Safety Evaluation of a Long-Span Steel Trestle with an Extended Service Term Age in a Coastal Port Based on Identification of Modal Parameters

Hongbiao Liu, and Ying Li

***Abstract*—Combining vibration testing and safety evaluation improves the understanding of structural vibration behavior, aids in the future design of similar structures, and provides key information for the design of remedial measures. This paper investigates the safety of a unique full-scale 40 year old steel trestle structure of an oil wharf based on the identification of modal parameters. This structure is a typical simply-supported through-type parabolic vierendeel steel truss (SSTTPVST) structure with a span of 106m in an extended service term age. Steel trestle vibration responses were measured using state-of-the-art methods, such as ambient vibration survey, initial velocity excitation method, and initial displacement excitation method. The natural frequencies, mode shapes, and damping ratios of the trestles located in land and in the sea were obtained in both the vertical and horizontal lateral directions. Test results showed that the vibration parameters identified by the three excitation methods were almost identical despite the differences in excitation levels between methods. It was also demonstrated that properly planned testing can be performed successfully even in limited conditions, such as low-level excitation. In addition, finite element (FE) modeling of this trestle and model consistency with both experimental results of natural frequencies and mode shapes were described. A mode shape node was found in the first vertical mode shape of this kind of trestle, which was proven in the time history and Fourier spectrum of the trestle vibration response. This result was considerably different than that of normal simply-supported concrete bridges on highways. The safety evaluation of the trestles located in land and in the sea was carried out using the natural frequency changes based on the frequencies obtained in three different years, including the years 2000, 2002, and 2014. The evaluation results indicated that the damage of the trestle located in the sea was more severe than that of the trestle in land, which paralleled with the visual inspection result of the trestle.**

***Index Terms*—modal testing, steel truss structure, trestle, oil wharf, safety assessment.**

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Hongbiao Liu is with Dalian University of Technology, Dalian, 116024 China and Tianjin Research Institute for Water Transport Engineering, Tianjin, 300456 China (corresponding author to provide phone: 86-15510867101; fax: 86-2259812373; e-mail: liuhbhit@hotmail.com).

Ying Li is with Tianjin Research Institute for Water Transport Engineering, Tianjin, 300456 China (e-mail: liuhbtks@163.com).

I. Introduction

THE steel structure bridge has been widely adopted in bridge construction, especially in long-span bridges, large-space structures, and trestles of oil wharfs, due to its various advantages, including high strength, good toughness, short construction period, and good seismic performance. The trestle of an oil wharf has two main functions, including supporting the oil pipeline and auxiliary piping and connecting the wharf to land, which is very important for oil loading, unloading, and circulation. However, many wharfs and adjacent structures in coastal ports age over time. Moreover, many of these structures have been in the extended service state, which threatens the production safety. This paper describes a full-scale 40 year old steel trestle of an oil wharf with an extended service term age in the Dalian port of China as well as the modal testing and safety evaluation of the wharf.

The health state of a trestle structure is directly related to the safety of cargo handling and the risk of marine environment pollution, and the health status of the wharf must be obtained timely to maintain production safety at the port. The wharf is active year-round in the harsh marine environment, making it easy for the material to weaken over time. The steel corrodes and experiences brittle fracture caused by chloride ion erosion, natural aging of the steel, human impact, and natural disasters, such as ship collision, overload operation, storm surge waves, and earthquakes [1-3]. This brings serious challenges to the safety of the trestle structure and its service life. It is crucial to carry out safety detection and assessment for long-span steel trestles with extended service term ages in coastal ports.

The simply-supported through-type parabolic vierendeel steel truss (SSTTPVST) structure is the main type of bridge structure used in offshore oil wharf trestles and railway bridges, because it has a long span, less construction difficulty, good practicability, and it is a reasonable structure to build. It has been used in the steel trestles in the 300,000 tons crude oil wharfs of both Qingdao Port and Dalian Port in China. Obtaining the dynamic properties of trestles can ensure that the stiffness of the trestle meets the structure requirements. Knowing the dynamic properties also allows for the evaluation of the safety status of the trestle, because the dynamic parameter changes can reflect the damage state of the structure [4]. Therefore, carrying out modal testing and obtaining dynamic parameters and parameter changes are

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essential for developing a safety assessment method for long-span steel trestles with extended service term ages in coastal ports. These safety assessments are crucial for ensuring the safety of these trestles.

There has not been a great deal of extensive research regarding the dynamic properties of the SSTTPVST trestle structure or the safety evaluation method for long-span steel trestles with an extended service term age in coastal ports. Dynamic parameters of bridge structures are important reference indexes for evaluating the state of in-service bridges [5]. The shifts of the structural mass, stiffness, and damping can reflect the changes of the health status of the structure. Identifying the changes in modal parameters, such as natural frequency, mode shape, and damping ratio, allows the shifts of structural mass and stiffness caused by damage to be determined, which can be used to evaluate the health status [6-7]. This paper combines field testing and numerical simulation to obtain the modal parameters of this structure in order to perform modal testing and analysis of the SSTTPVST trestle in a large oil wharf in Dalian Port. The safety status of this trestle was evaluated, while its weak vibration direction was estimated, which could provide the testing data support for studying the safety assessment method. This work could be helpful for future designs of similar SSTTPVST trestle structures and their safety inspection evaluations.

