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RESEARCH ON SEISMIC PERFORMANCE OF CONTINUOUS RIGID-FRAME BRIDGE WITH CORRUGATED STEEL WEBS

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Abstract

Continuous rigid-frame bridge with corrugated steel webs combine the advantages of rigid-frame bridge and box girder with corrugated steel webs. Compared to traditional continuous rigid-frame bridge with concrete webs, it is a new structure with a large spanning capacity, light dead weight, high efficiency of prestressed steel and so on. Generally speaking, lighter dead weight of upper bridge structure will lead to the reduction of seismic actions. But for the continuous rigid-frame bridge, its seismic performance not only affected by its own dead weight, but also the pier-girder stiffness ratio and regularity of the bridge layout scheme. Therefore, this paper will discuss the characteristics of seismic performance of continuous rigid-frame bridge with corrugated steel webs and the impact of regularity of the pier arrangement on seismic performance.

Firstly, based on the valley bridge in Japan, the FEA model of continuous rigid-frame bridge with corrugated steel webs and the corresponding continuous rigid-frame bridge with concrete webs are established with design principle of equivalent shear capacity of the girder cross-section. Through the seismic response spectrum analysis, for the case of irregularity of the pier arrangement as the real bridge, the displacements response of the main girder of rigid-frame bridge with corrugated steel webs is larger than the bridge with concrete webs, the seismic force of rigid-frame bridge with corrugated steel webs at the main girder and the lower pier are smaller than the bridge with concrete webs basically, but the seismic force of corrugated steel webs at the higher pier is larger than the concrete webs. In order to further analyze the impact of the regularity of the pier arrangement, the height of the piers are changed to the same, and then compared with the former irregularity situation. The results showed that: as to the regularity of the pier arrangement, the displacement response of the main girder of rigid-frame bridge with corrugated steel webs is still slightly larger than these of the bridge with concrete webs, but the internal force of the main girder and all piers of rigid-frame bridge with corrugated steel webs are smaller than these of the bridge with concrete webs. So the seismic performance of continuous rigid-frame bridge with corrugated steel webs is better than the bridge with concrete webs on the whole, while adverse effects caused by irregularity of the pier arrangement should be paid more attention in the design of a specific real bridge.

Keywords: corrugated steel web、seismic performance、regularity of pier arrange

1. Introduction

Composite box-girder bridge with corrugated steel webs is an improvement of the traditional box-girder bridge which using corrugated steel webs to replace the concrete webs. It has been widely used because of its light dead weight, high strength, good appearance, convenient construction and so on. Scholars from various countries have conducted a series of research on the static performance of bridge with corrugated steel webs. Compared with box girder bridge with concrete webs, stiffness and weight of the upper bridge structure of the box-girder bridge with corrugated steel webs are changed, so its dynamic characteristics and seismic performance will also different from the box-girder bridge with concrete webs.

According to the principle of equivalents static rigidity, the FEA model of simply supported composite box-girder bridge with corrugated steel webs and the corresponding concrete box-girder bridge were established [1]. The dynamic characteristics were compared and analyzed, it founded that the torsional stiffness of the box-girders with corrugated steel webs is lower than the box- girders with concrete webs. Theoretical analysis and field testing on dynamic characteristic of Po-he bridge were conducted, which is a PC composite box girder bridge with corrugated steel webs built in Henan province of China [2-3]. The results showed that: the first fourth order (both longitudinal bending) vibration frequencies of Po-he bridge are both higher than reinforced concrete beam bridge with similar span, indicating a higher bending stiffness of Po-he bridge. Based on the energy variation principle and combined with the characteristics of corrugated steel web plate, a formula of fundamental vibration frequency was deduced, which considering the effect of shear lag and shear deformation [4]. Through comparing with the measured values and finite element value, the validity of the formula was verified. The seismic responses of the bridge were calculated using response spectrum and time history methods respectively [5]. The result showed: lateral and longitudinal seismic excitation make a greater contribution to seismic response of the structure. The effect of vertical seismic excitation can be neglected. The basic dynamic characteristics and seismic response of the rigid-frame bridge excited by three kinds of seismic waves were studied [6]. The results showed that the axial force and the horizontal bending moment of the pier and girder are greater than continuous rigid-frame bridge with concrete webs, longitudinal bending moment is smaller than continuous rigid-frame bridge with concrete webs, the mid-span displacement of the girder are all greater than concrete webs under the seismic excitation. In the design of cross-section of main girder, it is still controlled by static calculation results. The paper [7] used continuous composite box-girder bridge with variable cross-sections as the prototype and analyzed dynamic characteristics and seismic response of this bridge by using finite element software Midas Civil. The results showed that the transverse bending deformation appeared under lateral seismic excitation. Under the influence of longitudinal and vertical earthquake, mainly produce vertical bending deformation, and the lateral deformation is outstanding than the other direction.

