Research Article

Experimental Investigation on the Anticollision Performance of Corrugated Steel-Reinforced Composites for Bridge Piers

Guicheng Chen , Haidong Huang, and Zhongfu Xiang

School of Civil Engineering, Chongqing Jiaotong University, Chongqing 400074, China

Correspondence should be addressed to Guicheng Chen; chengguicheng968@163.com

Received 13 July 2021; Revised 14 September 2021; Accepted 16 September 2021; Published 30 September 2021

Academic Editor: KANG Shao-Bo

Copyright © 2021 Guicheng Chen et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

To reduce the loss of life and property caused by the collision of a ship against a bridge pier, this study proposes a new type of anticollision facility. The facility uses corrugated steel plates and corrugated steel pipes (CSPs), or ordinary steel plates and corrugated steel pipes (OSPs), as structural elements to form a honeycomb structure, which can greatly improve the impact resistance of bridge piers and reduce any damage to ships. To evaluate the anticollision performance of the proposed anticollision facility, this work uses the CSPs and OSPs as study objects in the impact test research. A pendulum impact test system was utilized to compare and analyze the column with CSP and OSP specimens and the column without any anticollision facilities. Test results show that the CSP and OSP specimens have a relatively high energy dissipation effect. When the impact energy is small, the energy dissipation effect of the OSPs with the same plate thickness is stronger than that of the CSPs. When the impact energy is large, the energy dissipation effect of the CSPs with the same plate thickness is stronger than that of the OSPs. In addition, the extreme value analysis method is used to analyze the relationship curve between the peak value of the D1 lateral displacement and the specimen's plate thickness, weight, and natural frequency; the optimal thickness, weight, and natural frequency values of the CSP and OSP specimens are also deduced. Taking the optimal value of the specimen's natural frequency as a target, the structure of the CSP and OSP specimens is optimized. When the optimized plate thickness is 2.50 mm, the ratios of the optimal value of the specimen plate thickness, weight, and natural frequency to the optimal calculation value are all in the range of [0.80, 1.12]. OSP and CSP specimens are found to have the best energy dissipation effect. The peak value of the D1 lateral displacement of the top of the column equipped with the CSPs is at least 88.37% lower than that of the column without any anticollision facilities. For the top of the column equipped with the OSPs, the peak value of the D1 lateral displacement is at least 80.37% lower than that of the column without any anticollision facilities. Optimization results show that the extreme value analysis method is suitable for the optimal design of anticollision facilities for piers.

1. Introduction

Over the years, the incidence of ship collisions with bridge piers has increased, thereby causing serious property losses and endangering life and safety [1–3]. Advances in science and technology and anticollision measures have been realized, but the occurrence of ship-bridge collisions remains common [4, 5]. The new comprehensive transportation system proposed by infrastructure construction [6] has increased the density of crossovers between railways, highways, and water transportation. The increasing number, scale, and standardization of ships [7] increase the

probability and risk of collision with bridge piers. The problem of ship collision with bridge piers is mainly studied by experiments, theoretical analyses, and numerical calculations [8]. The common methods and theories include Minorsky theory [9], Woisin theory [10], Heins-Derucher theory [11], American AASHTO specification formula [12], calculation formula based on China's code for the design of railway bridges and culverts [13], and calculation formula based on China's general specifications for the design of highway bridges and culverts [14]. The experimental method and numerical calculation method are mutually verified and used together. Chen et al. [15] used the methods of

theoretical deduction, experimentation, and numerical calculation to determine the reduced kinetic energy coefficient based on China's calculation formula for the design of railway bridges and culverts. Huang et al. [16] conducted numerical simulation and experiments to verify the relationship between the force and energy of a flexible anticollision ring in different operating conditions. Do et al. [17] studied the failure model and dynamic response of a bridge pier through numerical simulation and experiment. Zhou et al. [18] used the parameterization method to study the collision response behavior of a vehicle hitting a bridge pier and its structural damage mechanism. Studies have shown that, after a ship hits a bridge pier, the impact resistance of the bridge structure can be improved in two ways: one is to improve the anticollision performance of the bridge, and the other is to set up an anticollision facility. For the former, it may indeed improve the anticollision performance of bridge piers, but the damage sustained by ships during the collision may be severe. In protecting both bridge piers and ships, the establishment of an anticollision facility is thus beneficial.

Anticollision facilities [19, 20] are divided into direct and indirect structures. According to different anticollision concepts, Chen et al. [21–24] divided bridge piers' anticollision facilities into active and passive types, with active types being warning signs, navigation lights, yellow fog lights, infrared monitoring, audio reminder systems, laser measurement distance warning systems, satellite navigation area systems, etc. Active anticollision facilities mainly prevent accidents and thus require high levels of shipping management and technology. Passive types include external piers, sand-filled cofferdams, artificial islands, external pile groups, floating blocks, pointed bridge pier anticollision facility, wooden structure fenders, and gravity pendulums. These facilities are built with consideration of the safety of bridges after impact, but they do not necessarily protect the functions of ships and waterways. Effective anticollision facilities must protect the safety of ships and bridges and reduce waterway occupation. For example, a flexible steel rope anticollision device was developed by Chen et al. [21–25] following the principle of "three nonbreaking." The device can shift the bow direction to reduce the impact force. Jiang et al. [2, 26] studied the anticollision pontoon composed of FRP and used its large deformation to extend the impact time; their results proved that the pontoon has good anticollision performance. Zhou et al. [27] proposed a steel-CFRP combined with the anticollision box, which is superior to the steel anticollision box, and studied its anticollision performance. Shan and Huang [28] proposed a curved-shaped anticollision floating box of a bridge pier with sandwich structure. Studies have shown that these types of anticollision facilities have good anticollision performance, but their production processes are complex and the material costs are high [29]. To reduce material costs, simplify the production process, and combine the characteristics of a honeycomb structure, this work proposes a new type of anticollision facility with CSPs or OSPs as the structural elements. The energy dissipation effect of the anticollision facility is adjusted by changing the thickness and

arrangement of the structural elements so that it meets the requirements of pier collision avoidance for different waterway levels.

