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Finite Element and Experimental Analysis and Evaluation of Static and Dynamic Responses of Oblique Pre-stressed Concrete Box Girder Bridge

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Abstract: Hashuang bridge is type of prestressed concrete box girder oblique bridge and it is located in Harbin City within Heilongjiang province in the east north of China. The objectives of this study are to investigate the appearance of the bridge structure and identify all the damages in the bridge structural members and to evaluate the structural performance of the bridge structure under dead and live loads. Finite element analysis is used to analyze the static designed internal forces and dynamic responses by adopting SAP200 software Ver. 14.2.0. Static and dynamic load test are adopted to evaluate the structural performance of the bridge structure. The results of field investigation process of the bridge appearance show that the bridge suffers from serious damages. The web of box girder of the second span near pier No.2 (in the quarter of middle span at 39m on the bridge length) suffers from serious shear cracks. The state of abutments, piers and sidewalks is good, but the bearing, drainage holes, steel rail and expansion joints are not good and they suffer from much damage. The steel rail is corroded and the expansion joint loses the material which fills the joint. There are many dusts and debris is collected on the bridge deck in the location near sidewalk. The analysis results of finite element and load tests show that there are high tensile stresses in the quarter of middle span at distance 39 m of the bridge length and the state of the bridge structure is not good and the main problem of the bridge structure in the original design of prestressed tendons. Therefore, this study recommends for repairing and strengthening the bridge structure to increase the stiffness and strength and to improve the bearing capacity of the bridge structural members to increase the service live of the bridge structure.

Keywords: Box girder, dynamic, stress, deflection, hashuang bridge, static

INTRODUCTION

The prestressed concrete systems can be defined as the preloading of a concrete structure before the application of the service loads to improve the structural performance in specific ways and it is a form of concrete in which internal stresses are introduced by means of high strength pre-strained reinforcement. (Lian, 2008; Arthur, 1987; PCI, 1968)

Prestressed concrete box-girder bridges have been widely used as fiscal and visual solutions for the over-crossings, under-crossings of deep valleys to which relatively long spans are required. The most previous researches on box-girder bridges had been conducted by using the finite element method. Prestressed concrete box girder bridge is used in many countries, but they have a crucial limitation compared to steel girders in that a single span length cannot be extended over 50 m due to its relatively heavy self-weight. (Choi *et al*., 2002; Meyer and Scordelis, 1971; Kwang *et al*., 2010)

The purposes of damages investigation of the bridge components are to sure whether a bridge structure is in safe state or not, identify any maintenance, repair and strengthening which that need to be done, provide a basis of planning for funding of any required maintenance and strengthening and provide information to designers and construction engineers on those features which need maintenance. Depending on its conditions, a bridge structure is inspected every two or more years. The inspection process is also used as a tool to identify the maintenance work required by several bridges. Ensuring safety of the general public consists of identifying those bridges that have an improper probability of failure. (Robert *et al*., 2005), Washington State Department of Transportation, 2010; Joao and Jorge, 2009; Ali and Wang, 2011a)

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The main purposes of experimental and theoretical analysis of the bridge structure are to check normal service stage, fatigue and ultimate loads; development of theoretical models to calculate the performance of the bridge structural members; and verifying the analytical results by comparing them with the obtained results from experimental tests. Field load tests of the bridges are an important method to evaluate the structural performance of the bridge structure. They make it possible to compare the theoretical assumptions with the actual behavior of the bridge subjected to the test loads. There are two types of load tests, static load test and dynamic load test. (Aktan *et al*., 1992; Jiamei *et al*., 2011; James *et al*., 2006; Ali and Wang, 2011b)

Load tests of bridges in situ are an important procedure for checking the quality of structures. During a static load test, it is necessary to measure the vertical deflections, stresses, strains and bending moment at the points where the maximum effects are expected (in the middle of spans, in the quarter of span). Dynamic load tests are normally applied only after the static load tests were performed and behaved structure within acceptable limits. When the bridges are subjected to dynamic vehicle traffic loads, the bridge will be subjected to vibration state. A moving vehicle on the bridge generates deflections and stresses that are generally greater than those caused by the same vehicle loads applied statically (Fry and Pirner, 2001; Gheorghiţa, 2009; Senthilvasan *et al*., 2002; Ali and Wang, 2011c).

The main objectives of this study are to investigate the appearance of the bridge structure and identify all the damages in the bridge structural members and to evaluate the structural performance of the bridge structure under dead and live loads.

DESCRIPTION OF THE BRIDGE STRUCTURE

Hashuang bridge is located in Harbin City within Heilongjiang province in the east north of China. This bridge is type of pre-stressed concrete box girder oblique bridge. The total length of the bridge is 95.84 m and has total width is 17m, including two box girders. The width of box girder web is varying from 35cm to 70 cm along the length of the bridge. The arrangement of spans is 28m+40m+28m. The transversal arrangement of the deck is 14.0 m carriageway and 2×1.5 m sidewalk and the deck which is paved by the 8cm waterproof concrete and 8 cm asphalted concrete pavement. The construction process of this bridge adopts the method of cast-in-place span-by-span method (Ali and Wang, 2011a). Figure 1 shows the layout of box girders.

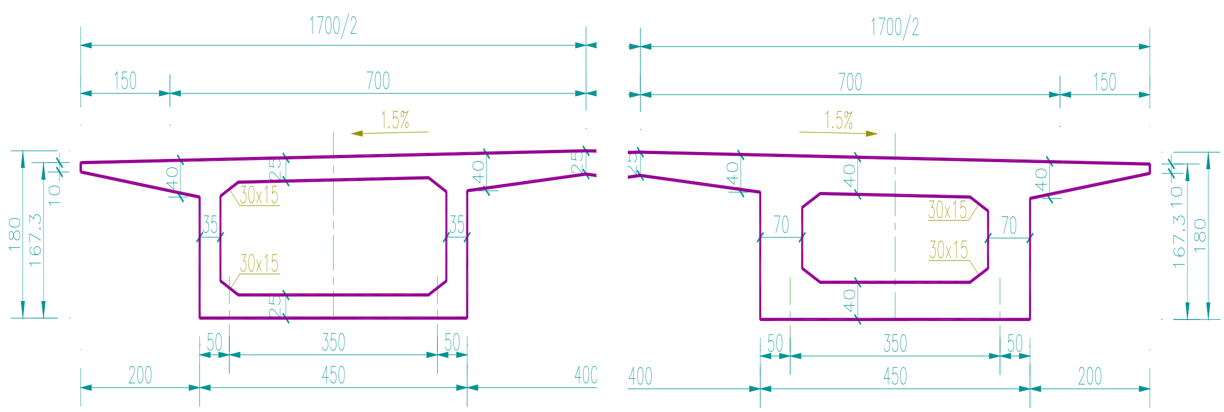


Fig. 1: The layout of transverse section of the bridge; (a) Half section of mid-span box girder, (b) Half section of pier box girder (dimension in cm)

Fig. 2: The cracks in the box girders; (a) outside of box girder, (b) inside of box girder

FIELD INVESTIGATION OF THE BRIDGE DAMAGES

Field investigation process is done on the structural members of the bridge structure such as all spans of outside and inside of box girders, piers, abutments, bearings, sidewalks and steel rail. The results of investigation process show that the web of box girder of the second span near pier No.2 (in the quarter of middle span at 39 m on the bridge length) suffers from serious shear cracks. The distance between cracked area and the mid-pier No. 2 is about 10.5 m. These cracks extend from the top to lower flange of box girder. There are two cracks incline 45° to the mid-span direction with widths are 0.5 to 2.0 mm and the widest cracks are found in the middle of web of box girder. Both of the outside web and inside web of box girders have the same crack position. The cracks degree of the box girder's outside web is more serious than the inside web. There are six transverse bending cracks on the bottom of box girder around quartile of middle span. The spacing between these cracks range from 20 cm to 30cm and the width is 0.35 mm. In the span No. 3 near the pier, the web of box girder appears 12 diagonal cracks have width range from 0.1 mm to 0.12 mm. Figure 2 shows the cracks in the box girders. From this figure, it can be noted that the state of the bridge structure is not good because there are serious cracks have large width.

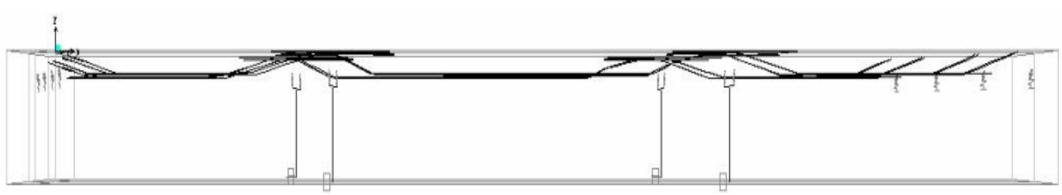
The investigation process of other parts of the bridge structure shows that the state of abutments, piers and sidewalks is good, but the bearing, drainage holes, steel rail and expansion joints are not good and they suffer from much damage. The steel rail is corroded and the expansion joint loses the material which fills the joint. There are many dusts and debris is collected on the bridge deck in the location near sidewalk.