Generally speaking, lighter dead weight of upper bridge structure leads to reduction of seismic forces. But the girder of continuous rigid-frame bridge is fixed with pier, not only upper structure but also pier-girder stiffness ratio and bridge layout scheme will influence its seismic performance. This paper selects valley bridge in Japan as a prototype, the FEA model of continuous rigid-frame bridge with corrugated steel webs and the corresponding bridge with concrete webs are established with design principle of equivalent shear capacity of the girder cross-section. Through changing the arrangement of pier, the influences of regularity of pier arrangement to the seismic performance of the bridge are analyzed. Then summarize the seismic performance characteristics of the continuous rigid-frame bridge with corrugated steel webs and provide a reference for the design of this kind of bridge.

2. Description of bridge structure

The valley bridge is the world's first continuous rigid frame bridge with corrugated steel webs which located at a central position of Hokkaido Hokuriku steam special roads in japan. The span arrangement of this bridge is: 44.013m + 97.202m + 55.978m, as shown in Figure 1. The section types of the main girder are single box single chamber composite girder with variable cross-section. The roof and bottom plate of the girder using C60 concrete, width of roof and bottom plate are 11.02m and 6.2m. The height of bearing sections are 6.4m and 5m, the height of edge sections of main girder are 2.2m and 2.0m, the height of mid-span section of the girder is 2.5m, as shown in Figure 2.The height of the main girder changing by 1.5 times parabola curve. The corrugated web use Q345 grade steel, the thickness is 8mm, as shown in Figure 3. Substructure is single thin-walled solid pier, the heights of the piers are 11.0m and 24.3m, the dimension of the cross-section of the pier is 4.2m × 6.2m.

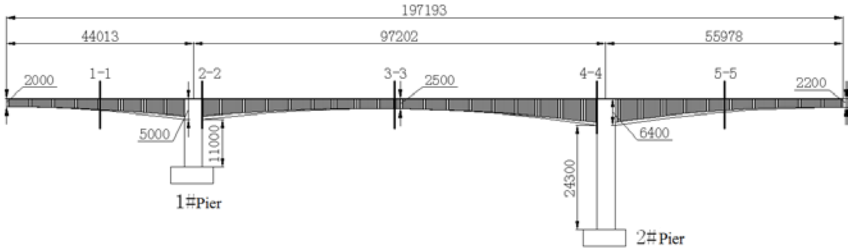
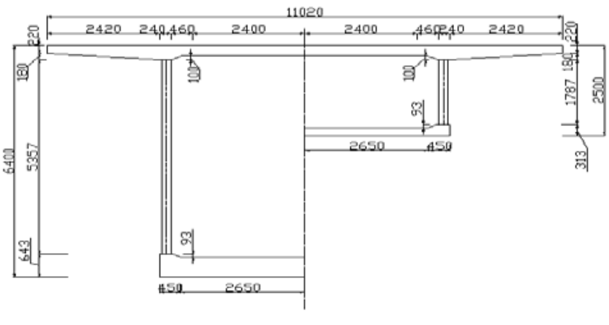


Fig.1 – Layout of overall bridge (mm)



a) bearing section b) mid-span section

Fig.2 – Cross-section size of box girder (mm)

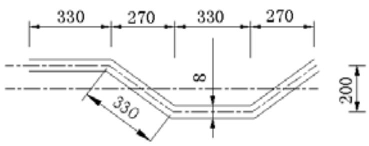


Fig.3 – Structure size of corrugated steel web (mm)

According to the design principle of equivalent shear capacity of the girder cross-section under the same load, the thickness of concrete web is 250mm [8]. The rest sizes of the girder with concrete webs are same as the girder with corrugated steel webs.