At present, the application and research on corrugated steel plates or corrugated steel pipes are mainly conducted in engineering fields, including culverts, bridges, pipelines, and industrial buildings. For example, Fang et al. [30] analyzed the mechanical behavior of concrete-filled corrugated steel tubular columns embedded with structural steel under the action of axial force by performing experiments and finite element comparisons; then, they revised the nominal hoop stress formula of the columns. Inaam and Upadhyay [31] evaluated the behavior of corrugated steel I-girder webs in a locally stressed structure by using the parametric numerical simulation method and then proposed an empirical model for determining the ultimate bearing capacity of cantilever beams. Based on experiments and finite element model verification, Degtyarev [32] studied the transverse distribution width of corrugated steel decks by performing parametric numerical analysis and presented a design equation for predicting the effective width; the results showed a good agreement with the finite element calculation results. Wang et al. [33] experimentally investigated the bending property of concrete infilled double-steel corrugated plate walls with T-shaped cross-sections under axial load experiments, established and verified a fine numerical analysis model, and proposed their elastic buckling behavior, buckling load, and bending torsion boundary. Zhu et al. [34] studied the axial carrying capacity and seismic characteristics of concrete infilled double-steel corrugated plate walls through experiments. Si et al. [35] analyzed the dynamic response of a box girder with corrugated steel webs and its equivalent concrete box girder and found that the dynamic response of the former is greater than that of the latter under the same conditions. Niknejad [36] conducted a quasi-static test to analyze the energy absorption of corrugated tubes under quasi-static axial and lateral loading conditions and found that corrugated tubes have better energy absorption under the former conditions than under the latter ones. Studies have shown that corrugated steel plates or corrugated steel pipes have strong shear resistance, bending resistance, seismic resistance, deformation, and energy absorption characteristics and can thus be used as structural elements of the anticollision facilities of bridge piers. However, their anticollision performance has not been studied in-depth and thus merits a comprehensive investigation.

In summary, the addition of anticollision facilities can effectively improve the impact resistance of bridge piers, reduce damage to ships, and reduce property losses. To address the complex production process and high material cost of existing anticollision facilities, this work proposes a new type of anticollision facility with CSPs or OSPs as structural elements. In the evaluation of the anticollision performance of these structural elements, they are used as study objects in the impact test research. The extreme value analysis method is subsequently proposed to solve the optimization design problem of the anticollision facility structure.

2. Test Overview

The honeycomb structure, which is a type of anticollision facility structure, has a good energy dissipation effect. As mentioned previously, corrugated steel pipes have good shear resistance, bending resistance, deformation, and energy absorption. Thus, they can be used as excellent structural elements for a new type of honeycomb anticollision facility. To design a corrugated steel pipe for use in a honeycomb structure, two different types of honeycomb anticollision facility structures are proposed. The first one is the CSP, which is composed of corrugated steel plates, bolts, and corrugated steel pipes. The other one is the OSP, which is composed of ordinary steel plates, bolts, and corrugated steel pipes. Under impact, the CSP's corrugated steel plate deforms first, followed by the corrugated steel pipes. The maximum deformation distance is the sum of the wave depth of all corrugated steel plates and the inner diameter of all corrugated steel pipes. The OSP's ordinary steel plates deform first, followed by the corrugated steel pipes. The maximum deformation distance is the sum of all corrugated steel pipes' inner diameters. The CSP and OSP absorb energy, prolong impact time through structural deformation, and reduce the energy transmitted to the bridge pier and the impact force received by the bridge pier. Thus, these elements enable collision avoidance and energy dissipation. During the test conducted in the current work, the bridge pier called CWACF-12.0 is simplified into a rectangular column with a base and diaphragm. The technical route of the experimental research is shown in Figure 1(d).

2.1. Specimen Design. The base of the CWACF-12.0 structure is 1,800 mm long, 1,600 mm wide, and 200 mm high. The rectangular column with a diaphragm measures 500 mm long, 500 mm wide, 1,500 mm high, and 12 mm thick. The CSP consists of two corrugated steel plates and two corrugated steel pipes. The OSP consists of two ordinary steel plates and two corrugated steel pipes. The corrugated steel plate measures 1,200 mm long, 600 mm wide, and H thick; its waveform parameters (wave distance $\times$ wave depth) are 400 mm $\times$ 150 mm. The corrugated steel pipe is 1,200 mm long and has a thickness of H and outer diameter of 500 mm; its wave parameters (wave distance $\times$ wave depth) are 200 mm $\times$ 55 mm. The ordinary steel plate is 1,200 mm long, 600 mm wide, and H thick. During the test, the impact velocities V of the pendulum are set to 2, 3, and 4 m/s to ensure that only the rectangular column has an elastic response. The schematic of the test model specimen structure is shown in Figure 1. The numbers of CSP and OSP specimens are summarized in Table 1.

2.2. Test Device and Design. The loading system of the pendulum impact test is designed to study the anticollision performance of the CSP and OSP (Figure 2). The pendulum weighs 454 kg. The swing arm is 3 m long. Controlling the angle θ makes the impact velocity V of the pendulum at the lowest point reach 2, 3, and 4 m/s. Such a setting ensures that only the rectangular column has an elastic response under

the impact of the pendulum. It also benefits the evaluation of the anticollision performance of the CSP and OSP. The test conditions and model composition are shown in Table 1.

2.3. Data Collection. The electrical measurement method is a physical or mechanical contact test method commonly used in static and dynamic tests and is made advantageous by its continuous collection. The noncontact optical test method [37] is a nondestructive experimental test method that is suitable for static and dynamic displacement and strain testing. In particular, the digital image correlation (DIC) method has been successfully applied to science and engineering [37]. Zhang et al. [38] used a high-speed camera to study the dynamic response and failure mode of segmented precast columns under impact loads. Fang et al. [39] took a rod disk as the experimental object, comparatively analyzed the advantages and disadvantages of a laser vibrometer, strain gauge, and 2D high-speed camera system, and verified that DIC technology is suitable for low-speed collision. On the basis of the three-dimensional dynamic DIC method, the real-time surface displacement field of a target plate underwater under impact load was determined by Xiang et al. [40]. Wang et al. [41] applied DIC to the evaluation of human-vehicle collision experiments. Research has shown that DIC technology is suitable for high-speed and low-speed impact tests and achieves high accuracy. Therefore, the DIC method and electrical measurement method are used for the data acquisition and calculation in the pendulum impact test in the current work.

The DIC measurement system includes cameras, triggers, light sources, a computer, and other equipment. Before the test, qualified speckle and mark points are made on the side of the rectangular column. The speckles should be imaged in the camera. The DIC measurement system used for the collection and processing of test image information is the PMLAB DIC-2D strain optical measurement system developed by Nanjing PMLAB* Sensor Tech. Co., Ltd. The image information acquisition frequency of this system is related to the image resolution and is equal to 83 Hz during the test. The dynamic signal measurement system used in the electrical measurement method is the DH5902N rugged dynamic signal test and analysis system developed by Jiangsu Donghua Testing Technology Co., Ltd.; its acquisition frequency is 50 kHz. These systems are used to collect the image information and the lateral displacement data of the rectangular column during the test. The DIC-2D measurement system and dynamic signal measurement system are shown in Figure 3.

3. Results of the Experimental Test

Under the effect of impact (impact velocity V values are 2, 3, and 4 m/s), the image information of the rectangular column is collected with a high-speed camera, and the lateral displacement field and the lateral displacement curve of D1 are obtained by analysis. Mutual verification with the curve obtained by the electrical measurement method is performed to ensure the accuracy of the test data. The

FIGURE 1: Schematic of the test model specimen structure. (a) CWACF-12.0. (b) OSP. (c) CSP. (d) The technical route of the experimental research.

TABLE 1: Test conditions, number of specimens, and test model composition.

