was studied by Yu et al. using the nonlinear finite element code LS-DYNA [16].

2.1.3. ABAQUS

ABAQUS is a finite element analysis software developed by Simulia Inc. in the United States. It is possible to solve a wide range of analysis problems using ABAQUS, including linear and nonlinear analysis, thermal analysis, dynamic response analysis, and optimization. In spite of this, ABAQUS is a relatively expensive commercial software and takes a long time to solve problems because of its complexity [17].

According to Obisesan et al., Abaqus software was used to simulate the response of a double-hulled tanker when it collided with a spherical iceberg. It is used to validate a crushable foam plasticity model of the iceberg material. In order to improve the reliability of ship structures, simulation results are used to deter-mine the most probable design points in the input random variables [18].

Using a steel grill, Zhang et al. investigated the structural response of a ship hull under sliding ice loads. The numerical solver used was Abaqus Explicit. It was taken into account the deformation and damage caused by ice and steel. For com-parison purposes, a rigid ice model was also simulated. An analysis is conducted of the local structural response of the hull under different load cases, including deformation, contact forces, and energy distribution [19].

Karlsson et al. used the commercial finite element software Abaqus/Explicit for their analysis. Using parametric sensitivity and experimental analysis, create a reliable and robust finite element model for ship collision simulations [20].

The response of ship structures under unexpected loading conditions that suffer from various failure modes, including tension, bending, tearing, and crushing, has been simulated using the explicit finite element code ABAQUS 6.10-2 by Marinatos et al [21].

Rigueiro et al. conducted a numerical analysis of the behavior of a steel offshore platform under collision with a ship. Based on the Merluza-1 platform in Brazil, the study considers two different velocities of the ship and two different stiffness conditions. In order to determine the deformations and dissipated energy in the ship and in the structure during the local collision, the finite element software ABAQUS was used. In conclusion, the results of the numerical analysis can be used to improve the design of the offshore platform and ensure its safety in the event of a collision with a vessel [22].

In their study, Cerik et al. present a simulation model for the coupled simulation of the external and internal mechanics of two colliding floating bodies. A rigid-body motion solver is used to calculate hydrostatic recovery forces, wave radiation forces, and six-degree-of-freedom motion components in the time domain. By using a user-defined loading subroutine, the rigid-body solver is combined with the structural analysis code Abaqus/Explicit. A benchmark analysis of the undulating motion of a sphere is used to validate the loading subroutine [23].

2.1.4. OpenFOAM

A computational fluid dynamics software called OpenFOAM allows users to access, use, modify and share the source code with a high degree of flexibility and customizability. There are a wide range of applications for OpenFOAM, ranging from numerical simulations in engineering fields, such as aviation, aero-space, automotive, and marine, to scientific fields, such as biology and the environment. The OpenFOAM software is based on the C^{++} programming language, which requires users to have a strong mathematical and programming background, as well as spend a great deal of time learning how to use the software [24,25].

Masoomi et al. used OpenFOAM to simulate a two-phase solver called InterFoam numerically. In order to simulate multiphase problems, a method called volume of fluid is used. This method was originally proposed by Hirt & Nichols. To identify the syntax of each cell of each fluid, indicator functions are used. A new equation is used to solve the continuity and momentum equations [26].

A bidirectional coupled fluid-structure coupling framework was applied by Khumar et al. in which the interaction between the flood water in the damaged tank and the wave field was modeled by the computational fluid dynamics toolbox OpenFOAM. Structural deformation was predicted using the multi-body solver MBDyn. Hydroelastic calculations are performed for two different damage scenarios [27].

2.1.5. Comparisons & Limitations

By comparing as well as synthesizing this four software, it can be concluded that the current simulation software has a high learning cost as well as high running costs. The paper will present suggestions for improving these issue.

2.2. Collision Experiment

In a crash test, reducing the scale or using a simplified model is a common method of reducing costs and complexity.

Following are some examples of full-size, reducedsize, and simplified models for discussion, comparison, and analysis.

Table 1. Comparison of the characteristics of different simulations.

Software	Simulation Cost	Data Accuracy	Difficulty of Operation
USFOS	High-Cost	High simulation accuracy for marine and underwater structures	Moderate
ANSYS/ LS-DYNA	High-Cost	Higher accuracy	Easy
ABAQUS	High-Cost	Higher accuracy	Difficult
OpenFOAM	Free and open	Higher accuracy	High demand for programming and numerical analysis skills

2.2.1. The Cases

According to Chen et al., it was the impact force model that was studied. This model plays a critical role in the design of bridge piers for impact resistance as well as the rapid assessment of bridge dynamic behavior under barge impact. By using scaled replicas, the fine barge and wharf finite element model (FEM) as well as the finite element analysis (FEA) method are verified [28].

Many studies have examined the use of ship collision piers in place of whole bridges. The simplification of such a mechanism will inevitably result in errors when reflecting the mechanical mechanism and dynamic characteristics of ship-bridge collisions. XIE et al. developed a delicate barge-whole bridge model to study the mechanical behavior of barge collisions with the whole bridge in order to resolve this issue [29].