3. Finite Element Model

In this paper, finite element model was established through finite element software Midas Civil. Girder and pier use the beam element. The connection between girder and pier is simulated by rigid connection. Suppose that the bottom of pier is fixed on the ground. The finite element model is shown as Figure 4.

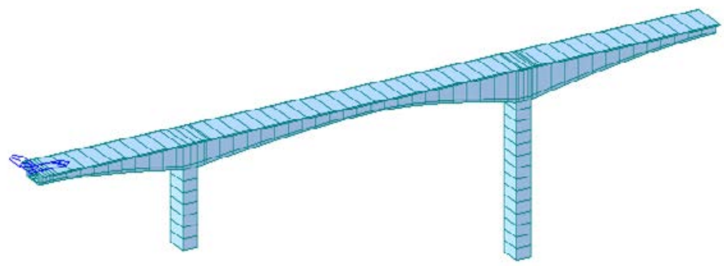


Fig.4 – Schematic of finite element model of continuous rigid-frame bridge

The first two natural frequencies of the bridge are quoted through the literature [9], the value of the measured and simulated frequencies are shown in Table1.

Table 1 – Comparison of the measured and simulated frequencies of the bridge

Natural frequency (Hz)	valley bridge		
	The value of finite element	The value of measured	percentage error (%)
1	1.753	1.648	5.9%
2	1.987	1.831	7.8%

As can be seen from Table 1, the simulated results by finite element method have a small difference from the measured values. Indicating that finite element model established in this paper is closer to the real situation, so it can be used in subsequent calculation.

4. Seismic Response Analysis

4.1 Response spectrum parameters

This bridge was built on the Class Ⅱ site. Supposed the degree of fortification intensity is 7 (seismic peak ground acceleration is 0.15g). According to the Guidelines for Seismic Design of Highway Bridges (GB50111-2006) [10], the characteristic period of the acceleration response spectrum is 0.4s, the structural important factor is 0.5, the site coefficients is1.0. And the damping ratio is chosen as 0.05.

4.2 Response spectrum analysis results

In the analysis of the seismic response results, only five check sections of the girders are chosen (1-1 section located at left side mid-span, 2-2 section located at the top of 1 # pier, 3-3 section located at mid-span of the middle span, 4-4 section located at the top of 2 # pier, 5-5 section located at right side mid-span), which are shown as figure 1. Then the top and bottom sections are chosen as the check sections for the pier.

1. Transverse seismic excitation

(1) Displacements of main girder

The displacements of the main girder at the five check sections under transverse seismic excitation are shown in Table2.

Table 2 –Displacements of the main girder under transverse seismic excitation (mm)

Section	1-1	2-2	3-3	4-4	5-5
Corrugated steel web	0.54	1.38	13.27	7.12	2.89
Concrete web	0.46	1.42	11.48	7.39	2.84

As can be seen from Table 2, the transverse displacements of the bridge with corrugated steel webs at the middle span section are greater than that of the bridge with concrete webs, indicating that lateral bending stiffness of the girder with corrugated steel webs is smaller than that of the girder with concrete webs. But the lateral displacements of the bridge with corrugated steel webs at the top of two piers are smaller than that of the bridge with concrete webs, indicating the seismic actions is reduced due to the lighter dead weight.

(2) Internal force of main girder

The seismic internal forces of the main girder at the five check sections under transverse seismic excitation are shown in Table3.

Table 3–Internal forces of the main girder under transverse seismic excitation

section / response	1-1 Bending moment (kN•m)	2-2 Shear force (kN)	2-2 Bending moment (kN•m)	3-3 Bending moment (kN•m)	4-4 Shear force (kN)	4-4 Bending moment (kN•m)	5-5 Bending moment (kN•m)
Corrugated steel web	4626.9	1220.5	21219.5	15114.8	1251.0	9091.6	5188.7
Concrete web	5429.1	1235.8	21786.3	15260.4	1258.9	6975.9	5402.4

As can be seen from Table 3, comparing the bending moment and shear force of each check section, the internal force of the main girder of the bridge with corrugated steel webs are greater than that of the bridge with concrete web basically. Only the bending moment of the bridge with corrugated steel webs at 4-4 section which on the top of 2# pier is greater than that of the bridge with concrete webs. It is because the irregularity of the pier arrangement.