FINITE ELEMENT ANALYSIS OF STATIC DESIGNED INTERNAL FORCES

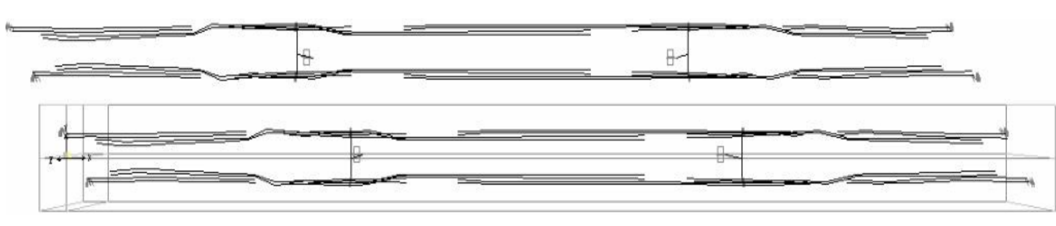
According to Chinese code (JTJ023-85, 1985), the original design of the Hashuang pre-stressed concrete box girder bridge was carried out. In this analysis, SAP200 software Ver. 14.2.0 is used to analyze the internal forces of the bridge structure due to dead load, live load, prestressed load, temperature load and crowded load.

Requirements of analysis: The following requirements are used in the analysis of the bridge structure. These requirements include:

- Concrete density = 26 kN/m3, Poisson ratio (μ) = 0.2, concrete compressive strength = 40MPa (C40).
- **Deck loads:** Deck weigh+sidewalk weight + railings weight = 40N/m, crowded load = 2.9 kN/m. The total weight per square meter = 40/17 (width of bridge) = 2.35 kN/m2.
- Anchorage set slip (Δl) = 6 mm.
- For prestressed losses, friction coefficient between steel beam and rubber tube (k) = 0.003 m-1， μ = 0.35.
- For concrete creep, efficiency coefficient of elasticity (K) = 0.3, creep factor (γ) = 0.021, creep ultimate value = 2.3.
- **Temperature load:** According to Chinese code (JTG D62-04, 2004), positive T1 = +14, negativeT1 = -7, positive T2 = +5, negative T2 = -2.5.
- **Load combination:**
  - Combination I (COMB I) = Dead load (structure weight)+Deck load+ Prestressed load.



(a)



(b)

Fig. 3: The layout of longitudinal pre-stressed tendons; (a) elevation view, (b) top view

- o Combination II (COMB II) = COMB1+Moving load (vehicle load)+Crowded load+Temperature load.
- **Pre-stressed tendons:** longitudinal prestressing tendons made of 1×7 wire 15.24-1860-II-GB/T5224-1995. Tendon area is equal to 1656mm2. The standard strength and controlled tension force of steel strands is equal to 0.75×1860 = 1395 MPa and 2310kN, respectively. Figure 3 shows the layout of longitudinal pre-stressed tendons.
- **Live load:** according to Chinese code (JTG D62-04, 2004), the live load is used shown in Fig. 4 Pk = 180 kN, if the length of span ≤5m, Pk = 360 kN, if the length of span ranges from 5 to 50 m. Uniform load (qk) = 10.5 kN/m. Table 1 lists the reduction factor of live load. The bridge consists of four lanes. Therefore, the reduction factor is equal to 0.67. The maximum span length is equal to 40m. Therefore, the pk is equal to 320 kN.

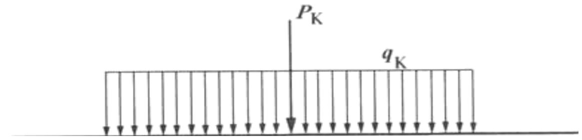


Fig. 4: The static live load (Senthilvasan *et al*., 2002)

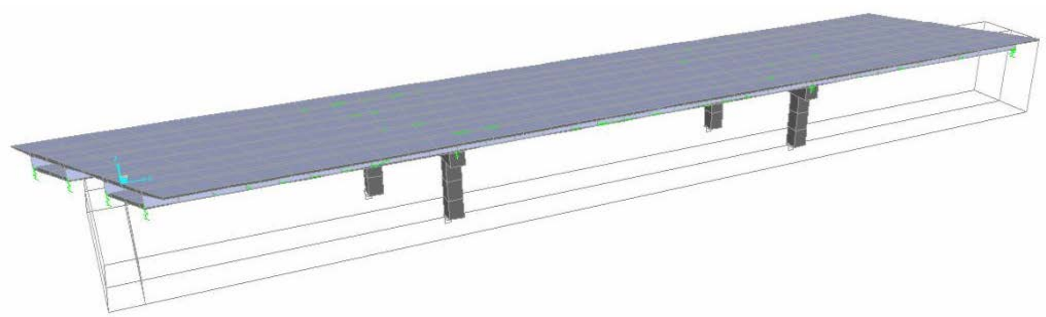
Table 1: The reduction factor of live load (Senthilvasan *et al*., 2002)

Number of lanes	2	3	4	5	6	7	8
Reduction factor	1	0.78	0.67	0.60	0.55	0.52	0.50

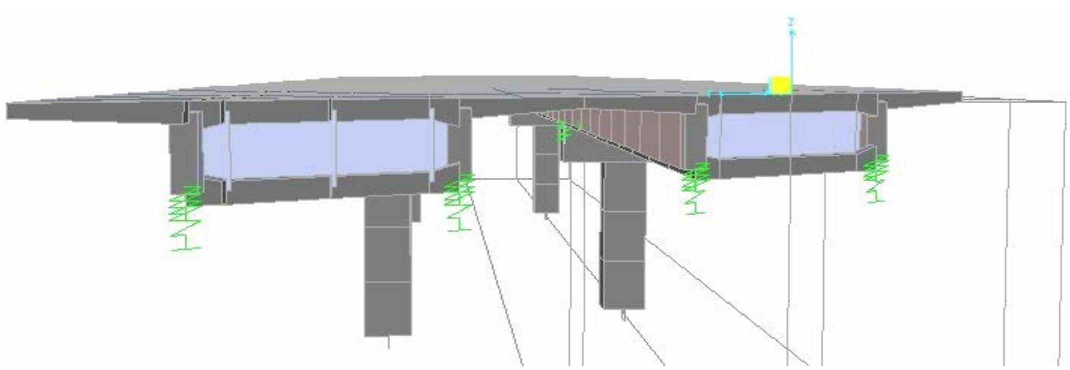
Description of finite element model of bridge structure: The bridge model consists of two shell element objects. The first object represents the right side of bridge (forward side) and the second object is the left side of bridge (backward side). Each object includes three spans. The first left span has length which is equal to 28 m. The second span is a middle span of the bridge which has length equal to 40 m and the third right span has length equal to 28 m. The bridge structure is type of skew bridge. The angle of skew is equal to N33oW. Figure 5 shows the bridge model.

Analysis of internal forces due to static live load:

- **Analysis of concrete strain:** Figure 6 shows the distribution of strain along the bridge length. From this figure it can be noted that the maximum positive values of strain for object 1 and object 2 are equal to 131 με and 127.69 με which locates in the bottom left and bottom right of box girder at distances 85 and 11 m of the bridge length respectively. For negative values of strain, the maximum value of strain of object 1 and



(a)



(b)

Fig. 5: The finite element model of bridge structure; (a) three-dimension view, (c) transverse view