A prototype double-column reinforced concrete bridge under barge impact was studied by Chen et al. First, multiple impact tests were conducted on three double-column reinforced concrete pier (DCBP) specimens with a 1/5 ratio of large hopper (JH) barge bows at different impact speeds using a horizontal impact device. They assessed the impact force of the barge's bow time history, breaking process, and dynamic performance of the impact and adjacent piers [30].

Through a series of collision tests and investigations, Sun et al. concluded that consideration of quasi-static and dynamic loads is essential for designing flexible floating collision avoidance systems (FFAS) to avoid possible failures [31].

A finite element model for the fender was developed by Wei et al. and validated by impact tests. To investigate the applicability of the proposed fenders in practice, an application study was conducted using the validated FE model [32].

Wan et al. conducted quasi-static compression tests and numerical simulations on a simplified bow model in order to investigate the static stiffness characteristics of the bow for further comparison with the dynamic stiffness. The main pier No. 217 of Shiyuhu Bridge was used as a scale model to evaluate the collision avoidance performance of reinforced concrete (RC) piers and guide the de-sign and collision avoidance of piers [33].

According to Xu et al., ship model collision experiments were conducted in a water tank with particular attention paid to the structure of the collision region. A dynamic response of the ship during a collision is studied by considering the coupling effect of external dynamics and internal mechanics [34].

Guo et al. conducted scale model tests and collision mechanism analysis using the non-navigable span of the East China Sea Crossing Bridge as the engineering background for their study. In order to evaluate the dynamic response of the sample bridge under impact forces and the local damage to vulnerable members, the test results were compared with finite element simulations [35].

In order to validate a proposed analytical method for estimating the ex-tent of structural damage in ship collisions Zhang et al. conducted 18 experiments. In the experiments, the energy absorption-penetration curves and the collision force-penetration curves of structural members were measured. These experiments were compared with analytical calculations and it was found that the analytical method consistently matched all the experiments analyzed in the study [36].

An analytical approach was proposed by Liu et al. to study the energy absorption mechanism of a double-hulled ship structure subjected to a flat-sided indenter. This approach is validated by numerically simulating a structural module of the stiffening plate obtained from previous experiments. This structural module represents a one-fifth scale double-hulled tanker side structure consisting of three frame spacings along the longitudinal direction and two strut spacings along the vertical direction [37].

Scaled specimens created by Liu et al. represent tubular joints on a jack-up or jacketed offshore platform. As a result of a falling wedge indenter, they are laterally impacted. It is possible to measure the impact force, the permanent deformation, and the displacement of the falling wedge. There are three distinct phases in the force-displacement response, namely the initial vibration phase, the stable deformation phase, and the rebound phase. As a result of the tests, it was found that the brace increased the energy absorption of the chord components and that T-joints were subjected to higher impact loads when subjected to impacts with higher impact velocities [38].

Bonabd et al. conducted a parametric centrifugal study to improve their understanding of soil-pile interaction under horizontal impact loading. With the assistance of a new ball gun, flexible piles equipped with different mass pile caps were subjected to different levels of impact forces[39].

He et al. studied the behavior of mild steel and aluminum beams under repeated mass impacts. A number of factors were measured and analyzed, including impact forces, velocities, displacements, and absorbed energy. In three of the four sets of repeated impact tests, pseudo-vibration was observed [40, 43-47].

In a study by Meng et al., 6082-T6 aluminum tubes with circular hollow sections were tested to determine their dynamic response under transverse impact loads [41, 48].

Lin et al. conducted wind tunnel tests that integrated accurate scale models and well-simulated loads to investigate the long-term performance of wind turbines (MWTs) [42].

2.2.2. Special Features

Based on a brief analysis of the above cases, it can be concluded that simplified or scaled-down crashes have the following characteristics:

2.2.2.1 Advantages

- If compared with the actual size of the test, reducing the scale or using a simplified model of the test can save a lot of time, money, and resources.
- It is possible to complete simplified or scaled-down model tests in a shorter period of time by using relatively small equipment and test environments, thereby making the testing process more efficient.
- In comparison with the size of the actual test, reducing the scale or using a simplified model can make the test process safer for the environment and personnel.
- Scaled-down or simplified model tests enable more accurate control of test conditions and parameters, thus improving the reliability and ac-curacy of experimental data.

2.2.2.2 Disadvantages

- The experimental data of the downscaled or simplified models have large errors and deviations from the real situation, and therefore re-quire several validations and corrections.
- The reduction or simplification of the model will be affected by scale effects, such as the Laplace effect, the inertia effect, the surface tension effect, etc.
- Consequently, the experimental results and the real situation will differ greatly.
- It is necessary to note that the test conditions of the reduced scale or simplified model are limited by the chosen scale or model, which can-not account for all the factors present in the real situation and may ignore some important ones.
- It requires a certain level of technology to test scaled-down or simplified models, including preparation, processing, and testing, as well as the testers to have relevant professional knowledge and skills.
- Certain situations cannot be scaled down or simplified, such as collision tests on large buildings, bridges, ships, and other complex structures.