II. Description of Test Trestle Structure

The oil wharf in Dalian Port is an offshore engineering structure, which consists of a steel trestle and a crude oil wharf. This wharf was built in 1975 and has been in service for 40 years, which classifies it as a typical wharf structure with an extended service term age in a coastal port. The investigated trestle was built with the typical SSTTPVST structure, which has 9 spans, each span being 106m long. The total length of the trestle is 954m (Fig.1).

Fig 1. Photograph of the trestle

The steel trestle structure of each span is the same, and the effective length and width of each span are 100m and 12m, respectively. Each span is divided into 12 parts (1×5m+10×9m+1×5m), the parabolic depth-span ration is 1/8, the rise of each arch is 12.5m, and the center distance of the two main trusses is 7.6m. The upper and lower chords, web members, and cross girders at the trestle end are made of Q345 steel with a box section, while the lateral bracing beam among the chord members and other cross girders are made of Q235 steel with an I-beam section. The beams are welded with gusset plates by two-side welding lines, while the gaps between the end of the beams and gusset plates are filled with paint. The windward area of the main truss of each span is 200m^2 in the horizontal direction. The oil pipe load is transferred to cross girders through the pipe supports, and the lower cross girders are designed by the principle of equal load.

The steel trestle of each span is a simply-supported structure with four supports, including two fixed supports and two sliding supports, which are set at the ends of the lower chord members of the two main trusses, respectively (Fig. 2). Each support is designed to carry 250 tons, has shockproof plates, and is fixed in the trestle pier by anchoring reinforcement plates. Each main truss, which is divided into 12 assembly units, is welded in a factory and has a 200mm pre-arch when lying flat. Each member of the main truss and other rods were manufactured in a factory and shipped for assembly.

(a) fixed support (b) sliding support

Fig 2. Photographs of trestle supports

III. Pre-test Finite Element Modeling

Modal testing of an as-built structure requires the development of a detailed finite element (FE) model before testing [8]. This first insight into dynamic behavior of the trestle helps test planning and preparation.

A 3D FE model for the trestle of the oil wharf was developed (Fig. 3) using the ABAQUS FE software. The aim was to construct a detailed model that would simulate the dynamic behavior of the structure based on the limited technical data available and best engineering judgement. The key modeling assumptions were as follows:

(1) The main steel box section chords, cross girders, and lateral bracing beams with I-beam sections were modeled using 3D B31 elements and assuming isotropic properties. These elements are capable of transferring both in-plane and out-of-plane loads. The local parts at the joints of the lower and upper chords, where the supports were located, were modeled using S4 elements assuming isotropic properties.

(2) Oil and oil pipes as well as water and drainage pipes were modeled as lumped masses along the connecting points of the lines, at which the pipes were supported on the cross girders. The mass was calculated based on the actual usage state of the pipes. It was assumed that liquid filled the volume of the pipes when performing the modal testing.

(3) Supports at one end of the main lower chords were modeled as fixed, while those at another end were modeled as pinned with a possibility to slide freely in the trestle longitudinal direction (Fig. 3).

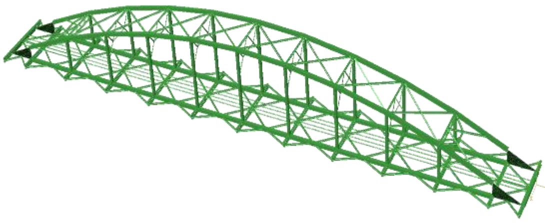
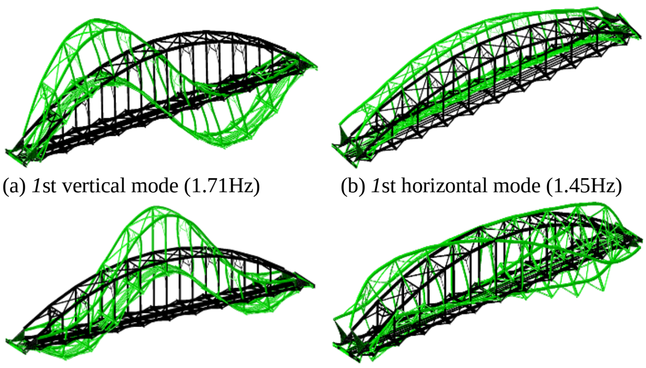


Fig 3. Finite element model of the trestle

The four lowest modes of vibration, including the 1st vertical mode, 1st horizontal mode, 2nd vertical mode, and 1st torsional mode, were calculated using this model (Fig. 4). The calculated frequency values are summarized in Table I.

TABLE I
NATURAL FREQUENCIES CALCULATED IN PRE-TEST FE ANALYSIS

Name	Direction	Calculated value (Hz)	Remark
Modal of trestle	Vertical	1.71	1st mode
	Horizontal	1.45	1st mode
	Vertical	2.46	2st mode
	Torsional	2.74	1st mode



(a) *1*st vertical mode (1.71Hz) (b) *1*st horizontal mode (1.45Hz)

(c) *2*nd vertical mode (2.46Hz) (d) *1*st torsional mode (2.74Hz)

Fig 4. Mode shapes of the trestle

It is demonstrated in Fig4 that the vibration mode shapes of this trestle are different from that of normal simply-supported concrete girder bridges. The first vertical mode shape of this trestle is anti-symmetric, as it has a mode shape node, which is similar to the second vertical mode shape of normal simply-supported concrete girder bridges. The second vertical mode shape of this trestle has two mode shape nodes and is symmetric, which is similar to the third vertical mode shape of normal simply-supported concrete girder bridges. Nevertheless, the first horizontal mode shape of this trestle is the same as that of normal simply-supported girder bridges. The first torsional natural frequency of this trestle is larger than its second vertical vibration frequency, which is different from that of normal simply-supported concrete girder bridges, whose first torsional frequency is generally between the vertical frequencies of the first and second nodes. These points are special in terms of dynamic properties of the SSTTPVST structure. The modal calculation results using the FE model can provide valuable insight into the vibration behavior and can aid in the modal test planning of this trestle.