Working condition number	H (mm)	Quantity	V (m/s)	CSP	OSP	CWACF-12.0
CSP-2.75-2	2.75	3	2	+	—	+
CSP-3.00-2	3.00	3	2	+	—	+
CSP-3.50-2	3.50	3	2	+	—	+
OSP-2.75-2	2.75	3	2	—	+	+
OSP-3.00-2	3.00	3	2	—	+	+
OSP-3.50-2	3.50	3	2	—	+	+
CWACF-12.0-2	0	1	2	—	—	+
CSP-2.75-3	2.75	3	3	+	—	+
CSP-3.00-3	3.00	3	3	+	—	+
CSP-3.50-3	3.50	3	3	+	—	+
OSP-2.75-3	2.75	3	3	—	+	+
OSP-3.00-3	3.00	3	3	—	+	+
OSP-3.50-3	3.50	3	3	—	+	+
CWACF-12.0-3	0	1	3	—	—	+
CSP-2.75-4	2.75	3	4	+	—	+
CSP-3.00-4	3.00	3	4	+	—	+
CSP-3.50-4	3.50	3	4	+	—	+
OSP-2.75-4	2.75	3	4	—	+	+
OSP-3.00-4	3.00	3	4	—	+	+
OSP-3.50-4	3.50	4	4	—	+	+
CWACF-12.0-4	0	1	4	—	—	+

“+”: assembled; “—”: not assembled.

FIGURE 2: Loading system. (a) CSP loading system. (b) On-site loading system.

FIGURE 3: Model test measurement system. (a) DIC-2D test system. (i) Pendulum. (ii) Specimen. (iii) Marked point. (iv) Speckle. (v) Camera. (vi) Light sources. (vii) Trigger. (viii) Computer. (b) Dynamic signal measurement system. (ix) Laptop. (x) Collection box.

anticollision performance of the CSP and OSP specimens is analyzed by comparing the deformation results of these elements at impact, the lateral displacement field of the rectangular column, the lateral displacement time history curve of D1, and other test results.

3.1. Deformation Result of Steel Plate. Under impact, the corrugated steel plate of the CSP is deformed, with the greatest deformation observed in the outer corrugated steel plate. The wave crest at the impact point is deformed and dented, and the wave trough connected to the corrugated steel pipe is deformed and arched. After disassembly, the joint between the inner corrugated steel plate and the corrugated steel pipe is partially deformed and dented. The corrugated steel pipe does not undergo plastic deformation. The deformation of CSP-2.75-4's inner and outer corrugated steel plates after impact is shown in Figure 4(a). The deformation of CSP-2.75-4's outer corrugated steel plates is the most serious after impact. Under impact velocities of 2, 3, and 4 m/s and plate thickness of 2.75 mm, the deformation of the CSP's outer corrugated steel plates after impact is shown in Figures 4(c), 4(e), and 4(g), respectively.

Under impact, the ordinary steel plate on the outside of the OSP is deformed and dented along the short side. The ordinary steel plate on the inside of the OSP does not show significant deformation. The bolt holes are locally sheared and deformed. The corrugated steel pipe has no obvious deformation. The deformation of OSP-2.75-4's inner and outer ordinary steel plates after impact is shown in Figure 4(b). The deformation of OSP-2.75-4's outer ordinary steel plates is the most obvious after impact. Under the impact velocities of 2, 3, and 4 m/s and the plate thickness of 2.75 mm, the deformation of the OSP's outer ordinary steel plates after impact is shown in Figures 4(d), 4(f), and 4(h), respectively.

The comparison of the experimental results shows that the deformation of the outer steel plates has the following two conditions. First, the plates have the same thickness, and the deformation of the inner and outer steel plates increases with the increase of the impact velocity. Second, they have the same impact velocity. Moreover, the deformation of the inner and outer steel plates decreases with the increase of plate thickness. When the impact velocities are 2, 3, and 4 m/s, the waveform of the CSP's outer corrugated steel plates changes obviously, and the wave crest at the impact has

FIGURE 4: Local deformation of the steel plate. (a) Deformation of CSP-2.75-4 outside and inside the corrugated steel plates after impact. (b) Deformation of OSP-2.75-4 outside and inside the ordinary steel plates after impact. (c) Deformation of CSP-2.75-2 outside the corrugated steel plates. (d) Deformation of OSP-2.75-2 outside the ordinary steel plates. (e) Deformation of CSP-2.75-3 outside the corrugated steel plates. (f) Deformation of OSP-2.75-3 outside the ordinary steel plates. (g) Deformation of CSP-2.75-4 outside the corrugated steel plates. (h) Deformation of OSP-2.75-4 outside the ordinary steel plates.

obvious dents. The deformation of the OSP's outer ordinary steel plate changes from being minimal to showing obvious dents. Therefore, the deformation of the CSP's outer corrugated steel plate is greater than that of the OSP's outer ordinary steel plate.

3.2. Lateral Displacement Field Results. The direction that is balanced with the initial impact velocity is the positive direction of the lateral displacement. When the pendulum strikes the CSP or OSP or CWACF-12.0, a high-speed camera collects the image information. The lateral displacement field of the rectangular column is obtained using the PMLAB DIC-2D two-dimensional strain optical measurement system.

The comparison of the displacement field results of the continuous time intervals (time interval $\Delta t = 12$ ms) of the working conditions shows that the lateral displacement field result of the column equipped with the CSP and OSP is significantly smaller than that of the column of CWACF-12.0. The transverse displacement field of three consecutive time intervals of a certain test under CSP-2.75-4, OSP-3.00-4, CWACF-12.0-3, etc., is shown in Figure 5. The results of the lateral displacement field on the side of the column show that the CSP and OSP have relatively high energy dissipation effects.

3.3. Lateral Displacement Time History Curve. The direction that is balanced with the initial impact velocity is the positive direction of the lateral displacement. When the pendulum hits the CSP or OSP or CWACF-12.0, the DIC-2D test results are smoothly processed, and the time history curve of the D1 lateral displacement is basically consistent with that obtained by the electrical measurement method. This result indicates that the time history curve of the D1 lateral displacement is accurate.

Figure 6 shows the D1 transverse displacement curve of the multiple impact test under each working condition when the impact speed of the pendulum is 4 m/s. The peak values of the D1 lateral displacement in multiple tests of CSP-2.75-4 were 2.53, 2.44, 2.33, and 2.66 mm. The curve showed two peaks at 18 and 40 ms, and the time of the first return to the initial position was 78 ms. The peak values of the D1 lateral displacement in multiple tests of CSP-3.00-4 were 3.15, 3.16, 3.13, and 3.86 mm. The curve showed two peaks at 18 and 40 ms, and the time of the first return to the initial position was 72 ms. The peak values of the D1 lateral displacement in multiple tests of CSP-3.50-4 were 5.59, 5.55, 5.21, and 5.59 mm. The curve had two peaks at 18 and 40 ms, and the time of the first return to the initial position was 60 ms. The peak values of the D1 lateral displacement in multiple tests of CWACF-12.0-4 were 22.86, 23.29, 25.68, and 21.75 mm. The peak value of the curve was 11 ms, and the time of the first return to the initial position was 30 ms. In multiple tests of OSP-3.00-4, the peak values of the D1 lateral displacement were 5.00, 4.95, 5.02, and 5.96 mm. The peak value of the curve was 24 ms, and the time of the first return to the initial position was 38 ms. The peak values of the D1 lateral displacement in multiple tests of OSP-3.50-4 were 9.24, 10.30,

11.90, and 11.86 mm. The peak value of the curve was 24 ms, and the time of the first return to the initial position was 34 ms. Table 2 summarizes the peak values of the D1 lateral displacement of multiple tests and the time T of the first return to the initial position.