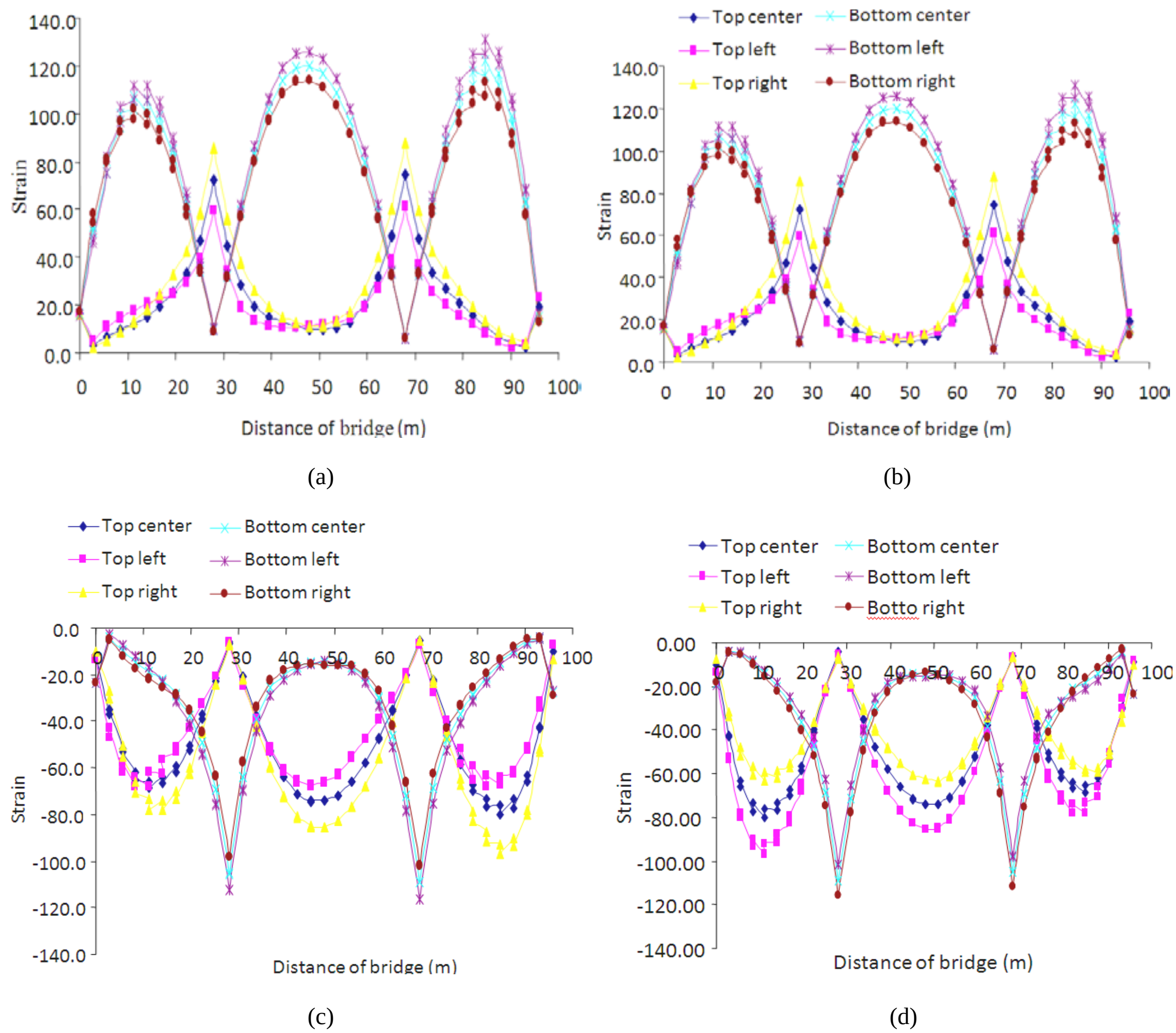


Fig. 6: The values of strain under live load; (a) Positive values of object 1; (b) Positive values of object 2; (c) Negative values of object 1; (d) Negative values of object 2

object 2 is equal to -116.4 and -116.06με which occurs in the bottom left of pier box girder (pier No.2) and bottom center of pier box girder (pier No.2).

- **Analysis of vertical deflection:** The analysis results of vertical deflection due to static live load shows that the maximum downward vertical deflection is equal to -16mm which occurs in the center of the bridge structure at distance 48 m. Figure 7 shows the vertical deflection due to static live load. This value is less than the allowable limit value which is equal to 66.6 mm. Therefore, the value meets the requirement:

$$\delta = \frac{L}{600} = \frac{40000}{600} = 66.6mm$$

Analysis of internal forces due to load combination I:

- **Analysis of stress:** Figure 8 shows the distribution of stresses along the bridge length. For top of box girders, the maximum compressive stress occurs in the top right of box girder in the center of middle span at distance 48m of object 1 which is equal to -5.3MPa and is less than the allowable limit value in Chinese codes (JTJ023-85, 1985; JTG D62-04, 2004) which are equal to -19.6 and -18.78MPa. The tensile stress is appeared in the top left of pier box girder at distance 68 m of object 2 and the maximum value of tensile stress is equal to 1MPa which is less than the allowable limit values in codes. For bottom box girder, the maximum compressive stress is equal to -7.2MPa which occurs in the bottom right of pier box girder at distance 68m of object 2 and it is less than the value allowable limit in Codes (-19.6 and -18.78 MPa). The maximum value of tensile stress is

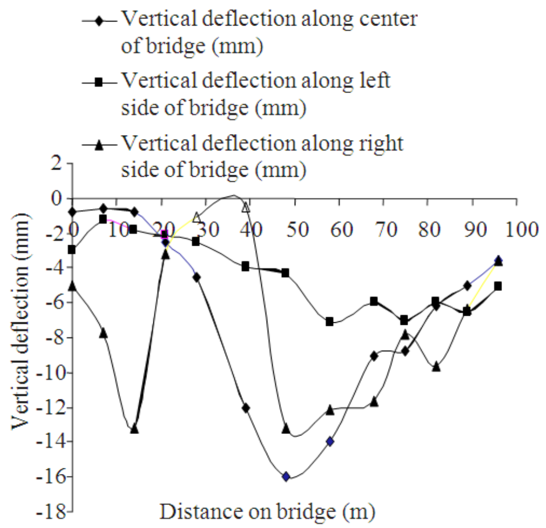
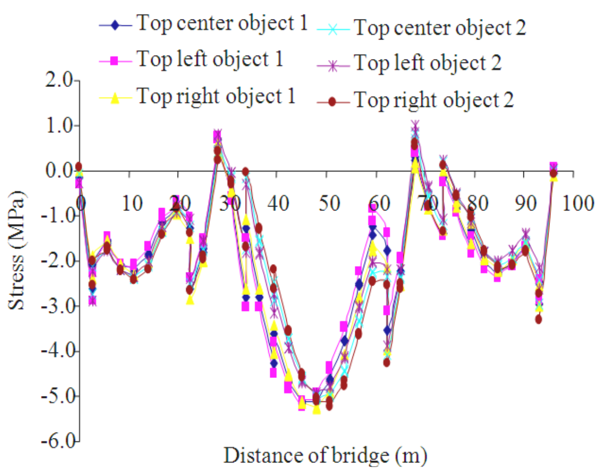
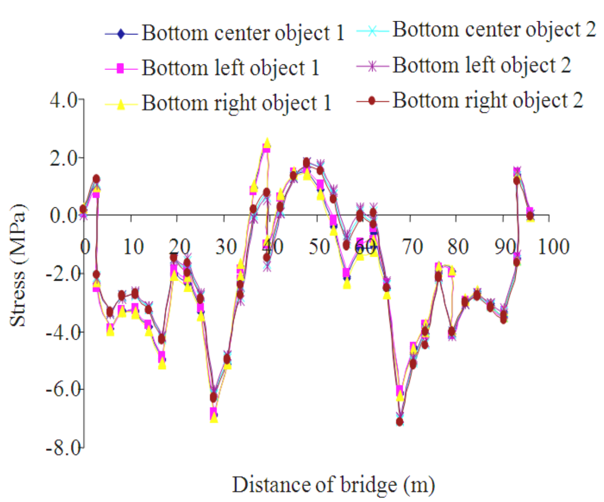


Fig. 7: The vertical deflection due to static live load



(a)



(b)

Fig. 8: The distribution of stresses along the bridge length; (a) Top of box girder, (b) bottom of box girder

equal to 2.5 Mpa which is located in the quarter of middle span at bottom right of box girder at 39m of object 1. This value is less than the value in Code-JTJ023-85 (2.99 MPa), but it is more than the value in the Code-JTG D62-04 (1.68MPa). Also there are tensile stress values are appeared in the bottom left of box girder at distance 39 m of object 2, bottom right of box girder in the center of middle span at distance 48 m, bottom center of box girder in the at distance 39 m of object 1 and bottom left of box girder at distance 39 m of object 1, these values are 1.8, 2.4 and 2.3 MPa, respectively. Therefore, the cracks will be appeared in these locations of the bridge structure.