IV. MODAL TESTING

A. *Test Methodology*

The primary aim of the modal testing was to identify the lowest modes of vibration in both the vertical and horizontal lateral directions. The initial velocity excitation method, initial displacement excitation method, and ambient vibration survey [9-10] were all employed, where only the trestle responses were measured. The second aim was to compare results and to check consistency.

The initial velocity excitation method, initial displacement excitation method, and ambient vibration survey are all methodologies based on response-only measurements. The initial velocity excitation method and initial displacement excitation method use manual labor or ancillary equipment to make structural vibration. The initial velocity excitation method uses an external force, such as a heel-drop, to create and initial vibration, whereas the initial displacement excitation method pushes or pulls the structure to create an initial displacement and then releases it to make the structure vibrate. The ambient vibration survey uses environmental excitation, such as ground vibration and wind, to measure structural vibration. The modal properties can then be identified by processing the vibration data obtained. A comparison was done among results after these three testing methods were performed. The sensors setup and field testing are shown in Fig.5. In this test, the trestle was impacted in the vertical direction by the weight of a person jumping. This person then stood still during data collection after the impact. Meanwhile, the trestle in land was impacted in the horizontal lateral direction by people pushing it to cause a displacement, followed by immediate release for data capture. The vibration data from three accelerometer channels were digitized and further processed in situ using a Diagnostic Instruments INV3020 portable digital spectrum analyzer.

Fig 5. Transducers and test setup in the field

Based on the structural damped free vibration of the structure impacted by the initial velocity excitation method and initial displacement excitation method, the modal damping ratio can be calculated according to the following equation:

$$\xi = \frac{1}{2\pi n} \ln \frac{y_k}{y_{k+n}} \tag{1}$$

where y_k and y_{k+n} are the amplitudes of structural damped free vibration and n represents the amount of periods between them.

When conducting the modal testing on the trestle, the frequency sample was set to 51.2Hz, and the sampling length was set to 30 seconds. When performing the ambient survey on the trestle, multi-sampling (30 times) was conducted at each measurement point, and data was then averaged to reduce the influence of external noise on test results [9-10]. The transducer set-up was divided into a horizontal layout and a vertical layout. The accelerometers were set at the measurement points in the lower chords of the trestle when performing the vertical measurements. After testing, the direction of sensors was shifted to perform the horizontal measurements.

All tests required the trestle to be empty, which meant it had to be closed to pedestrians and vehicles during measurements. Due to the importance of this oil wharf and the demand for wharf production, the tests could only be conducted during the night immediately after the staff was released from work. The tests were scheduled to last up to six hours starting at 5:00pm during two nights in December 2014.

B. Testing Instrumentation and Layout

Testing was conducted at three measurement points in each span of trestle (Fig. 6) based on the mode shapes identified in the FE model (Fig.4) and the fact that there were insufficient accelerometers available for measurements because of the long distance. These measurement points were chosen to avoid problems with spatial aliasing of mode shapes [11] and to enable the identification of the lowest few modes of vibration presented in Fig. 4. Three accelerometers were set to the three measurement points, CH1, CH2, and CH3, respectively. The distances between CH1 and CH2 and between CH2 and CH3 were both 18m. The test was first conducted to identify the vertical modes and then repeated for the horizontal lateral modes.

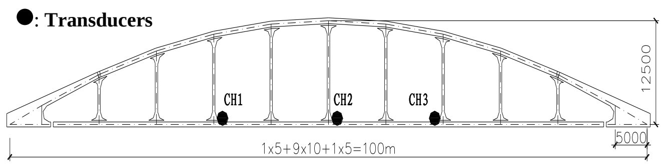


Fig 6. Transducer setup

Modal testing instrumentation mainly consists of the accelerometers and the data collector. After the structure was impacted by one of the three aforementioned excitation methods, the structural vibration was measured by accelerometers attached to the structure surface at the three measurement points. The same type of transducer was used for structural response measurements. Because of the low vibration frequency of the trestle and the lack of an AC power source, all transducers used were INV9828 piezoelectric accelerometers with LEPE circuits, having a nominal sensitivity of 500mV/g and a band width of 0.2~2.5kHz. These accelerometers are equipped for low frequency measurements down to less than 1Hz, making them suitable for measurements in long-span bridges, high-rise buildings, etc.

Test point 2 (CH2), located at the middle of the main span (Fig. 6), was chosen as an excitation point for both directions. Both the vertical and horizontal response measurements were measured at all three points.

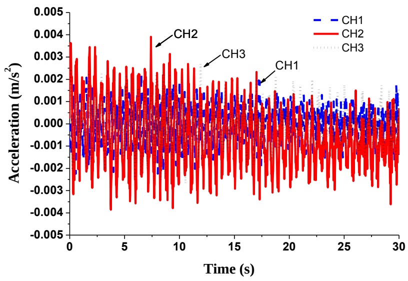
The vibration signal is generally weak when performing structural modal testing *in situ*. Therefore, a 16-channel portable data acquisition and dynamic signal analyzer (INV3020) was used to acquire the time domain acceleration data and to process them into a set of Fourier spectrums of response points. The device had the following parameters: precision, 24Bit; measurement range, ±10.0V; maximum sampling rate, 102.4kHz/channel; function, anti-aliasing filter with attenuation gradient = -300dB/oct. This equipment is highly suitable for structural vibration measurements *in situ*.