When the impact velocities are 2, 3, and 4 m/s, the plate thickness is 2.75 mm; and the peak values of the D1 lateral displacement of the CSP are 1.27, 2.37, and 2.49 mm, respectively, thereby accounting for only 9.30%, 13.72%, and 10.64% of the total values of CWACF-12.0. For a plate thickness of 3.00 mm, the peak values of the D1 lateral displacement of the CSP are 1.41, 2.32, and 3.32 mm, which account for only 10.33%, 13.43%, and 14.19% of the results of CWACF-12.0, respectively. The OSP's D1 lateral displacement peak values are 1.29, 3.63, and 5.23 mm, which account for only 9.45%, 21.01%, and 22.35% of the results of CWACF-12.0, respectively. For a plate thickness of 3.50 mm, the peak values of the D1 lateral displacement of the CSP are 2.79, 3.56, and 5.57 mm, which account for only 20.43%, 20.60%, and 23.80% of the results of CWACF-12.0, respectively. The peak values of the D1 lateral displacement of the OSP are 2.08, 5.21, and 10.83 mm, which account for only 15.24%, 30.15%, and 46.28% of the results of CWACF-12.0, respectively. The peak values of the D1 lateral displacement of CWACF-12.0 are 13.65, 17.28, and 23.40 mm. The test results show that the CSP and OSP specimens have a high energy dissipation effect. The D1 lateral displacement peak of CSP-2.75-2 only accounts for 9.30% of CWACF-12.0, while the D1 lateral displacement peak of OSP-3.00-2 only accounts for 9.45% of CWACF-12.0.

When the impact velocities are 2, 3, and 4 m/s, the plate thickness is 2.75 mm; and the time values of the first return of D1 of the CSP to the initial position are 59, 59, and 77 ms, respectively. For a plate thickness of 3.00 mm, the time values of the first return of D1 of the CSP to the initial position are 53, 52, and 67 ms; for the OSP, the time values are 50, 38, and 40 ms. Given a plate thickness of 3.50 mm, the time values of the first return of D1 of the CSP to the initial position are 44, 54, and 54 ms; for the OSP, the time values are 44, 37, and 34 ms. For CWACF-12.0, the time values of the first return of D1 to the initial position are 38, 29, and 39 ms. The impact speed is constant. The shorter the time of the first return to the initial position is, the greater the response frequency of the rectangular column and the greater the impact force received by the rectangular column will be.

When the impact velocity is the same, the average peak value of the D1 lateral displacement increases with the increase of the plate thicknesses of the CSP and OSP. The smaller the plate thickness of the CSP and OSP is, the longer the rectangular column takes to return to the initial position for the first time. When the CSP and OSP have the same thickness, the peak value of the D1 lateral displacement increases with the increase of impact velocity. The greater the impact speed is, the smaller the thickness of the CSP and OSP and the more serious the deformation of the inner and outer steel plates will be. With the inner and outer steel plates absorbing most of the energy, less energy is transmitted to the rectangular column, and the longer D1 takes to

FIGURE 5: Lateral displacement field of the rectangular column side (unit: mm). (a) CSP-2.75-4. (b) OSP-3.00-4. (c) CWACF-12.0-3.

return to the initial position for the first time, the smaller the peak value of the D1 lateral displacement is.

4. Optimization Analysis

To further optimize the structure of the CSP and OSP specimens and improve their anticollision performance, this study investigates the influence of factors such as the impact speed, the specimens' weight, plate thickness, and natural vibration frequency which effected on the lateral displacement peak value. The curve relationship of the peak values and the application of the extreme value analysis method are considered to optimize the structure of the CSP and OSP.

4.1. Impact Velocity. The effect of impact velocity on the lateral displacement peak value of point D1 is shown in Figure 7. When the impact velocity is less than 3 m/s, the lateral displacement peak values of point D1 of CSP-2.75 and CSP-3.00 are almost coincident. The lateral displacement peak value of point D1 of OSP-3.00 gradually approaches those of CSP-3.00 and CSP-2.75. When the impact velocity is greater than 3 m/s, the lateral displacement peak value of point D1 of CSP-3.00 is greater than that of CSP-2.75. The lateral displacement peak values of point D1 of CSP-3.50 and OSP-3.00 are almost equal. When the impact velocity is 2 m/s, the lateral displacement peak value of point D1 of OSP-3.00 is almost the same as that of CSP-2.75 and is smaller

FIGURE 6: Continued.

FIGURE 6: Lateral displacement time history curve of point D1 when $V = 4$ m/s. (a) CSP-2.75-4. (b) CSP-3.00-4. (c) CSP-3.50-4. (d) CWACF-12.0-4. (e) OSP-3.00-4. (f) OSP-3.50-4.

TABLE 2: Point D1's lateral displacement peak values and duration (T) of the return to the initial position for the first time.

Working condition number	Displacement peak values (mm)		Average (mm)	T (ms)
	EM-test	DIC-smooth		
CSP-2.75-2	1.37, 1.10, and 1.17	1.46	1.27	59
CSP-3.00-2	1.43, 1.33, and 1.38	1.51	1.41	53
CSP-3.50-2	2.73, 2.53, and 2.80	3.11	2.79	44
OSP-2.75-2	—	—	—	—
OSP-3.00-2	1.26, 1.21, and 1.25	1.43	1.29	50
OSP-3.50-2	1.93, 2.22, and 1.86	2.34	2.08	44
CWACF-12.0-2	12.34, 13.47, 13.57, 13.69, 14.39, 14.18, and 14.18	13.39	13.65	38
CSP-2.75-3	1.97, 2.92, and 2.15	2.43	2.37	59
CSP-3.00-3	1.94, 2.34, and 1.99	3.00	2.32	52
CSP-3.50-3	4.00, 2.98, and 3.73	3.55	3.56	54
OSP-2.75-3	—	—	—	—
OSP-3.00-3	3.58, 3.59, and 3.87	3.50	3.63	38
OSP-3.50-3	5.03, 5.15, and 5.35	5.31	5.21	37
CWACF-12.0-3	16.43, 17.13, 17.12, 17.80, 17.74, and 17.91	16.84	17.28	29
CSP-2.75-4	2.53, 2.44, and 2.33	2.66	2.49	77
CSP-3.00-4	3.15, 3.16, and 3.13	3.86	3.32	67
CSP-3.50-4	5.59, 5.55, and 5.21	5.59	5.57	54
OSP-2.75-4	—	—	—	—
OSP-3.00-4	5.00, 4.95, and 5.02	5.96	5.23	40
OSP-3.50-4	9.24, 10.30, and 11.90	11.86	10.83	34
CWACF-12.0-4	22.86, 23.29, and 25.68	21.75	23.40	39

than those of CSP-3.00 and CSP-3.50. Moreover, the lateral displacement peak value of point D1 of OSP-3.50 is smaller than that of CSP-3.50. However, the lateral displacement peak values of point D1 of OSP-3.50 and CWACF-12.0 show a linear growth trend with the change of impact velocity.