2.2.2.3 Applicable Scenarios

- The study of the mechanical properties of complex objects or systems, such as nanomaterials and microfluidic systems.
- Assess the accuracy and reliability of numerical simulation results and optimize the design of models and algorithms.
- Analyze the performance and safety of new materials and products in collision situations.
- Investigate and optimize accident emergency measures and prevention strategies in order to minimize the impact of collision accidents on personnel and equipment.

The above features will be discussed in greater detail in Chapter 3. The corresponding suggestions will also be presented in Chapter 3.

3. Conclusions

3.1. Difficulties and Limitations

3.1.1. Shortcomings of the Simulation Software

(1) Creating simulation models: Currently, simulation models reflect real structures only to a limited extent, making it difficult to achieve high accuracy and comprehensive detail modeling. In current software, it is difficult to fully consider the interaction of floating objects with water during model building, and some important physical properties such as friction may be neglected.

(2) An evaluation of performance is necessary after a collision event, in order to determine the extent of the damage and predict subsequent consequences such as environmental pollution, casualties, etc. As a result, current simulation software is unable to accurately determine the structural damage to hulls, fiber optic cables, pipelines, etc. In addition, it is difficult to accurately assess the enormous waves generated by complex factors such as periodic storms and surge waves following a collision. Thus, the assessment results are often only a rough guide, while the actual assessment results may differ.

(3) Simulating conditions: Different parameters must be entered into the simulation software, such as speed, load, sea state, etc. If the real values of these parameters are difficult to obtain, or if the information obtained is not complete enough, the validity of the simulation results cannot be assured. The simulation results may differ significantly from the actual situation if the dark currents and eddies in the ocean are not taken into account during the simulation process.

(4) Accuracy and authenticity: For complex physical phenomenon, such as the influence of waves, wind, and waves, etc., simulation software is unable to fully replicate the reality. Moreover, the simulation results may not be able to accurately reflect the real situation, and there is a certain chance of error in the prediction results. Also, due to different ship types, different structures, and other factors, the damage caused by the collision will differ, and these differences will further limit the software's accuracy and realism.

(5) Calculation speed and efficiency: In order to obtain accurate simulation results, many calculations and simulations must be performed. There is also a great deal of time and computational resources required for this process, which is also a challenge for current simulation and simulation software. It takes a great deal of time and resources to simulate a complex hull, which in-creases the cost and difficulty of the simulation.

3.1.2. Limitations and Difficulties of Simulation Experiments

(1) The lack of realism: Due to factors such as equipment specifications and re-sources, simulation experiments are often unable to accurately simulate various

complex situations that occur in real environments, including the effects of waves, air currents, tides, and other factors on collision behavior. Due to this, it is often difficult to predict the actual situation based on the experimental results.

(2) Scale effect: Because of the size of the ship, scaled-down experiments are not able to fully reflect the actual situation. Despite scaling, it is difficult to retain physical phenomena and behaviors at a given scale.

(3) Model simplification: If experiments are to be conducted efficiently, it is of-ten necessary to simplify the object to be studied. These simplifications, however, may ignore some key properties, affecting the accuracy of the experimental results. In a ship-bridge collision experiment, it may be necessary to simplify the hull structure, the bridge structure, etc., but these simplifications may affect the collision mechanics.

3.2. Suggestions & Future Prospects

(1) It is necessary to study various physical phenomena involved in collisions at sea in order to better simulate collisions at sea. For example, we need to study the interaction between water waves and the hull of the ship, as well as the effect of airflow on the motion of the ship. A more detailed model of the ship hull and equipment structure is also required in order to more accurately reflect the real situation.

(2) Enhance modeling techniques: Building high-quality numerical models is essential for ensuring the accuracy of simulation results. In order to achieve a more accurate and faster model, we can use a variety of modeling techniques, such as multi-body dynamics and finite element methods. There may be limitations to traditional modeling methods, and new techniques must be adopted and continuously optimized.

(3) Improving evaluation capabilities: The methods and tools for evaluating simulation results also need to be continuously improved. We can use advanced computer technologies, such as deep learning and model predictive control, to predict possible scenarios and damage scenarios. In addition, the simulation results can be visualized with the help of virtual reality technology to further improve the assessment.

(4) The accuracy of simulation results depends on the collection of comprehensive and realistic data. In the marine environment, various sensors and monitoring equipment can be used to collect a large amount of data that can be incorporated into a simulation model. By doing this, we will be able to obtain a more realistic picture of possible scenarios and environmental changes, therefore improving the accuracy of the simulation.

(5) Optimize computational speed: Complex simulation tasks often require a high level of computational speed. It is possible to accelerate computation speed by using technologies such as high-performance computers and GPUs. The computation algorithm should also be optimized to reduce redundant computation, machine overhead, etc., so that the simulation task can be completed in an acceptable amount of time.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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