C. Data Acquisition and Analysis

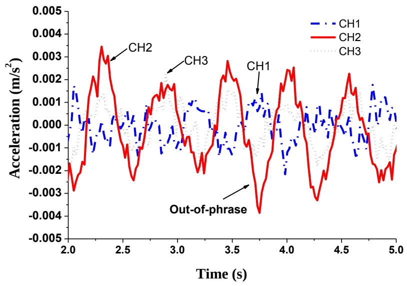
The trestle has 9 continuous spans, 5 of which are located in the sea, 3 of which are located in land, and one of which crosses the sea-land demarcation. Even though the structure form and size of each span are identical, the corrosion level of steel varies due to the difference between land environment and marine environment. One span of land trestle and one span of sea trestle were selected for modal testing, and the results were then compared.

Modal testing was conducted for the two spans of trestle with the initial velocity excitation method, initial displacement excitation method, and ambient vibration survey in order to compare results obtained through the different excitation methods. Excitation methods were assigned to the various trestle types based on actual conditions *in situ*. The vertical vibration data of the span of trestle in land was acquired by the initial velocity excitation method, and the horizontal vibration measurements were done by the initial displacement excitation method; the vertical and horizontal vibration measurements of the span of trestle in the sea were all conducted by the initial velocity excitation method. Ambient vibration survey was used to perform the modal testing of the two spans of trestle in all directions in order to compare results and check consistency.

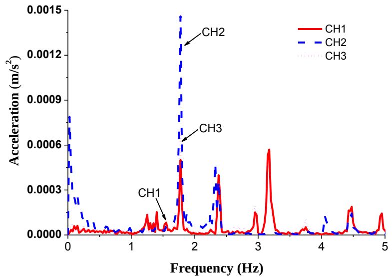
Firstly, the modal testing of the span of trestle in land was conducted using the three excitation methods above, and the structural time history of vibration under different excitation methods was obtained. The Fourier spectrums were obtained by the fast Fourier transform (FFT) method (Figs. 7-10). The first vertical and horizontal natural frequencies and damping ratios of the span of trestle in land were identified based on data processing and analysis (Table II). The structure damping ratios were calculated according to Eq. 1 based on the time history of damped-free vibration obtained by the initial velocity excitation method and initial displacement excitation method.



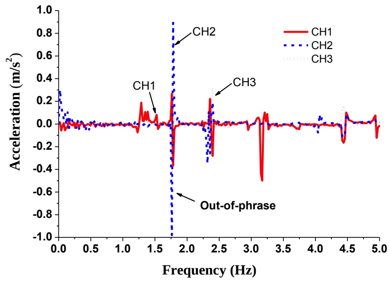
(a) Time history



(b) Zoom in

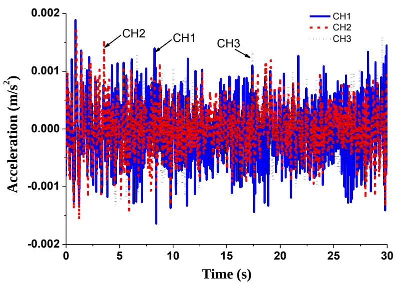


(c) Fourier magnitude spectrum

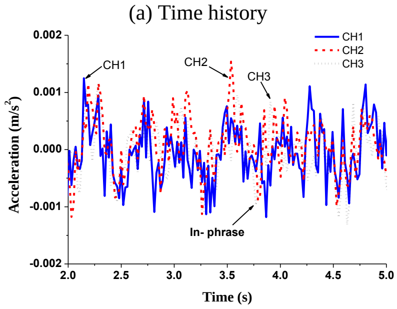


(d) Fourier real part spectrum

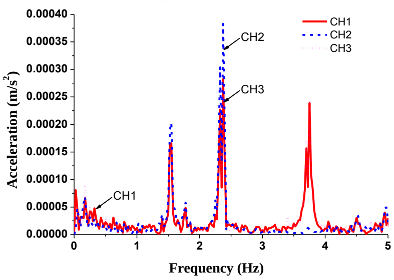
Fig 7. Time history and its Fourier spectrum of vibration in vertical direction of the trestle in land (ambient measurement)



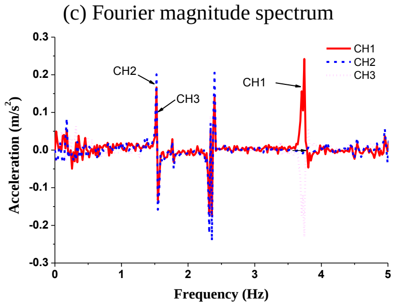
(a) Time history



(b) Zoom in

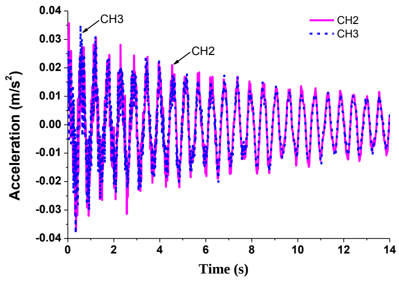


(c) Fourier magnitude spectrum

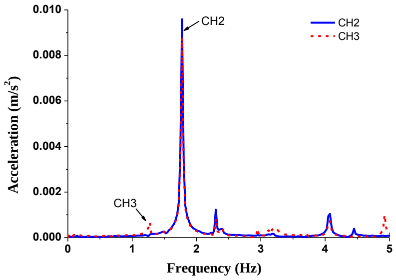


(d) Fourier real part

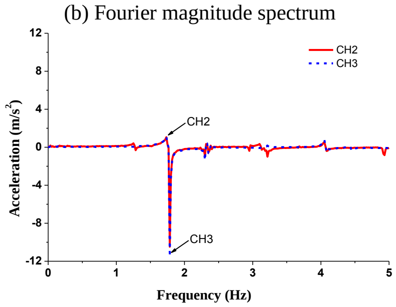
Fig 8. Time history and its Fourier spectrum of vibration in horizontal direction of the trestle in land (ambient measurement)