(3) Internal force of pier

The seismic internal forces of the piers at the five check sections under transverse seismic excitation are s shown in Table 4.

Table 4–Internal forces of the pier under transverse seismic excitation

Internal force			Shear force (kN)	Bending moment (kN•m)
1#pier	Corrugated Steel web	top of pier	1221.2	8224.0
		bottom of pier	1720.4	33826.4
	Concrete web	top of pier	1785.6	8464.6
		bottom of pier	1950.0	34840.6
2#pier	Corrugated Steel web	top of pier	1496.4	8699.9
		bottom of pier	2117.7	61596.6
	Concrete web	top of pier	1509.9	7118.1
		bottom of pier	2186.0	59456.7

As can be seen from Table 4, the shear force and bending moment of the bridge with corrugated steel webs at the top and bottom of 1# pier are smaller than these of the bridge with concrete webs, while the bending moment of the bridge with corrugated steel webs at the top and bottom of 2# pie are greater than these of the bridge with concrete webs. The reason is also the irregularity of the pier arrangement.

2. Longitudinal seismic excitation

(1) Displacements of main girder

The displacements of the main girder at the five check sections under longitudinal seismic excitation are shown in Table 5.

Table 5 –Displacements of the main girder under longitudinal seismic excitation (mm)

Section	1-1	2-2	3-3	4-4	5-5
Corrugated Steel web	3.04	3.19	3.15	3.85	4.04
Concrete web	2.88	3.11	2.87	3.59	3.55

As can be seen from Table 5, the longitudinal displacements of the bridge with corrugated steel webs are all greater than the bridge with concrete webs, indicating that the vertical bending stiffness of the bridge with corrugated steel webs is smaller and the frame effect is reduced. The influence of reduced stiffness to the displacements of structure is bigger than the seismic action reduction effect caused by decrease of the dead weight of the girder.

(2) Internal force of main girder

The seismic internal forces of the main girder at the five check sections under longitudinal seismic excitation are shown in Table 6.

Table 6–Internal forces of the main girder under longitudinal seismic excitation

section / response	1-1 Bending moment (kN•m)	2-2 Shear force (kN)	2-2 Bending moment (kN•m)	3-3 Bending moment (kN•m)	4-4 Shear force (kN)	4-4 Bending moment (kN•m)	5-5 Bending moment (kN•m)
Corrugated steel web	3933.2	515.2	9989.1	2247.4	656.4	10478.6	5517.2
Concrete web	5081.8	769.0	17848.5	4626.0	964.0	18010.1	6708.6

As can be seen from Table 6, comparing the bending moment and shear force of each control section, the internal force of the bridge with corrugated steel webs are all smaller than the bridge with concrete webs.

(3) Internal force of pier

The seismic internal forces of piers at the check sections under longitudinal seismic excitation are shown in Table 7.

Table 7–Internal forces of the pier under longitudinal seismic excitation

Internal force			Shear force (kN)	Bending moment (kN•m)
1#pier	Corrugated Steel web	top of pier	3301.4	12185.8
		bottom of pier	3525.8	43769.2
	Concrete web	top of pier	3560.1	14200.4
		bottom of pier	3751.7	44163.5
2#pier	Corrugated Steel web	top of pier	783.2	16161.1
		bottom of pier	1435.7	20005.5
	Concrete web	top of pier	1008.5	19227.9
		bottom of pier	1392.3	18765.4

As can be seen from Table 7, the shear force and bending moment of the bridge with corrugated steel webs at the top of 1#and 2#pier and at the bottom of 1# pier are smaller than these of the bridge with concrete webs, while the shear force and bending moment of the bridge with corrugated steel webs at the bottom of 2# pier are greater than these of the bridge with concrete webs. This is also caused by the irregularity of the pier arrangement.