For JTJ023-85: Allowable compressive stress = -0.7×28 = -19.6M Pa Allowable tensile stress = 1.15×2.6 = MPa

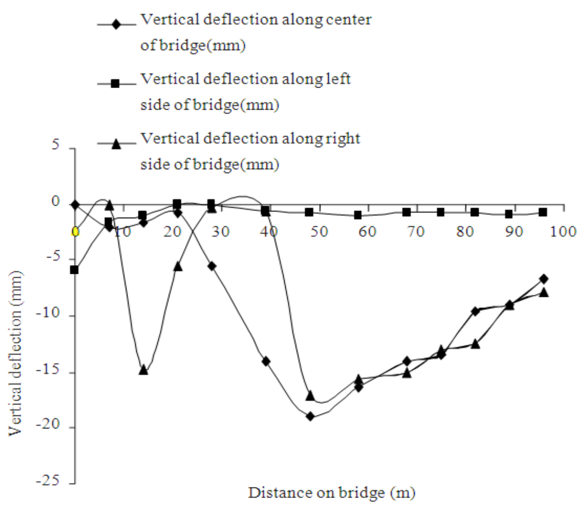
For JTG D62-04: Allowable compressive stress = -0.7×26.8 = -18.78MPa Allowable tensile stress = 0.7×2.4 = 1.68MPa

- **Analysis of vertical deflection:** The distribution of vertical deflection due to load combination I is shown in Fig. 9. From this figure it can be seen that the maximum value of downward deflection is equal to -19 mm in the right side of middle span center (center of bridge).

Analysis of internal forces due to load combination II:

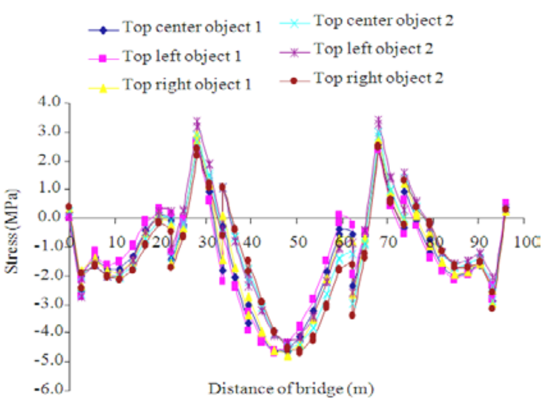
- **Analysis of stress:** The analysis results of stresses are shown in Fig. 10. For maximum top stresses of box girder, the maximum value of compressive stress occurs in top right of box girder in the center of middle span at distance 48m of object 1 which is equal to -4.8MPa and it is less than the allowable limit values in the Codes (-14 and -13.4 MPa). Tensile stresses are appeared in the tope pier box girder which ranges from 2.5 to 3.4 MPa and these values are more than the allowable value in Code-JTJ023-85 (2.34 MPa) and Code-JTG D62-04 (1.68 MPa). Therefore, the cracks will be appeared in these locations of the bridge. For maximum bottom stresses of box girders, the maximum value of compressive stress is equal to -8 MPa which locates bottom right of pier box girder at distance 68 m of object 2 and it is less than the allowable values in the Codes (14 and 13.4 MPa). Tensile stresses are appeared in the bottom of box girders and the maximum value is equal to 3.8 Mpa which is located in the quarter of middle span at bottom right of box girder at 39m of object 1. This value is more than the allowable limit value in Code-JTJ023-85 (2.34 MPa) and Code-JTG D62-04

(a)



(b)

Fig. 9: The vertical deflection due to static live load; (a) elevation view, (b) transverse view, (c) vertical deflection curve



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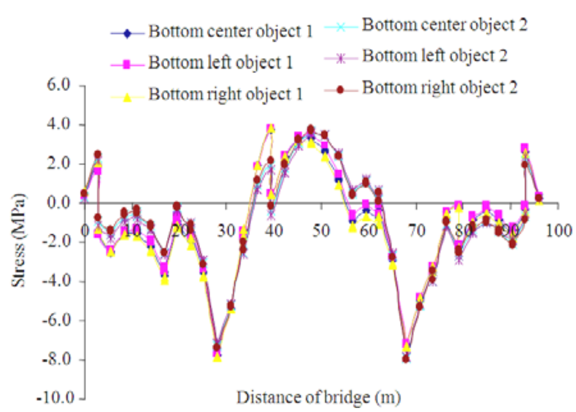

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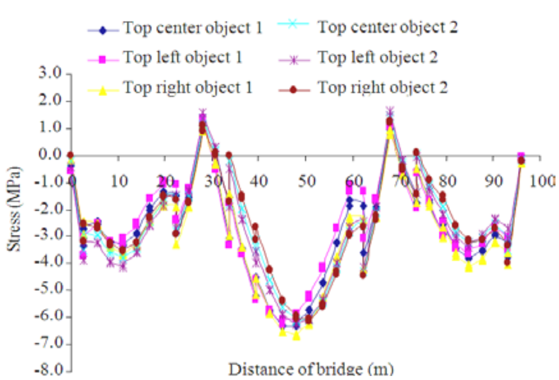

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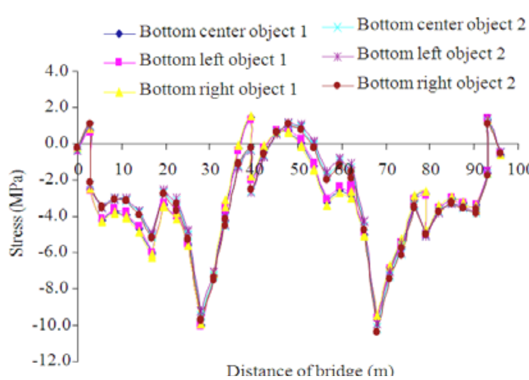


(d)

Fig. 10: The distribution of stresses along the bridge length; (a) maximum top stresses, (b) maximum bottom stresses, (c) minimum top stresses, (d) minimum bottom stresses

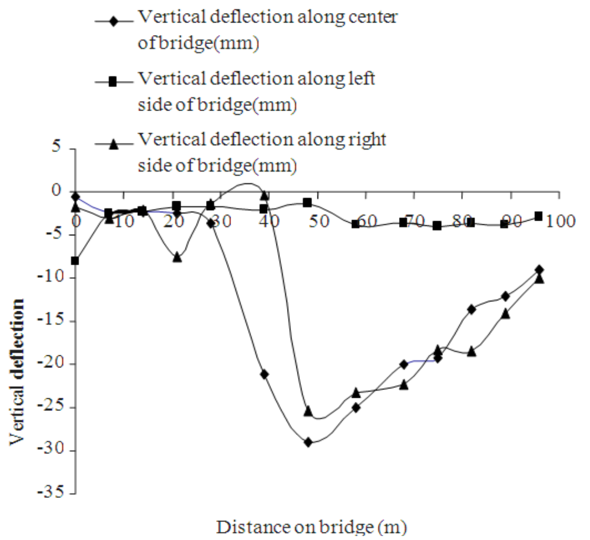


Fig. 11: The vertical deflection due to load combination II; (a) vertical deflection curve, (b) distribution of vertical deflection on longitudinal bridge model

(1.68 MPa). Therefore, the cracks will be appeared in this location of the bridge. For minimum top stresses, the maximum value of compressive stress occurs in top right of box girder in the center of middle span at distance 48 m of object 1 which is equal to -6.7 MPa and it is less than the allowable limit values in the Codes (-14 and -13.4MPa). There are tensile stresses in the tops box girders. The maximum value is equal to 1.6 MPa which locates in the top left of pier box girder (pier No. 1 and No.2) at distance 28 and 68 m of object 2. This value is less than the allowable limit values in Code-JTJ023-85 (2.34 MPa) and Code-JTG D62-04 (1.68 MPa). For minimum bottom stresses, the maximum value of compressive stress is equal to-10.4 MPa which locates in the bottom right of pier box girder at distance 68 m of object 2 and it is less than the values in the Codes (-14 and -13.4MPa). The maximum value of tensile stress is equal to 1.6 MPa which occurs in the bottom right of box girder at distance 48 m of object 1. This value is less than the allowable limit value in Code-JTJ023-85 (2.34 MPa) and Code-JTG D62-04 (1.68 MPa).

For JTJ023-85: Allowable compressive stress = - 0.5 ×28 = -14MPa Allowable tensile stress = 0.9×2.6 = 2:34MPa

For JTG D62-04: Allowable compressive stress = -0.5×26.8 = 13.4MPa Allowable tensile stress = 0.7×2.4 = 1.68MPa

- **Analysis of vertical deflection:** The results of vertical deflection of load combination II are shown in Fig. 11. The maximum value of vertical deflection is equal to -29 mm which is located in the center side of the middle span center of the bridge.

FINITE ELEMENT ANALYSIS OF DYNAMIC RESPONSES

Shell element model is used in the dynamic analysis of Hashuang pre-stressed concrete box Girder Bridge. Three joints are selected to determine the dynamic responses which are located in the center of the bridge structure at the area of maximum downward vertical deflection. The first joint has number 2598 which is located in the center of the bridge, the second joint has number 3022 which is located in the left center of the bridge and the third joint has number 2640 which is positioned in the right center of the bridge. Figure 12 shows the location of the selected joints. Linear direct integration time-history type and Hilber-Hughes-Taylor method is used in the dynamic analysis. For modal analysis, Eigen vector modal type is used and the maximum numbers of modes is equal to 20 modes. Six damping ratios are used in this analysis. These damping ratios include 0.0, 0.02, 0.03, 0.05, 0.07 and 0.10. in this analysis, natural frequency and vibration frequency will be analyzed to compare with experimental results of dynamic load test.