(a) Time history

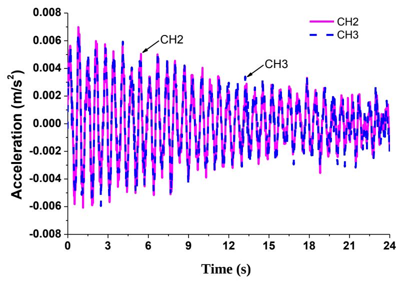


(b) Fourier magnitude spectrum

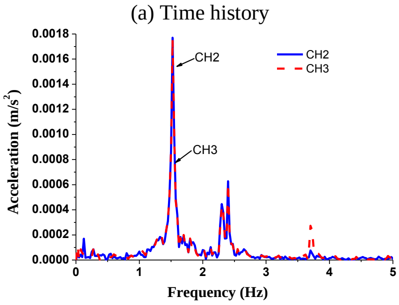


(c) Fourier real part spectrum

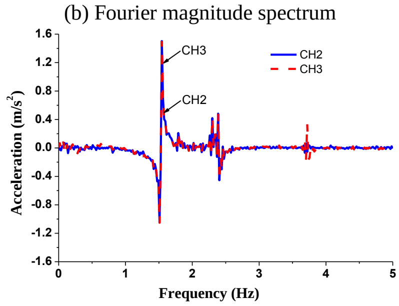
Fig 9. Time history and its Fourier spectrum of vibration in vertical direction of the trestle in land (initial velocity excitation method)



(a) Time history



(b) Fourier magnitude spectrum



(c) Fourier real part spectrum

Fig 10. Time history and its Fourier spectrum of vibration in horizontal direction of the trestle in land (initial displacement excitation method)

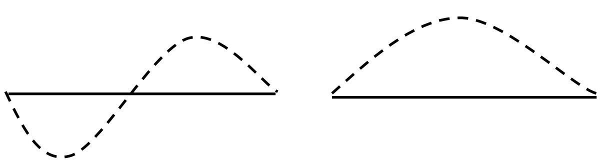
Results presented in Table II clearly show that the first natural frequencies in all directions of the trestle in land obtained by the ambient vibration survey are almost identical with those identified with both the initial velocity excitation method and the initial displacement excitation method. Therefore, the three excitation methods can be selected freely when performing modal testing of the structure based on the response-only measurements.

TABLE II
TEST RESULTS OF MODAL PARAMETERS OF THE TRESTLE IN LAND

Name	Excitation method	Direction	1st natural frequency(Hz)	Damping ratio
Trestle in land	ambient	Vertical	1.78	/
	ambient	Horizontal	1.55	/
	initial velocity	Vertical	1.78	0.012
	initial displacement	Horizontal	1.53	0.007

The first damping ratios of the trestle in land in vertical and horizontal directions were all approximately 0.01, which are similar with those from the modal testing of other types of structures [11]. However, these ratios are significantly different than the damping ratio of 0.04 commonly used for the seismic response calculation of steel structures. The modal testing results can provide reference parameters for the time history response analysis of this kind of trestle.

It is shown in Figs.7(b) and 7(d) that the vibration direction of test point CH1 is opposite to that of points CH2 and CH3, with a phase difference of 180 °. Thus, there is a mode shape node at least in the first vertical mode shape, whose shape looks like that presented in Fig.11 (a). This shape agrees with the calculated result from the pre-test FE model analysis (Fig.4 (a)). Contrastingly, the horizontal vibrations of test points CH1 to CH3 are consistent with each other (Fig.8(b) and (d)), so the first mode shape in horizontal vibrations looks like that presented in Fig.11(b). This result also agrees with the pre-test FE model modal calculation results. Based on the comparison between the test results (Table II and Fig.11) and calculation results with the FE model (Table I and Fig.4), it can be concluded that the preliminary analysis performed by the FE model is accurate enough according to the experimental dynamic identification results.