When the impact velocity is 2 m/s and the CSP and OSP have the same plate thickness, the lateral displacement peak value of point D1 of the OSP is smaller than that of the CSP. The lateral displacement peak value of point D1 of CSP-2.75 is 1.27 mm while that of OSP-3.00 is 1.29 mm; the difference

between them is only 0.01 mm. Therefore, the lateral displacement peak value of point D1 of OSP-2.75 is also smaller than that of CSP-2.75. When the impact velocity is 3 m/s, the difference between the lateral displacement peak value of point D1 of CSP-2.75 and CSP-3.00 is 0.05 mm, which is due to the small difference in their plate thickness and the difference in the test assembly specimens. The difference between the lateral displacement peak value of point D1 of CSP-3.50 and that of OSP-3.00 is 0.07 mm because the amounts of energy absorbed by the deformation of OSP-3.00

FIGURE 7: Impact velocity effect on the lateral displacement peak value of point D1. (a) Change curve of the lateral displacement peak value of point D1. (b) The lateral displacement peak value of point D1 at each impact velocity.

and CSP-3.50 are equivalent. When the impact velocity is 4 m/s, the lateral displacement peak values of point D1 of the CSP and OSP increase with the increase of the impact velocity. The lateral displacement peak value of point D1 of CSP-2.75-4 is the smallest, accounting for only 10.6% of that of CWACF-12.0-4.

When the impact velocity is 2 m/s, the lateral displacement peak value of point D1 of CSP-2.75-2 is 1.27 mm and that of OSP-3.00-2 is 1.29 mm, which is about 9.3% of the lateral displacement peak value of point D1 of CWACF-12.0-2. When the impact velocity is 3 m/s, the lateral displacement peak value of point D1 of CSP-2.75-3 is 2.37 mm and that of CSP-3.00-3 is 2.32 mm, which is about 13.7% of the lateral displacement peak value of point D1 of CWACF-12.0-3. When the impact velocity is 4 m/s, the lateral displacement peak value of point D1 of CSP-2.75-4 is the smallest and is 10.6% of that of CWACF-12.0-4. Therefore, when the impact velocity is 2 m/s and the plate thickness is the same, the OSP has a better energy dissipation effect than the CSP. When the impact velocity is greater than 3 m/s and the plate thickness is the same, the CSP has a better energy dissipation effect than the OSP.

4.2. Specimen Weight. Before the test, the specimen weight is measured several times, and the average weights of CSP-2.75, CSP-3.00, CSP-3.50, OSP-3.00, and OSP-3.50 are 13,810, 145,011, 168,011, 129,755, and 146,095 g, respectively. The relationship between the specimen weight and the lateral displacement peak value of point D1 is shown in Figure 8. When the impact velocity is constant, the CSP specimen weight increases from 0 g to 168,011 g, and the change of the lateral displacement peak value curve of point D1 with the specimen weight is a quadratic parabola. The lateral displacement peak value of point D1 decreases first and then increases, and it has the minimum point. When the impact velocity is 4 m/s, the change rate of the lateral displacement peak value of point D1 of the CSP is the largest.

When the impact velocities are 3 and 4 m/s, the two curves intersect at the point (117,935, 2.39). When the impact velocities are 2, 3, and 4 m/s, the minimum points of each curve are (124,873, 1.14), (131,810, 2.27), and (117,935, 2.39), respectively.

The OSP specimen weight increases from 0 g to 146,095 g, and the lateral displacement peak value curve of point D1 is a quadratic parabola. With the increase of the specimen weight, the lateral displacement peak value of point D1 decreases first and then increases, and it has a minimum point. The greater the impact velocity is, the greater the change rate of the lateral displacement peak value of point D1 of the OSP. When the impact velocities are 2 and 4 m/s, the two curves intersect at points (38,009, 6.55) and (111,406, 1.04), respectively. When the impact velocities are 3 and 4 m/s, the two curves intersect at points (26,213, 10.76) and (121,891, 3.16), respectively. When the impact velocities are 2, 3, and 4 m/s, the minimum points of each curve are (112,716, 1.02), (102,231, 2.64), and (86,503, -1.08), respectively. When the impact velocity is 4 m/s, the lateral displacement peak value of point D1 of the OSP shows a negative value (the direction is opposite to the initial impact velocity) because of the dispersion of the lateral displacement peak value of point D1 in the test data. However, the minimum value of the curve is close to zero, indicating that the curve is reliable.

In the comparison of the extreme points of the curves, the impact velocity is 2 m/s, and the optimal values of the CSP and OSP specimen weights are 124,873 and 112,716 g, respectively. When the impact velocity is 3 m/s, the optimal values of the CSP and OSP specimen weights are 131,810 and 102,231 g, respectively. When the impact velocity is 4 m/s, the optimal values of the CSP and OSP specimen weights are 117,935 and 86,503 g, respectively. Therefore, by analyzing the extreme point of the change of the lateral displacement peak value curve of point D1 with the specimen weight, the optimal value of the specimen weight is deduced.

FIGURE 8: Relationship between the lateral displacement peak value of point D1 and the specimen weight. (a) CSP. (b) OSP.

4.3. Specimen Plate Thickness. The plate thickness of each specimen is measured several times before the test. The average plate thicknesses of CSP-2.75, CSP-3.00, CSP-3.5, OSP-3.00, and OSP-3.5 are 2.76, 2.98, 3.54, 3.11, and 3.47 mm, respectively. The relationship between the plate thickness H and the lateral displacement peak value of point D1 is shown in Figure 9. When the impact velocity is constant, the plate thickness of the CSP specimen increases from 0 mm to 3.54 mm, and the lateral displacement peak value curve of point D1 that changes with the plate thickness is a quadratic parabola and first decreases and then increases; it also has an extreme point. The greater the impact velocity is, the greater the change rate of the lateral displacement peak value of point D1 will be. When the impact velocities are 3 and 4 m/s, the two curves intersect at point (2.2, 2.95). The minimum points of each curve are (2.62, 1.20), (2.67, 2.31), and (2.54, 2.53).