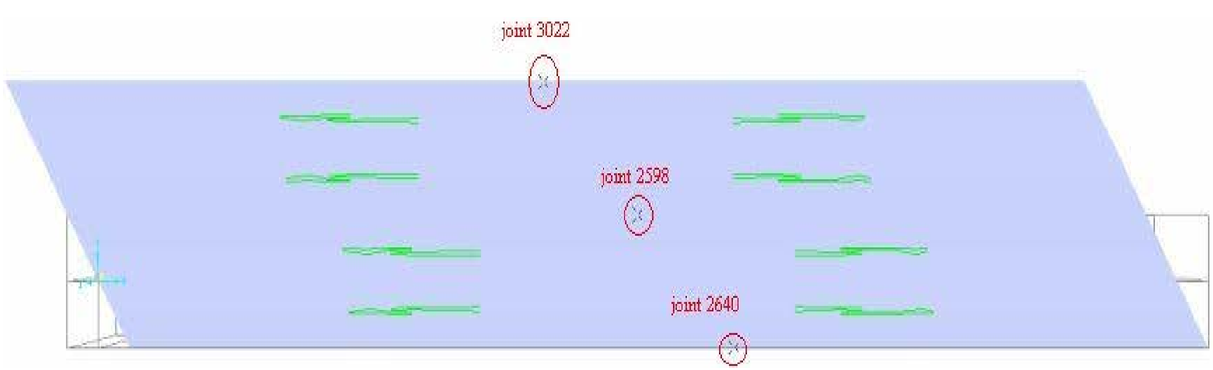


Fig. 12: The location of the selected joints

Table 2: The values of natural frequency for modal modes

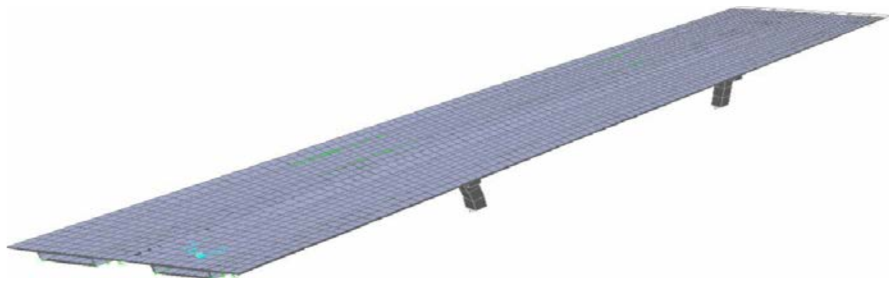
Mode No.	Natural Frequency (Hz)	Time (sec)
1	1.163	0.859
2	3.165	0.315
3	3.747	0.266
4	4.963	0.201
5	5.477	0.182

Table 3: The values of impact factor

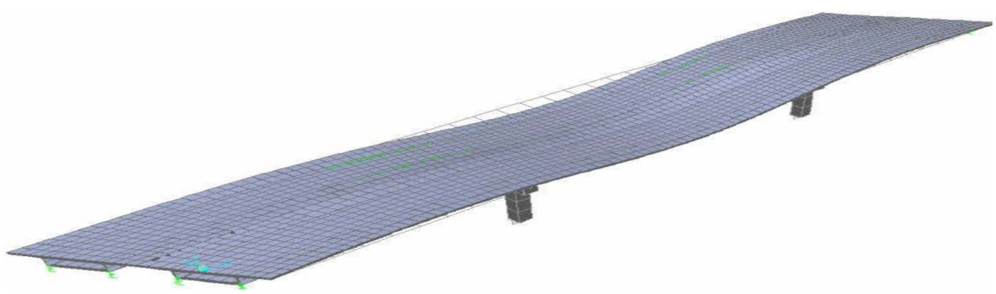
Bridge structure natural frequency (Hz)	Impact factor (μ)	Bridge structure natural frequency (Hz)
f<1.5 Hz	0.05	f<1.5Hz
1.5≤f≤14	0.1767 lnf-0.0157	1.5≤f≤14
f≥14	0.45	f≥14

Analysis of natural frequency and modal shape: Table 2 lists the values of natural frequency for modal modes. Figure 13 shows the first five modes of the bridge structures. According to deflection shape of modal mode No.3, the natural frequency of the bridge structure is equal to 4.9635 Hz. According to Table 3, the impact factor (1+μ) of the bridge structure is equal to 1.266.

Analysis of vibration frequency and impact factor: Ten speeds are used in the analysis of dynamic responses. These speeds are 10k, 20k, 30k, 40, 50k,



(a)



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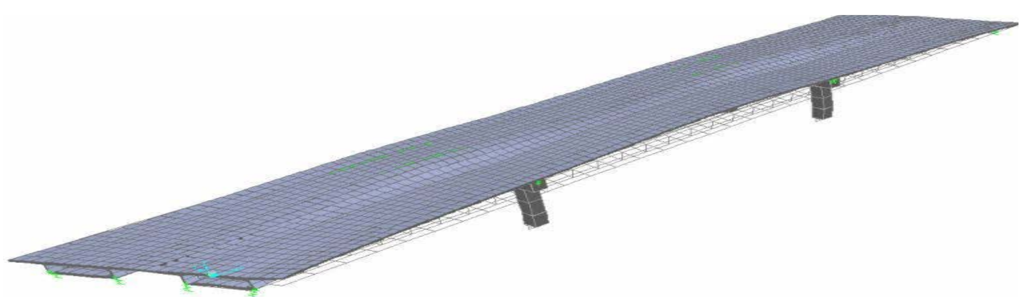

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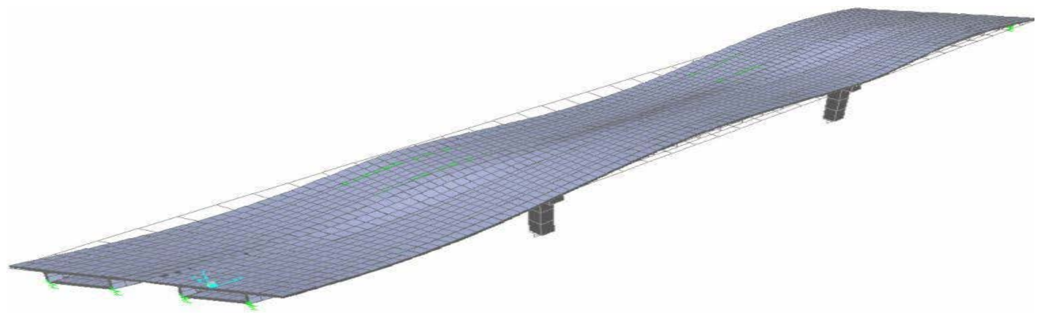


(e)

Fig. 13: The mode shapes of modal; (a) Mode No. 1; (b) Mode No. 2; (c) Mode No. 3; (d) Mode No. 4; (e) Mode No. 5

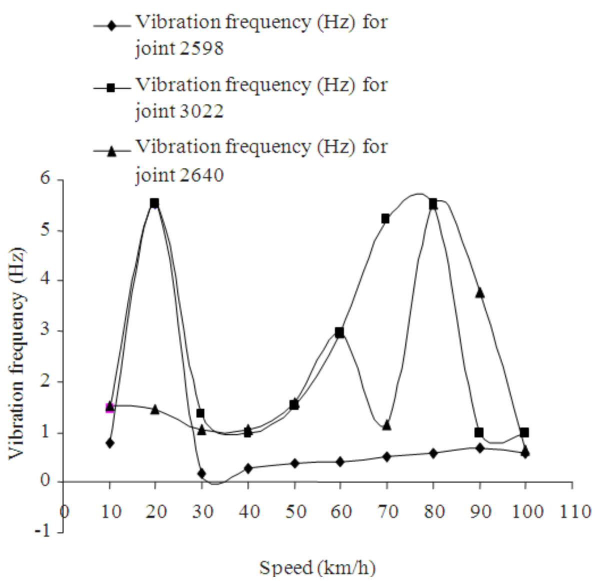


Fig. 14: The values of vibration frequency for joint 2598, joint 3022 and joint 2640