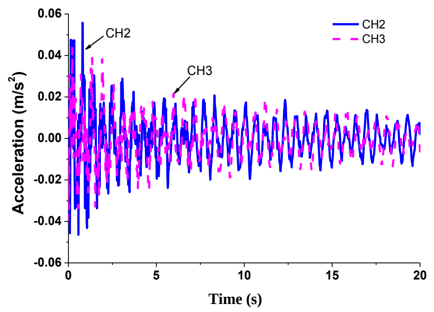
(a) Vertical (b) Horizontal

Fig 11. First mode shape of the trestle

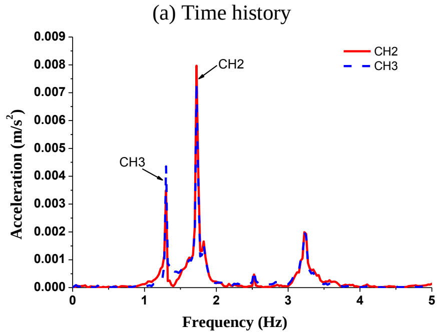
Next, the modal testing of the span of trestle in the sea was conducted with the same excitation methods used for the trestle in land. The time history of trestle vibration was acquired as well as its Fourier spectrum (Figs.12 and 13). The first natural frequencies and damping ratios were obtained by data processing (Table III). Comparing results with modal testing results of the trestle in land (Table II) shows that the first vertical natural frequencies of the trestle in land and the trestle in the sea are almost identical, which suggests that their vertical stiffness is the same and that the marine environment does not weaken the vertical stiffness through serious corrosion. The trestle may be protected by the use of fluorocarbon paint and annual maintenance. However, the horizontal natural frequency of the trestle in the sea is slightly less than that of the trestle in land, which shows that the horizontal lateral stiffness of the trestle in the sea was weakened. This is resultant of corrosion damage, making reinforcement measures against corrosion necessary for the trestle in the sea.

TABLE III
TEST RESULTS OF MODAL PARAMETERS OF THE TRESTLE IN THE SEA

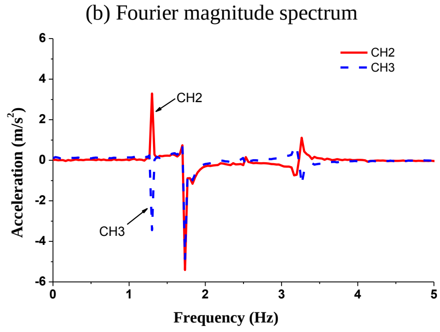
Name	Excitation method	Direction	1st natural frequency(Hz)	Damping ratio
Trestle in sea	ambient	Vertical	/	/
	ambient	Horizontal	1.38	/
	initial velocity	Vertical	1.73	/
	initial velocity	Horizontal	1.38	0.03



(a) Time history

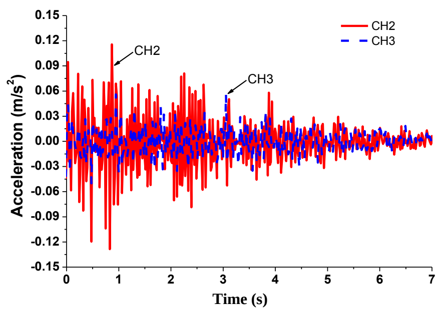


(b) Fourier magnitude spectrum

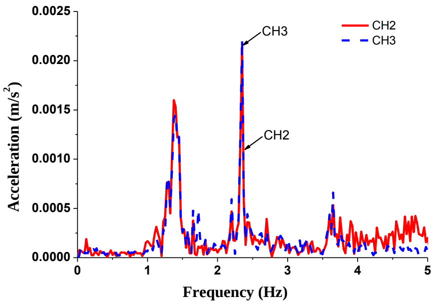


(c) Fourier real part spectrum

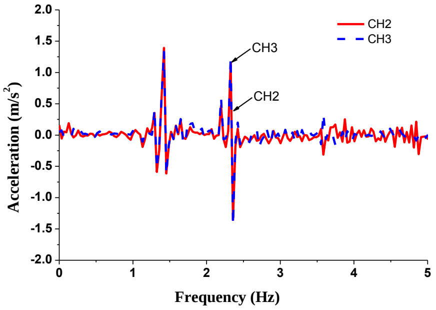
Fig 12. Time history and its Fourier spectrum of vibration in vertical direction of the trestle in the sea (initial velocity excitation method)



(a) Time history



(b) Fourier magnitude spectrum



(c) Fourier real part spectrum

Fig 13. Time history and its Fourier spectrum of vibration in horizontal direction of the trestle in the sea (initial velocity excitation method)

V. Safety Evaluation of the Trestle with the Identified Frequency Changes

Studies on structural damage detection methods based on dynamic property changes began in the 1970s [12]. Initially, the natural frequency changes were used to identify structural damage [4, 13]. Several damage detection methods then began to appear, such as the modal curvature method, strain modal method, DLV method, and music tone law method, all of which fall under the dynamic fingerprint identification method [14-15]. These methods can be used for structure safety assessment [16-19]. This work conducted the safety evaluation of the investigated trestle by combining natural frequency changes and visual inspection.

In order to satisfy the project demand, the modal testing of this trestle of an oil wharf in Dalian Port of China was performed continuously over many years. The modal parameters were obtained in different years, including the years 2000, 2002, and 2014, and the natural frequencies of this trestle were measured (Table IV). The external conditions were nearly identical during each modal test in the different years, as traffic was prohibited, the oil pipe lines were off, wind was minimal, and the season was consistent to maintain temperatures during testing.

TABLE IV
COMPARISON OF TRESTLE NATURAL FREQUENCIES

Name	Direction	Natural frequency(Hz)			Remark
		2014	2002	2000	
Trestle in land	Vertical	1.78	1.76	1.77	Mode 1
	Horizontal	1.53	1.48	1.50	Mode 1
Trestle in sea	Vertical	1.73	1.76	1.90	Mode 1
	Horizontal	1.38	1.46	1.47	Mode 1

Results show that the first natural frequencies of the trestle in land obtained in 2014 have no obvious mutation compared with data acquired in 2002 and 2000, and all results are similar. Although the natural frequencies of the trestle in the sea decrease gradually over time, the variation is little. This comparison reveals that there is little damage in the main components of the trestle in land, and it is safe.