When the impact velocity is constant, the plate thickness of the OSP specimen increases from 0 mm to 3.47 mm. Moreover, the lateral displacement peak value curve of point D1 that changes with the plate thickness is a quadratic parabola and first decreases and then increases; it also has a minimum point. The greater the impact velocity is, the greater the change rate of the lateral displacement peak value curve of point D1 of the OSP will be. When the impact velocities are 2 and 4 m/s, the two curves have two intersection points (0.82, 7.08) and (2.72, 0.96), respectively. When the impact velocities are 3 and 4 m/s, the two curves have two intersection points (0.57, 11.09) and (2.93, 3.09), respectively. The minimum points of each curve are (2.67, 0.95), (2.43, 2.43), and (2.00, -1.98). When the impact velocity is 4 m/s, the lateral displacement peak value of point D1 of the OSP has a negative value (the direction is opposite to the initial impact velocity) because of the dispersion of the lateral displacement peak value of point D1 in the test data. However, the minimum value of the curve is close to zero, indicating that the curve is reliable.

In the comparison of the extreme points of the curves, when the impact velocity is 2 m/s, the optimal plate thickness of the OSP and CSP specimens are 2.67 and 2.62 mm, respectively. When the impact velocity is 3 m/s, the optimal plate thicknesses of the OSP and CSP specimens are 2.43 and 2.67 mm, respectively. When the impact velocity is 4 m/s, the optimal plate thicknesses of the OSP and CSP specimens are 2.00 and 2.54 mm, respectively. Therefore, by analyzing the extreme point of the lateral displacement peak value that changes with plate thickness, the optimal value of the plate thickness is deduced.

4.4. Natural Frequency. According to structural dynamics theory [42], the natural frequencies of the CSP and OSP are only related to their own stiffness and mass matrices. Therefore, the effects of natural frequency on the lateral displacement peak value of point D1 are discussed herein. The ANSYS/LS-DYNA software is used to calculate the first 100 modes and frequencies of the CSP and OSP. The frequency response functions (FRFs) are shown in Figure 10. The peaks of the FRF points of OSP-3.00, OSP-3.50, CSP-2.75, CSP-3.00, and CSP-3.50 are (14.29, 40.2684), (17.09, 45.9884), (47.77, 452.293), (49.57, 436.842), and (55.58, 449.452), respectively. Therefore, the natural frequencies of OSP-3.00, OSP-3.50, CSP-2.75, CSP-3.00, and CSP-3.50 gradually increase.

The lateral displacement peak value curve of point D1 changes with the natural frequency of the CSP specimen, as shown in Figure 10(b). The impact velocity is constant. The lateral displacement peak value curve of point D1 changes with the natural frequency of the CSP specimen and is a quadratic parabola. The lateral displacement peak value of point D1 first decreases and then increases, and it has a minimum point. When the impact velocities are 2, 3, and 4 m/s, the minimum points of each curve are (39.60, 0.66), (42.10, 1.99), and (38.52, 1.41), respectively. When the impact velocities are 3 and 4 m/s, the two curves intersect at

FIGURE 9: Relationship between the lateral displacement peak value of point D1 and plate thickness. (a) CSP. (b) OSP.

points (22.15, 5.43) and (45.50, 2.09), respectively. These results indicate that the lateral displacement peak values of point D1 at these two natural frequencies are equal.

The lateral displacement peak value curve of point D1 changes with the natural frequency of the OSP specimen, as shown in Figure 10(c). The impact velocity is constant. The lateral displacement peak value curve of point D1 is a quadratic parabola, and the lateral displacement peak value of point D1 first decreases and then increases, and it has a minimum point. When the impact velocities are 2, 3, and 4 m/s, the minimum points of each curve are (13.66, 1.26), (12.73, 3.35), and (10.47, 2.43), respectively. When the impact velocities are 3 and 4 m/s, the two curves intersect at points (4.70, 8.80) and (12.69, 3.37), respectively. This result indicates that the lateral displacement peak values of point D1 at the two natural frequencies are equal.

In the comparison of the extreme points of the curves, when the impact velocity is 2 m/s, the optimal natural frequencies of the CSP and OSP are 39.60 and 13.66 Hz, respectively. When the impact velocity is 3 m/s, the optimal natural frequencies of the CSP and OSP are 42.10 and 12.73 Hz, respectively. When the impact velocity is 4 m/s, the optimal natural frequencies of the CSP and OSP are 38.52 and 10.47 Hz, respectively. Therefore, by analyzing the extreme point of the lateral displacement peak value curve of point D1 that changes with the natural frequency, the optimal value of the natural frequency is deduced.

4.5. Structural Optimal Design. A corresponding relationship exists between the optimal values of plate thickness, weight, and natural frequency of the CSP and OSP specimens. The optimal value of the natural frequency of the CSP and OSP specimens is taken to optimize the structure of the CSP and OSP specimens. The optimized calculation values of the thickness, weight, and natural frequency of the test piece can be calculated using ANSYS/LS-DYNA software to

determine the modal and frequency of the optimized test piece. The frequency response function is used to determine the optimized natural frequency of the test piece. The optimized calculation values of the influencing factors are compared with the corresponding optimal values to verify their accuracy. The comparison of the optimal values of the influencing factors and the optimal calculation values is summarized in Table 3.

Plate thickness ratio is the ratio of the optimal value of plate thickness to the optimal calculation value of plate thickness. Weight ratio is the ratio of the optimal value of the specimen weight to the optimal calculation value of the specimen weight. Frequency ratio is the ratio of the optimal value of the specimen's natural frequency to the optimal calculation value of the specimen's natural frequency. When the impact velocity is 2 m/s, the plate thickness ratio, mass ratio, and frequency ratio of the CSP are 1.05, 1.03, and 0.98, respectively, while those of the OSP are 1.07, 1.04, and 1.12, respectively. When the impact velocity is 3 m/s, the thickness ratio, mass ratio, and frequency ratio of the CSP are 1.07, 1.09, and 1.04, respectively, while those of the OSP are 0.97, 0.94, and 1.04, respectively. When the impact velocity is 4 m/s, the thickness ratio, mass ratio, and frequency ratio of the CSP are 1.02, 0.98, and 0.95, respectively, while those of OSP are 0.80, 0.80, and 0.86, respectively. The thickness ratios, mass ratios, and frequency ratios of the CSP and OSP are all within [0.80, 1.12], and the accuracy is high. Hence, introducing a thickness of 2.50 mm is reasonable.

The natural frequency of the CSP of 40.60 Hz and the natural frequency of the OSP of 12.20 Hz are, respectively, substituted into the curves in Section 4.4 to compare the energy dissipation effects of the CSP and OSP when the plate thickness is 2.50 mm. The peak value of the D1 lateral displacement of the rectangular column can then be obtained. When the impact velocity is 2 m/s, the peaks of the D1 lateral displacement of the CSP and OSP are 0.67 and

FIGURE 10: Frequency response function and the relationship between the natural frequency and the lateral displacement peak value of point D1. (a) Frequency response function of CSP. (b) Relationship between natural frequency and lateral displacement peak value of point D1 of the CSP. (c) Frequency response function of the OSP. (d) Relationship between natural frequency and lateral displacement peak value of point D1 of the OSP.