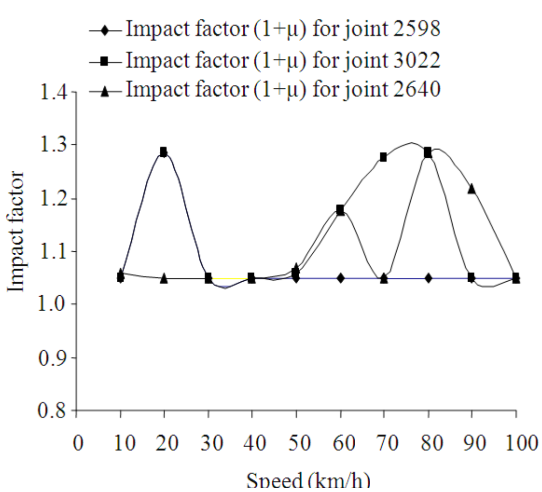


Fig. 15: The values of impact factor under different speeds

60k, 70k, 80k, 90 and 100k m/h, respectively. The selected vehicle has total weight is equal to 300 kN. The front axles have 60 kN and the two rear axles have 240 kN, each one has 120 kN. Figure 14 shows the relationship between vehicle speeds and vibration frequency. The average values of vibration frequency for joint No. 2598, No.3022 and No.2640 is equal to 1, 2.65 and 2.08Hz, respectively. Therefore, the average value of vibration frequency of the bridge structure is equal to 1.91 Hz which is less than the natural frequency 4.963 Hz, indicating that the vibration state of the bridge structure in good state. According to Table 3 and vibration frequency, the impact factor of the bridge structure can be calculated. Figure 15 shows the values of impact factor under different speeds. From this figure it can be noted that the most values for the selected joints are near for each others and the maximum value of impact factor is equal to 1.286 which occurs under speeds 20km/h and 80km/h. the average value of impact factor of the bridge structure is equal to 1.104 which is less than the value from natural frequency 1.266, indicating that the vibration state of the bridge structure is good.

STATIC LOAD TEST

The aim of static load test of Hashuang bridge is to measure the vertical deflection, strains, stresses and the development situation of cracks, then compare them with theoretical analysis results to judge synthetically the working state and the bearing capacity of whole bridge structure. According to the inspection results of the bridge structure appearance, the half of middle span (span No.2) is selected as a tested span.

Loading of vehicles and measuring point's arrangement: The static load test is determined by using method of equivalent load. There are 4 automobiles FAW produced by the heavy-duty factory in Changchun City in China. The overall weight is 300 kN. The characteristic parameters of the vehicles for static load test are listed in Table 4. The static load test is done only on the middle span. Therefore, there is just one condition in the analysis of the results. Table 5 gives the arrangement situation of measuring points.

Table 4: The characteristic parameters of the vehicles

	Axle load (kN)				Wheel distance (cm)	
Model of vehicle	Front axle load	Middle axle	Rear axle	Total weight	Between front and middle axles	Between middle and rear axle
FAW	60	120	120	300	325	125

Figure 16 shows the selected tested span and longitudinal location of vehicles loading. Figure 17 shows the transverse location of vehicles loading. Figure 18 shows the transverse arrangement of deflection measuring points.

Table 5: The arrangement situation of measuring points

Tested section	Tested project	Measuring points
Section No.1: (Pier box girder)	Section No.1: (Top edge strain)	Section No.1: Four strain gauges are installed on the web of box girder near the roof.
Section No.2: (1/4 of middle span)	Section No.2: (Bottom edge strain and cracks changes)	Section No.2: Four strain gauges are installed on the bottom of box girder and two dial gauges are installed on the web cracks.
Section No.3: (1/2 of middle span)	Section No.3: (Lower edge strain)	Section No.3: Four strain gauges are installed on the bottom of box girder

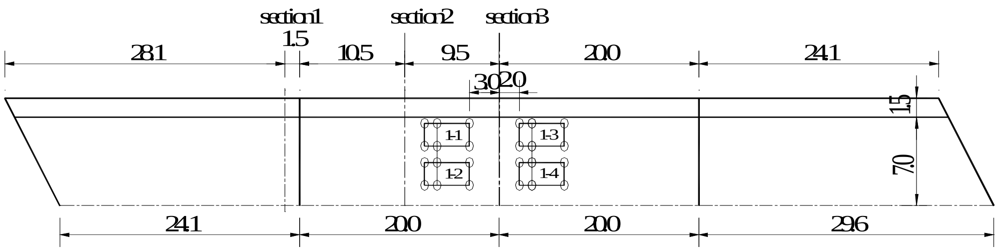


Fig. 16: The selected tested span and longitudinal location of vehicles loading

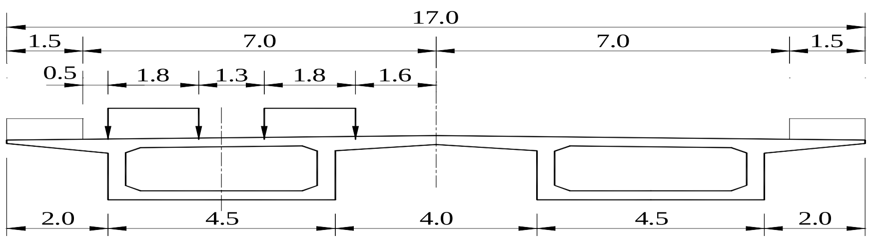
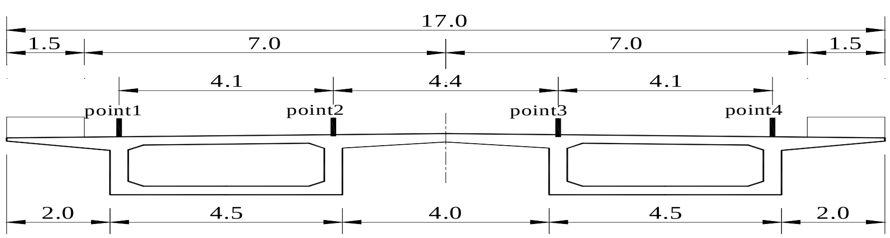


Fig. 17: The transverse location of vehicles loading



(a)

(b)

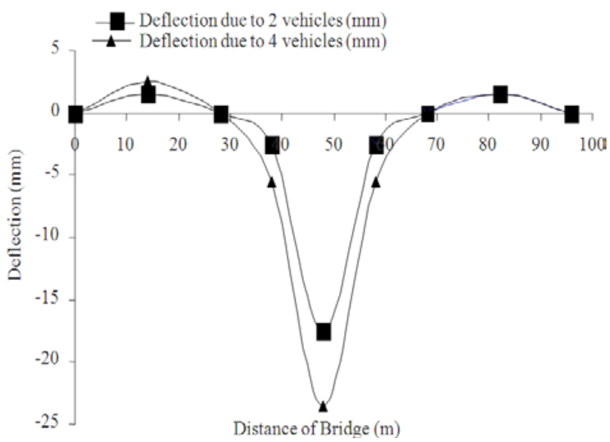
Fig. 18: The transverse arrangement of deflection measuring points

Table 6: The results of stresses of concrete under static load

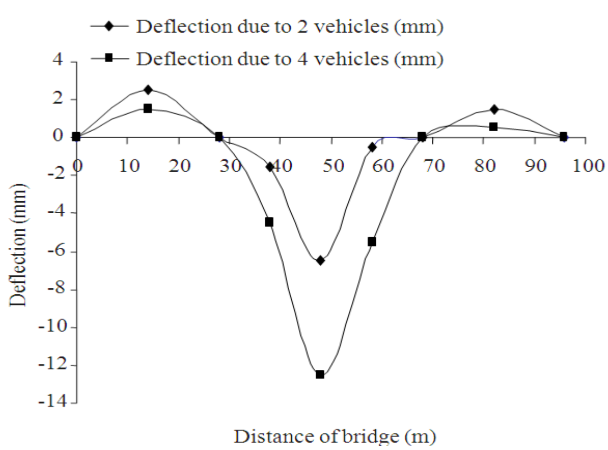
Location	Measured stress of inside of box girder (Mpa)	Measured stress of outside of box girder (Mpa)
Section No.1 (pier box girder)	1.180	1.529
Section No.2 (1/4 of middle span)	1.333	1.294
Section No.3 (1/2 of middle span)	1.747	1.708

Table 7: The measuring values of concrete strain (με)

Location	Measured strain of inside of box girder	Measured strain of inside of box girder	Average strain
Section No.1: (pier box girder)	36.2	46.9	41.55
Section No.2: (1/4 of middle span)	49.9	39.7	40.3
Section No.3: (1/2 of middle span)	53.6	52.5	53



(a)



(b)

Fig. 19: The deflection values; (a) Measuring point 1; (b) Measuring point 2

Analysis of static load test results:

- **Stress results:** The results of tensile stress of concrete under static load are listed in Table 6

Table 8: The changes in crack width of the box girder web under the action of static load test (mm)

Measuring point	2 Vehicles	3 Vehicles	4 Vehicles	Unloaded residual
Dial indicator No.1:	0.17	0.17	0.17	0.01
Dial indicator No.2:	0.20	0.201	0.205	0.01

- **Vertical deflection results:** Figure 19 shows the deflection of measuring points 1 and 2. From this Figure it can be noted that the maximum downward deflection is equal to -23.5 mm which locates within half of middle span No.2 under 4 vehicles loads in the measuring point No. 1 and it is less than the allowable limit value which is equal to 66.6m.
- **Stain results:** Table 7 shows the measuring values of concrete strain.
- **Observation of cracks:** Table 8 lists the changes in crack width of the box girder web under the action of static load test. From this table it can be noted that the crack widths of box girder web have been increased by 0.205 mm under the action of load test. After unloading, the cracks are repristination and the residual deformation is 0.01mm. The relative residual deformation is 4.9% which are much less than 20%. It indicates that whole deformation and integrality of structure fit the request of design and have good elasticity working state.