Nevertheless, some slight damage was observed in local components of the trestle in the sea. However, it still can be judged as safe based on the fact that the change in natural frequencies was only slight. The visual inspection data was also used to identify the damage location and damage level in order to verify the conclusion above. This combination of results gives a comprehensive evaluation conclusion for the trestle in the sea. The visual inspection of the trestle was conducted, and it was found that there were more damages on the trestle in the sea than there were on the trestle in land (Fig.14). This result agrees with the evaluation conclusion. This result is also shown in the actual section thickness value of the main components of the trestle (Table V), which was measured during the inspection process. It is clear that the components' section thickness of the trestle in the sea is thinner than that of the trestle in land, due to the steel rusting caused by the marine environment.

(a) Damage on upper chord

(b) Damage on cross girders

Fig 14. Rusting damage of the trestle in the sea

TABLE V
ACTUAL SECTION THICKNESS MEASURED OF TRESTLE COMPONENTS

Component	Location	Measured thickness(mm)		Design(mm)
		Trestle in land	Trestle in sea	
Upper chord	Flange	15.6	15.2	16.0
	Web	13.7	13.4	14.0
Lower chord	Flange	15.6	15.3	16.0
	Web	13.6	13.2	14.0
Web member	Flange	13.5	13.1	14.0
	Web	9.7	9.3	10.0
Cross girder	Flange	15.5	15.2	16.0
	Web	13.6	13.2	14.0

Mechanical response evaluation was also conducted in order to evaluate the safety of the trestle in the sea further. This calculation was done with the FE model under actual loads, which included dead load, oil pipe load, crowd load, and mechanical load. The actual section thickness measured of each component was adopted in the FE model to calculate the actual load response of the trestle. The stress response of the trestle in the sea was obtained using the static calculation method. The stress contour of this trestle is shown in Fig.15.

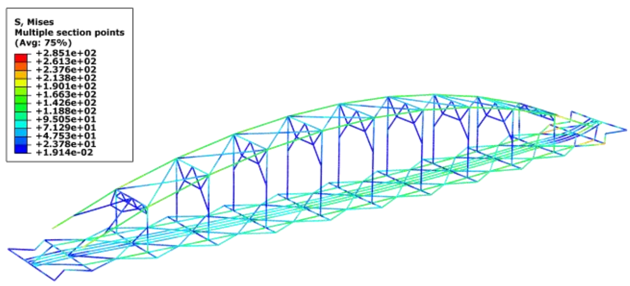


Fig 15. Stress contour of the trestle in the sea

The maximum Mises stress of each component was acquired according to data processing (Table VI). The safety state of this trestle was judged based on the comparison between the maximum Mises stress of each component and its allowable stress. A trestle is deemed safe if the maximum stress of each component is less than the allowable stress.

TABLE VI
THE CALCULATED STRESS RESULTS OF TRESTLE COMPONENTS

Component	Maximum stress σ_{max} (MPa)	Allowable stress $[\sigma]$(MPa)	Judgment
Upper chord	230.2	295.0	Pass
Lower chord	243.2	295.0	Pass
Web member	239.2	295.0	Pass
Cross girder	285.1	295.0	Pass

The maximum Mises stress of each component was less than the allowable stress. Thus, it can be concluded that the bearing capacity of each component satisfies the user request. Meanwhile, it was found that the steel rusting grade was low and that the welding seam was qualified based on the inspection of the steel rusting grade and welding seam quality. The trestle located in the sea can be recognized as safe, but the parts experiencing rust should be repaired. The trestle in land can also be judged as safe, because the steel rusting grade of the trestle in land is lower than that of the trestle in the sea. This conclusion is consistent with the evaluation result based on frequency changes.

The high level of safety associated with this trestle has to do with the fluorocarbon paint used and the annual steel anti-rust measurements conducted by the administrative department. Nevertheless, the fluorocarbon paint is very expensive, and the cost of trestle maintenance is high. This elicits a necessity for further discussion of the steel structure used in the trestles of oil wharfs in coastal ports where the marine environment can easily cause the rusting of steel.

VI. CONCLUSION

Modal testing was conducted to identify the dynamic properties of a long-span steel trestle with an extended service term age in a coastal port. This testing successfully identified the lowest modes of vibration in both the vertical and horizontal lateral directions. The trestle of the oil wharf was a typical SSTTPVST structure, which has been used widely in as-built large-scale oil wharfs of China. The modal testing was done using state-of-the-art methods, such as the ambient vibration survey, initial velocity excitation method, and initial displacement excitation method, where only the steel trestle responses were measured. The testing methods were efficient and sufficiently accurate, even though the excitation level of the methods varied. The results acquired by the initial velocity excitation method and initial displacement excitation method compared well with those obtained in the ambient vibration survey conducted in the vertical and horizontal lateral directions. Therefore, the three excitation methods can be selected freely based on the testing conditions in situ when performing the modal testing of structures based on the response-only measurements.

A detailed pre-test FE model, which was developed based on the design data available and best engineering judgement, was crucial for identifying the dynamic properties of this kind of trestle. Combining the FE model calculation and modal testing, the modal parameters were identified for the trestles located in land and in the sea, whose environmental differences elicited slightly dissimilar results. The first vertical mode shape, with a low natural frequency of about 1.70Hz, had a mode shape node, which was different from that of the normal simply-supported concrete girder bridge, and the trestle had a very low damping ratio of about 1.0% associated with the first vertical mode of vibration. The first horizontal natural frequency of 1.40Hz, together with the maximum damping ratio of 3% for the horizontal mode, was also very low. The low damping identified by the modal testing significantly varies from the damping ratio of 0.04 that is commonly used for the seismic response calculation of steel structures. The modal testing results can provide reference parameters for the dynamic time history response analysis of this kind of trestle in oil wharfs.