TABLE 3: Comparison between each influence factor's optimal values and optimal calculation values.

Type	Velocity (m/s)	Plate thickness (mm)	Optimal value		Optimal calculation value		Plate thickness ratio	Weight ratio	Frequency ratio
			Weight (g)	Frequency (Hz)	Plate thickness (mm)	Weight (g)			
CSP	2	2.62	124873.00	39.60	2.50	120888.00	1.05	1.03	0.98
	3	2.67	131810.00	42.10			1.07	1.09	1.04
	4	2.54	117935.00	38.52			1.02	0.98	0.95
OSP	2	2.67	112716.00	13.66	2.50	108407.00	1.07	1.04	1.12
	3	2.43	102231.00	12.73			0.97	0.94	1.04
	4	2.00	86503.00	10.47			0.80	0.80	0.86

1.39 mm, respectively, accounting for 4.91% and 10.18% of the D1 lateral displacement peaks of CWACF-12.0, respectively. When the impact velocity is 3 m/s, the peak values

of the D1 lateral displacement of the CSP and OSP are 2.01 and 3.36 mm, respectively, accounting for 11.63% and 19.44% of the peak lateral displacements of the CWACF-

12.0 column, respectively. When the impact velocity is 4 m/s, the peak values of the D1 lateral displacements of the CSP and OSP are 1.47 and 3.01 mm, respectively, accounting for 6.28% and 12.86% of the peak lateral displacements of the CWACF-12.0 column, respectively. The results show that when the plate thickness is 2.50 mm, the CSP and OSP have the best energy dissipation effects, but the energy dissipation effect of the CSP is better than that of the OSP. The introduction of the extreme value analysis method can optimize the structural design of anticollision facilities so that anticollision structures have the best energy dissipation effect.

5. Conclusion

An impact test was conducted on the steel rectangular column under the buffer condition of whether to install the structural elements CSP or OSP of the new type of anti-collision facility. The D1 lateral displacement field of the column and the D1 lateral displacement time history curve of the top of the column were also analyzed. In addition, this study investigated the relationship curve between the peak values of the D1 lateral displacement at the top of the column and impact velocity, the specimens' thickness, weight, natural frequency, and other factors. The main conclusions are as follows:

- (1) Given impact velocities of 2, 3, and 4 m/s, the peaks of the D1 lateral displacement of CSP-2.75 only account for 9.30%, 13.72%, and 10.64% of those of CWACF-12.0, respectively. The D1 lateral displacement peak values of CSP-3.00 only account for 10.33%, 13.43%, and 14.19% of those of CWACF-12.0. The peak values of the D1 lateral displacement of OSP-3.00 only account for 9.45%, 21.01%, and 22.35% of those of CWACF-12.0. The peak values of the D1 lateral displacement of CSP-3.50 only account for 20.43%, 20.60%, and 23.80% of those of CWACF-12.0. The peak values of the D1 lateral displacement of OSP-3.50 only account for 15.24%, 30.15%, and 46.28% of those of CWACF-12.0. The test results show that the CSP and OSP specimens have a relatively high energy dissipation effect and that the energy dissipation effect of the OSP with the same plate thickness is stronger than that of the CSP when the impact energy is small. When the impact energy is large, the energy dissipation effect of the CSP with the same plate thickness is stronger than that of the OSP.
- (2) The extreme value analysis method is used to analyze the relationship curve between the peak value of the D1 lateral displacement and impact velocity, specimens' thickness, weight, and natural vibration frequency to deduce the extreme value points of each curve. The optimal value corresponding to the extreme point is used to optimize the structural design of the CSP and OSP. When the optimized plate thickness is 2.50 mm, the plate thickness ratios, mass ratios, and frequency ratios of the CSP and OSP are all in the range of [0.80, 1.12], and the D1 lateral

displacement peaks of the CSP and OSP account for the smallest percentage of CWACF-12.0. The optimization results show that the extreme value analysis method can optimize the structural design of collision avoidance facilities so that the best energy dissipation effect can be realized.

- (3) The lateral displacement curve of point D1 obtained by the DIC-2D technology is basically consistent with that collected by the electrical measurement method. This result indicates that the DIC-2D technology is also suitable for the evaluation of the anticollision performance of anticollision facilities.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

The opinions, findings, and conclusions do not reflect the opinions of the funding agencies or other individuals.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors are grateful for the support from the School of Civil Engineering, Chongqing Jiaotong University, State Key Laboratory of Mountain Bridge and Tunnel Engineering, and State Key Laboratory of Mountain Bridge and Tunnel Engineering co-built by Provincial Government and the Ministry of Transport. The first author also thanks the Research Project of the Ministry of Transport of the People's Republic of China (no. 2011318223190). Special thanks are due to Dr. Haiyang Yi for his assistance in the writing and translation of the paper and to Nanjing PMLAB* Sensor Tech. Co., Ltd. for the assistance during the test data collection. The research and publication of this article was funded by the Research Project of Ministry of Transport of the People's Republic of China (The Ministry of Transport of the People's Republic of China, no. 2011318223190).

References

- [1] C. Guoyu, "Summarize of the research and design on anti-collision ship with bridge for 30 years in China," shanghai association of old scientific and technical workers," in *Proceedings of the 9th Annual Conference of Shanghai Association of Old Science and Technology Workers Shanghai Ocean Steel Structure Research Institute*, pp. 253–259, Shanghai, China, 2011.
- [2] H. Jiang and M. G. Chorzepa, "Evaluation of a new FRP fender system for bridge pier protection against vessel collision," *Journal of Bridge Engineering*, vol. 20, no. 2, Article ID 5014010, 2015.
- [3] Van, "Ship collision with bridges, review of accidents," *Ship Collision Analysis*, Routledge, Oxford, England, 1998.