DYNAMIC LOAD TEST

When the traffic loads pass on the bridge structure, the bridge suffers from large vibration and the duration of vibration is long. In this test, dynamic responses such as natural frequency, impact factor and dynamic deflection are measured when the bridge is opened to traffic loads to determine the state of the bridge vibration in safe working or not. One vertical 941B-vibration pickup device and transverse 941B-vibration pickup are set on the mid-span of span No.1 (side span of the bridge) and the mid-span of span No.2 (middle span of the bridge) (Ali and Wang, 2011a).

Natural and vibration frequency: Figure 20 shows the spectral analysis curve of natural frequency and dynamic acceleration of mid-span No.2 when the bridge is opened to traffic load. From this figure it can be seen that the values of measured natural frequency is equal to 4.482 Hz. The vibration frequency of bridge structure is equal to 5 Hz which is close to the natural frequency 4.482 Hz of the structure. So under the action of vehicles loads, bridge can easily cause a resonant phenomenon, resulting in dynamic acceleration, dynamic strain and dynamic displacement by a big

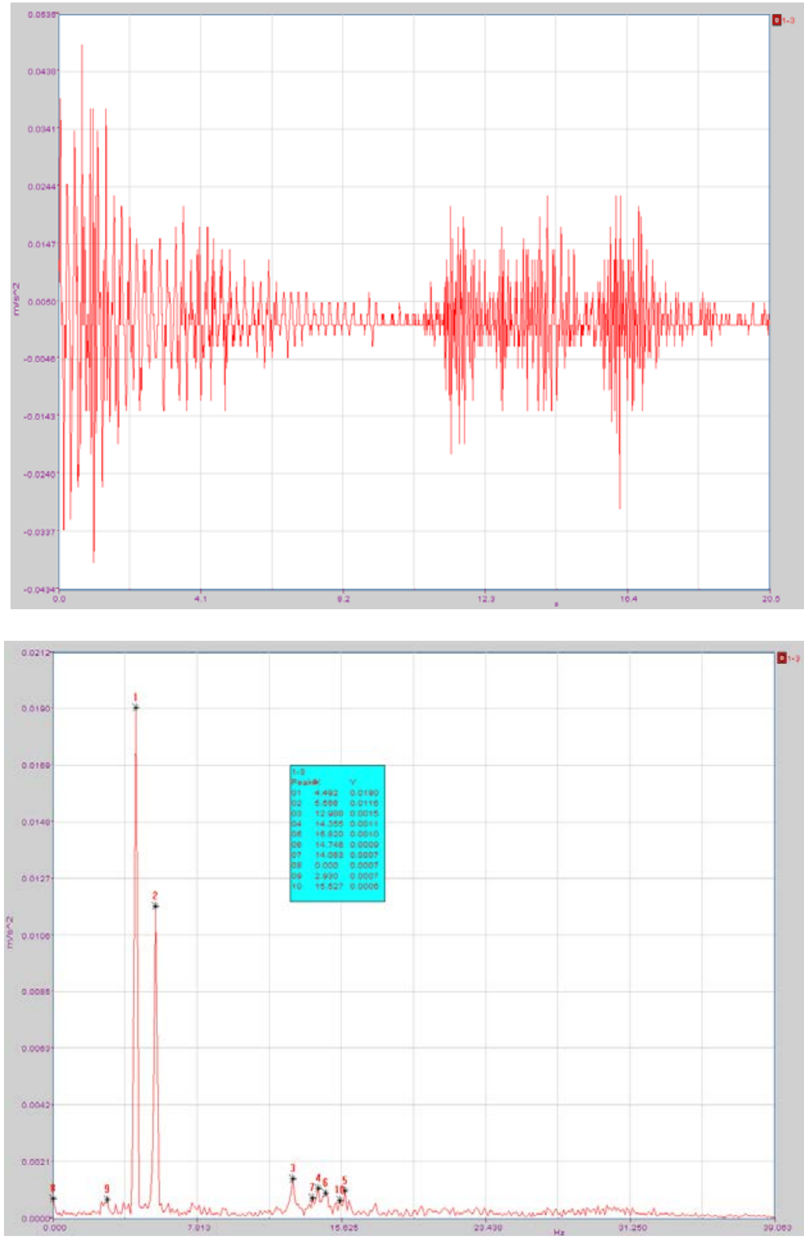


Fig. 20: The spectral analysis curve of natural frequency and dynamic acceleration of mid-span No. 2

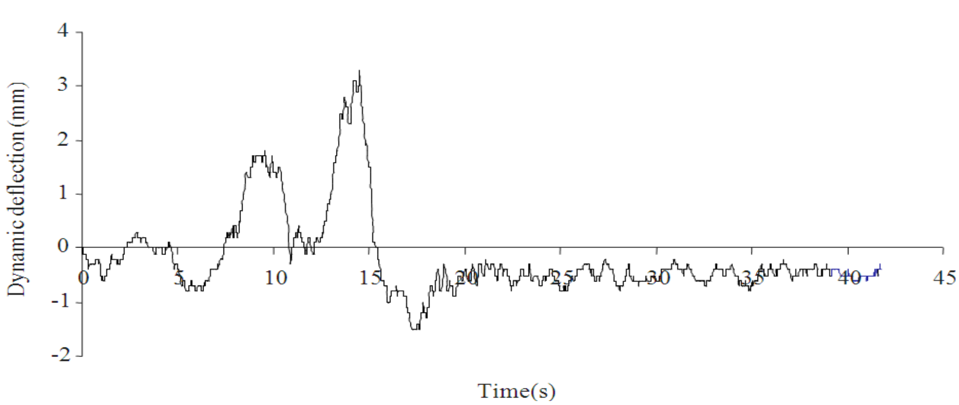


Fig. 21: The curve of dynamic deflection

margin which will affect its normal use of the bridge structure.

Dynamic deflection and impact factor: In free traffic condition, the dynamic deflection of mid-span of span No.2 (middle span of the bridge) is monitored in-situ continuously 60 min by using the laser deflection device. After processing the data, the impact factor of bridge is 1.14. Figure 21 shows the curve of dynamic deflection when the traffic loads pass on the bridge.

COMPARING THE NUMERICAL AND EXPERIMENTAL RESULTS

Static results: According to Chinese Code, to evaluate the structural performance of the bridge structure, finite element and load test results of vertical deflection, strain and stress are compared. The efficiency coefficient of load test (η) is used in the evaluation and it can be calculated by using equation No. 1:

$$\eta = \frac{S_s}{S(1+\mu)} \tag{1}$$

where,

η = The efficiency coefficient of load test
Ss = The load test values
S = The theoretical values
1+u = Iimpact factor

For strain (or stress) and vertical deflection, Table 9 list the allowable values of the efficiency coefficient of load test (η).

Strain of concrete: Table 10 lists the theoretical and load test values of longitudinal concrete strain for pier box girder, ¼ of middle span and center of middle span. From this table it can be noted that the load test values are less than the theoretical and the values efficiency coefficient (η) of load test ranges from 0.35 to 0.42 which are less than the allowable value of efficiency coefficient (η = 0.90), indicating that the structural strength of the bridge structure meets the design requirements.

Vertical deflection: Table 11 lists the theoretical and load test values of downward deflection. From this table it can be noted that the values efficiency coefficient of load test (η) ranges from 0.40 to 1.46. The maximum load test downward deflection in the center of the bridge structure are more than the theoretical value and the values efficiency coefficient of load test (η) is equal to 1.46 which is more than the allowable efficiency coefficient (η) of load test (η =1.0). Therefore, the bridge structure dose not meets the design requirements of stiffness and the elastic working state is not good.