Finally, the safety evaluation of the trestles in land and in the sea was conducted based on the natural frequency changes of the trestle obtained by the modal testing in three different years. The calculation results showed that the stress of each main component did not exceed the allowable stress, suggesting that all components of the trestle can be judged as safe. This conclusion was verified by the load response result from the FE model calculation that used both the actual section thickness measured and actual loads. However, it could be concluded that there was more slight damage on the trestle in the sea than the trestle in land, which would agree with the visual inspection result. This result also suggests that the steel structure that services in the marine environment is more likely to rust, which would sharply increase its anti-rust maintenance costs. These results imply that further discussion is needed regarding steel structures used in the trestles of oil wharfs in coastal ports.

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REFERENCES

[1] Shafieezadeh A, DesRoches R, Rix G J, et al, "Seismic performance of pile-supported wharf structures considering soil-structure interaction in liquefied soil," Earthquake Spectra, vol.28, no.2, pp729-757, 2012

[2] Wall, Henrik, and Lars Wadsö, "Corrosion rate measurements in steel sheet pile walls in a marine environment," Marine Structures, vol.33, pp21-32, 2013

[3] Chin, King H., Daniel W. Mageau, and Scott T. Peterson, "Comparison of Panama wharf performance using numerical analysis and limit equilibrium methods," Geotechnical Earthquake Engineering and Soil Dynamics IV, ASCE, pp1-10, 2008

[4] Salawu, O. S, "Detection of structural damage through changes in frequency: a review," Engineering structures, vol.19, no.9, pp718-723, 1997

[5] Maeck, Johan, and Guido De Roeck, "Damage assessment using vibration analysis on the Z24-bridge," Mechanical Systems and Signal Processing, vol.17, no.1, pp133-142, 2003

[6] Brownjohn, James Mark William, et al, "Assessment of highway bridge upgrading by dynamic testing and finite-element model updating," Journal of Bridge Engineering, vol.8, no.3, pp162-172, 2003

[7] Siddique, A. B., B. F. Sparling, and L. D. Wegner, "Assessment of vibration-based damage detection for an integral abutment bridge," Canadian Journal of Civil Engineering, vol.34, no.3, pp438-452, 2007

[8] Pavic A and P. Reynolds, "Modal testing and dynamic FE model correlation and updating of a prototype high-strength concrete floor," Cement and Concrete Composites, vol.25, no.7, pp787-799, 2003

[9] Rubin S, "Ambient vibration survey of offshore platform," Journal of the Engineering Mechanics Division, vol.106, no.3, pp. 425-441, 1980
[10] Benedettini, Francesco, and Carmelo Gentile, "Operational modal testing and FE model tuning of a cable-stayed bridge," Engineering Structures, vol.33, no.6, pp2063-2073, 2011
[11] Zivanovic Stana, A. Pavic, and P. Reynolds, "Modal testing and FE model tuning of a lively footbridge structure," Engineering Structures, vol.28, no.6, pp857-868, 2006
[12] Vandiver JK, "Detection of structural failure on fixed platform by measurement of dynamic response," Journal of Petroleum Technology, vol.29, no.5, pp305-310, 1977
[13] Zhao J, and John T. DeWolf, "Sensitivity study for vibrational parameters used in damage detection," Journal of structural engineering, vol.125, no.4, pp410-416, 1999
[14] Liu H B, Guo X, and Li G D, "Musical Tone Law Method and its application in structural damage detection," Journal of Vibration and Shock, vol.30, no.10, pp254-259, 2010
[15] Alvandia A, and Cremona C, "Assessment of vibration-based damage identification techniques," Journal of Sound and Vibration, vol.292, pp179-202, 2006
[16] Boroschek, Rubén Luis, Hugo Baesler and Carlos Vega, "Experimental evaluation of the dynamic properties of a wharf structure," Engineering Structures, vol.33, no.2, pp344-356, 2011
[17] Aktan A E, Lee K L, et al. "Modal testing for structural identification and condition assessment of constructed facilities," Proceedings of the 12th International Modal Analysis, vol.2251, pp462-468, 1994
[18] Dong L, Jingxian T, Chuang D, et al. "Full Scale Experimental Evaluation for Cable Dampers," Engineering Letters, vol.22, no.2, pp47-52, 2014
[19] Chen Z, Zhu Y, Di Y, et al. "Optimized Self-adaptive Fault Tolerance Strategy in Simulation System based on Virtualization Technology," IAENG International Journal of Computer Science, vol.42, no.4, pp305-312, 2015

Hongbiao Liu was born in February 1981 and received his Ph.D. in Structural Engineering from the Institute of Engineering Mechanics, China Earthquake Administration in 2012. He has been an Assistant Professor of structural engineering at Tianjin Research Institute for Water Transport Engineering of China since 2014, where he currently studies the assessment theory of long-span bridges.

Hongbiao worked in the Tianjin Research Institute for Water Transport Engineering of China from 2012-2015, where he conducted research mainly on visual inspection technology and assessment methods of hydraulic structural engineering, including long-span bridges in coastal ports. He has published more than 20 articles in several international journals and is currently paying more attention to research regarding the health monitoring technology of costal wharfs and evaluation methods of long-span steel bridges in costal ports.