- [4] Knott, "Vessel collision design codes and experience in the united states," *Ship Collision Analysis*, Routledge, Oxford, England, 1998.
- [5] T. Dai, *Ship Impact against Bridge and its Risk Assessment*, Harbin Institute of Technology, Harbin, China, 2002.
- [6] State Council of the People's Republic of China, *Plan for the Development of Modern Comprehensive Transportation System during the 13th Five-Year Plan Period*, Central Compilation & Translation Press, Beijing, China, 2017.
- [7] Ministry of Communications, PRC, *National inland waterways and ports layout planning*, vol. 7, pp. 6-7, 2007.
- [8] G. Chen, C. Zhang, L. Wang, H. D. Zhang Zhongwei, and L. Zonglin, "Research progress on flexible collision avoidance of bridge pier," in *Proceedings of the 17th National Conference on Bridges*, China Society of Civil Engineering, pp. 1239-1346, Bridges, chongqing, China, August 2006.
- [9] V. U. Minorsky, "An analysis OF SHIP collisions with reference to protection OF nuclear power plants," *Journal of Ship Research*, vol. 3, no. 2, 1958.
- [10] G. Woisin, *Structural Design Against Collision Effects*, International Symposium on Advances in Marine Technology, Trondheim, Norway, 1979.
- [11] K. N. Derucher, "Analysis OF concrete bridge piers for vessel impact," *Civil Engineering for Practicing and Design Engineers*, vol. 1, no. 4, pp. 393-421, 1982.
- [12] AASHTO LRFD Bridge Design Specifications, 8th edition [j], American Association of State Highway and Transportation Official, Washington, DC, USA, 2017.
- [13] National Railway Administration of China, *Code for Design of Concrete Structures of Railway Bridge and Culvert*, TB 10092-2017, China railway Publishing House Co., LTD, Beijing, China, 2017.
- [14] Jiaotong Ministry of Transport and PRC, *General Specifications for Design of Highway Bridges and Culverts*, JTG D60-2015, China Communications Press Co., LTD, Beijing, China, 2015.
- [15] G. Chen, B. Ni, Y. Li, and Y. Liming, "Experimental study and actual test of impact force on bridge sustained collision by ship," *Shipbuilding of China*, vol. 54, no. 2, pp. 507-516, 2013.
- [16] D. J. Huang, L. L. Wang, N. Bu-you, and C. Guo-yu, "The numerical analysis and experiment of synchronism on multi-anti-collision ring within the anti-collision device with outer steel gate," in *Proceedings of the International Symposium on Ship-Bridge Collision and its Protection*, pp. 146-153, Hamburg, Germany, September 2014.
- [17] T. V. Do, T. M. Pham, and H. Hao, "Dynamic responses and failure modes of bridge columns under vehicle collision," *Engineering Structures*, vol. 156, no. 1, pp. 243-259, 2018.
- [18] D. Zhou, R. Li, J. Wang, and C. Guo, "Study on impact behavior and impact force of bridge pier subjected to vehicle collision," *Shock and Vibration*, vol. 2017, Article ID 7085392, 12 pages, 2017.
- [19] O. D. Larsen, "Ship collision with bridges," *International Association for Bridge and Structural Engineering*, vol. 57, pp. 51-65, 1993.
- [20] S. Iwai and K. Chuang, "On the safety measures between ship and bridge," *Navigation of China*, vol. 2, pp. 153-164, 1986.
- [21] G. Chen, "Three missions to defend against ship hitting a bridge," in *Proceedings of the 6th Annual Conference of Shanghai Association of Senior Scientists and Technicians*, pp. 169-171, Shanghai, China, 2008.
- [22] G. Chen, "New equipment of ship collision with the pier and its mechanism research," *Ship Engineering*, vol. 29, no. 4, pp. 40-43, 2007.
- [23] G. Chen, "The history and new development of the device for preventing ships from collision with bridges-"Three Not Bad" bridge pier anti-collision devices," in *Proceedings of the Mechanics 2000 Academic Conference*, pp. 657-658, Montreal, Canada, May 2000.
- [24] G. Chen and W. Lili, *Ship Hitting a Bridge and its Defences*, China railway Publishing House Co., Ltd., Beijing, China, 2006.
- [25] G. Chen, w. Lili, Y. Liming, and N. Buyou, *Collection of Papers on Flexible Anti-collision Devices for Preventing Ships from Impacting Bridge*, Shanghai Scientific & Technical Publishers, Shanghai, China, 2015.
- [26] H. Jiang, B. Geng, and X.-X. Zhang, "A new fender system for bridge pier protection against vessel collision," *Journal of Vibration and Shock*, vol. 33, no. 17, pp. 154-160, 2014.
- [27] X. Zhou, Z. Hu, and Y. U. Zhao, "Research on anti-collision performance of combined anti-collision box," *Journal of Wuhan University of Technology (Transportation Science & Engineering)*, vol. 41, no. 2, pp. 662-667, 2017.
- [28] C. Shan and Z. Huang, "Collision performance analysis of curved-shaped anti-collision floating box of bridge pier with sandwich structure," *Journal of South China University of Technology*, vol. 47, no. 2, pp. 662-667, 2019.
- [29] G. Chen, "Evaluation of glass fiber composite bridge anti-collision device from energy absorption," *Fiber Reinforced Plastics*, vol. 2014, no. 4, pp. 22-28, 2014.
- [30] Y. Fang, C. Liu, H. Yang, and L. Yang, "Axial behaviour of concrete-filled corrugated steel tubular column embedded with structural steel," *Journal of Constructional Steel Research*, vol. 170, 2020.
- [31] Q. Inaam and A. Upadhyay, "Behavior of corrugated steel I-girder webs subjected to patch loading: parametric study," *Journal of Constructional Steel Research*, vol. 165, 2020.
- [32] V. V. Degtyarev, "Concentrated load distribution in corrugated steel decks: a parametric finite element study," *Engineering Structures*, vol. 206, 2020.
- [33] M.-Z. Wang, Y.-L. Guo, J.-S. Zhu, and X. Yang, "Flexural buckling of axially loaded concrete-infilled double steel corrugated-plate walls with T-section," *Journal of Constructional Steel Research*, vol. 166, 2020.
- [34] J.-S. Zhu, Y.-L. Guo, M.-Z. Wang, X. Yang, and Y. L. Pi, "Seismic performance of concrete-infilled double steel corrugated-plate walls: experimental research," *Engineering Structures*, vol. 215, 2020.
- [35] C. Si, X. Su, E. L. Chen, and Z. Yan, "Comparative study on dynamic response of deck pavement of two kinds of box girder bridges under moving loads," *Shock and Vibration*, vol. 201913 pages, 2019.
- [36] NIKNEJAD, "Experimental study on the energy absorption capability of circular corrugated tubes under lateral loading and axial loading," *Proceedings of the Institution of Mechanical Engineers - Part D: Journal of Automobile Engineering*, vol. 229, no. 13, 2015.
- [37] Q. Zhao, *Optical Mechanics Tutorial*, Higher Education Press, Beijing, China, 1996.
- [38] X. Zhang, H. Hao, and C. Li, "Experimental investigation of the response of precast segmental columns subjected to impact loading," *International Journal of Impact Engineering*, vol. 95, pp. 105-124, 2016.
- [39] Y. Fang, D. Xiaowei, Y. Zhengyue, and H. Jiazhen, "The experiment of in-plane impact based on a two-dimensional high speed camera system," *Journal of Vibration and Shock*, vol. 35, no. 24, pp. 84-87, 2016.

- [40] D.-L. Xiang, J. -L. Rong, X. He, and H Liu, "Dynamics analysis of AL plate subjected to underwater impulsive loads based on 3D DIC," *Acta Armamentarii*, vol. 35, no. 8, pp. 1210–1217, 2014.
- [41] Y.-H. Wang, D. Xi-zuo, Y. Hu, C. Jun, and X. Bing, "Car-pedestrian impact test based on high speed digital image correlation," *Journal of Optoelectronics - Laser*, vol. 28, no. 1, pp. 81–86, 2017.
- [42] R. Clough and P. Joseph, *Dynamics of Structures*, Routledge, Oxford, England, 2006.