Table 9: The allowable values of the efficiency coefficient of load test (η)

Type of bridge	Strain (or stress)	Deflection
Reinforced concrete slab bridge	0.30-0.70	0.40-0.80
Reinforced concrete girder bridge	0.40-0.80	0.5-0.90
Prestressed concrete bridge	0.5-0.90	0.60-1.00

Table 10: The theoretical and load test values of longitudinal concrete strain

Location	Theoretical value	Load test average value	Load test coefficient (η)
Pier box girder (28m)	116.4	41.55	0.35
¼ of middle span(39m)	106.0	23.50	1.46
Half of middle span (48m)	14.00	5.500	0.40

Table 11: The theoretical and load test values of downward deflection (mm)

Location	Theoretical value	Load test value	Load test coefficient
¼ of middle span (39 m)	12	5.50	0.45
Half of middle span (48 m)	16	23.5	1.46
¼ of middle span (58 m)	14	5.50	0.40

Table 12: The allowable values of the dynamic load test coefficient

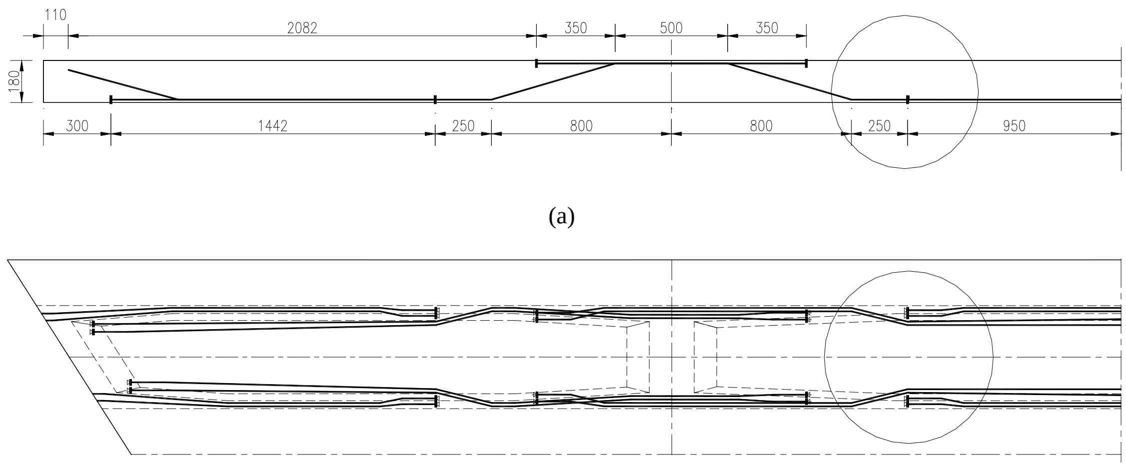
Bridge components	Superstructure		Substructure	
Evaluation level	$\frac{f_{mi}}{f_{di}}$	State	$\frac{f_{mi}}{f_{di}}$	State
1	≥1.1	Very good	≥1.2	Very good
2	1.0-1.1	good	1.0-1.2	Good
3	0.9-1.0	poor	0.95-1.0	Poor
4	0.75-0.90	Very poor	0.80-0.95	Very poor
5	Less than 0.75	Dangerous	Less than 0.80	Dangerous

Dynamic results: To evaluation of dynamic performance of the bridge structures, Chinese evaluation code is used to compare between theoretical and dynamic load test natural frequency. Table 12 lists the allowable values of the dynamic load test coefficient.

The value of measured natural frequency is equal to 4.40 Hz which is less than the theoretical natural frequency which is equal to 4.963 Hz. The value of dynamic load test coefficient is equal to 0.88 which is within the fourth level that represents the very poor state, indicating that the bridge structure suffers from long time vibration because of the connection between the two sides of box girders (forward and backward direction) is not good. Therefore, the measured vibration frequency under passing the vehicles on the bridge is equal to 5 Hz which is more than the measured natural frequency which is equal to 4.482 Hz. Therefore, to reduce the vibration of the bridge structure, the connection between two sides of the bridge must be strengthened by adopting cross beams to increase the rigidity of the connection areas.

EVALUATION OF STRUCTURAL PERFORMANCE OF T HE BRIDGE STRUCTURE

According to the finite element analysis of the bridge structure, there are high tensile stresses in the quarter of middle span at distance 39 m of the bridge



(a)

(b)

Fig. 22: The arrangement of pre-stressed tendons in the quarter of middle span; (a) Elevation view; (b) Top view

length. The value of maximum tensile stress is equal to 3.8 MPa which occurs in the bottom of box girder. This value exceeds and dose not meets the allowable limit values in Code-JTJ023-85 (2.99 MPa) and Code-JTG D62-04 (1.68 MPa). These tensile stresses are related to the position of anchorage of bottom pre-stressed tendons which leads to decrease the effect of pre-stressed of the section and become not enough and decreased the compression stress. Therefore, the cracks appeared in the sections which have high tensile stresses. Figure 22 shows the arrangement of pre-stressed tendons in the quarter of middle span at distance 39 m of the bridge length. According to the observation process for the traffic loads, there are serious overloading phenomenon exist universally when vehicles passing the bridge. The maximum vehicles weight more than 150 tons which is two times higher than the weight of live load vehicles in the design code. Serious overloading will cause large main tensile stress in the part of quartiles of middle span which leading to appear the cracks and causes the downward defection in the center of the bridge. According to dynamic load test, when the vehicles pass on the bridge, it suffers from a greater vibration which leading to causes grater dynamic stresses in the bridge structure and then the cracks appeared. Therefore, this study recommends for repairing and strengthening the bridge structure to increase the stiffness and strength and to improve the bearing capacity of the bridge structural members to increase the service live of the bridge structure.

CONCLUSION

The main conclusions of this study are:

- Field investigation process of the bridge appearance shown that the bridge suffers from serious damages. The web of box girder of the second span near pier No.2 (in the quarter of middle span at 39 m on the bridge length) suffers from serious shear cracks. These cracks extend from the top to lower flange of box girder. There are two cracks incline 45° to the mid-span direction with widths are 0.5 to 2.0 mm and the widest cracks are found in the middle of web of box girder. Both of the outside web and inside web of box girders have the same crack position. The cracks degree of the box girder's outside web is more serious than the inside web. There are six transverse bending cracks on the bottom of box girder around quartile of middle span. The investigation process of other parts of the bridge structure shows that the state of abutments, piers and sidewalks is good, but the bearing, drainage holes, steel rail and expansion joints are not good and they suffer from much damage. The steel rail is corroded and the expansion joint loses the material which fills the joint. There are many dusts and debris is collected on the bridge deck in the location near sidewalk.
- The results of finite element analysis of the bridge structure show that there are high tensile stresses in the quarter of middle span at distance 39 m of the bridge length. The value of maximum tensile stress is equal to 3.8 MPa which occurs in the bottom of box girder. This value exceeds and dose not meets the allowable limit values in Code-JTJ023-85 (2.99 MPa) and Code-JTG D62-04 (1.68 MPa). These tensile stresses are related to the position of anchorage of bottom pre-stressed tendons which leads to decrease the effect of pre-stressed of the section and become not enough and decreased the compression stress. Therefore, the cracks appeared in the sections which have high tensile stresses.
- The results of static load test show that the load test values are less than the theoretical values. The

values of efficiency coefficient (η) of load test concrete strains ranges from 0.35 to 0.42 which are less than the allowable value of efficiency coefficient (η = 0.90), indicating that the structural strength of the bridge structure meets the design requirements. The values of efficiency coefficient of load test vertical deflection (η) ranges from 0.40 to 1.46. The maximum load test downward deflection in the center of the bridge structure are more than the theoretical value and the values efficiency coefficient of load test (η) is equal to 1.46 which is more than the allowable efficiency coefficient (η) of load test vertical deflection (η = 1.0). Therefore, the bridge structure dose not meets the design requirements of stiffness and the elastic working state is not good.

- The analysis results of dynamic load test show that the value of measured natural frequency is equal to 4.40 Hz which is less than the theoretical natural frequency which is equal to 4.963 Hz. The value of dynamic load test coefficient is equal to 0.88 which is within the fourth level that represents the very poor state, indicating that the bridge structure suffers from long time vibration because of the connection between the two sides of box girders (forward and backward direction) is not good. Therefore, the measured vibration frequency under passing the vehicles on the bridge is equal to 5Hz which is more than the measured natural frequency which is equal to 4.482 Hz.
- According to the results of damage investigation process, finite element analysis, static load test and dynamic load test, the main problem of the bridge structure in the original design of prestressed tendons. Therefore, this study recommends for repairing and strengthening the bridge structure to increase the stiffness and strength and to improve the bearing capacity of the bridge structural members to increase the service live of the bridge structure.

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