5. Impact of Regularity of Pier Arrangement

5.1 Regularity method

The above analysis shows that the seismic behavior of the rigid frame bridge with corrugated steel webs at the main girder and lower piers is better than the rigid frame bridge with concrete webs, but seismic response of the rigid frame bridge with corrugated steel webs at the higher pier is greater than the rigid frame bridge with concrete webs. Indicating that when the bridge arrangement is irregular, seismic performance of the rigid frame bridge with corrugated steel webs is not totally superior to the bridge with concrete webs. In order to analysis the impact of the regularity of the pier arrangement, this section analyzes the seismic performance under the condition of same pier height. The height of the lower pier of the real bridge changed to the same as the higher pier.

5.2 Response spectrum analysis results

1. Transverse seismic excitation

(1) Displacements of main girder

The displacements of the main girder at the five check sections when the height of piers is identical under transverse seismic excitation are shown in Table8.

Table 8 –Displacements of the main girder under transverse seismic excitation (mm)

Section	1-1	2-2	3-3	4-4	5-5
Corrugated Steel web	1.927	6.428	17.302	7.037	2.668
Concrete web	1.809	5.96	15.190	6.886	2.583

As can be seen from Table 8, the transverse displacements of the bridge with corrugated steel webs are all greater than these of the bridge with concrete web. The results show that when the bridge arrangement is regular, the effect caused by the reduction of the dead weight of the girder is not more outstanding than the bending stiffness decreases of the girder.

(2) Internal force of main girder

The seismic internal forces of the main girder at the five check sections when the height of piers is identical under transverse seismic excitation are shown in Table 9.

Table 9–Internal forces of the main girder under transverse seismic excitation

section / response	1-1 Bending moment (kN•m)	2-2 Shear force (kN)	2-2 Bending moment (kN•m)	3-3 Bending moment (kN•m)	4-4 Shear force (kN)	4-4 Bending moment (kN•m)	5-5 Bending moment (kN•m)

Corrugated steel web	7125.1	1168.1	14378.3	18137.7	1252.8	14376.5	6183.9
Concrete web	7825.7	1179.1	14387.6	18594.0	1276.1	13376.7	6938.3

As can be seen from Table 9, after the bridge arrangement is regular, the internal forces of the bridge with corrugated steel webs are greater than these of the bridge with concrete webs basically. Only the bending moment of the bridge with corrugated steel webs at the top of 2# pier is 7.5% larger than the bridge with concrete webs, while compared to the irregularity of bridge arranged in front (the former 30.3% larger than the latter), the gap was significantly reduced. The main reason is the influence of side span arrangement irregularity.

(3) Internal force of pier

The seismic internal forces of the piers at the five check sections when the height of piers is identical under transverse seismic excitation are shown in Table 10.

Table 10–Internal forces of the pier under transverse seismic excitation

Internal force			Shear force (kN)	Bending moment (kN•m)
1#pier	Corrugated Steel web	top of pier	1265.7	6000.4
		bottom of pier	1880.4	51047.9
	Concrete web	top of pier	1282.4	7936.9
		bottom of pier	1983.1	53710.7
2#pier	Corrugated Steel web	top of pier	1462.8	8744.8
		bottom of pier	1986.6	56928.9
	Concrete web	top of pier	1496.9	10017.8
		bottom of pier	2035.5	58153.6

As can be seen from Table 10, the internal forces of piers of the bridge with corrugated steel webs are all smaller than these of the bridge with concrete webs.

2. Longitudinal seismic excitation

(1) Displacements of main girder

The displacements of the main girder at the five check sections when the height of piers is identical under longitudinal seismic excitation are shown in Table11.

Table 11 –Displacements of the main girder under transverse seismic excitation (mm)

Section	1-1	2-2	3-3	4-4	5-5

Corrugated Steel web	10.26	10.62	9.74	10.48	10.19
Concrete web	9.13	9.55	8.65	9.51	9.08

As can be seen from Table 11, the longitudinal displacements of the bridge with corrugated steel webs are all greater than these of the bridge with concrete webs, this is same to the bridge arrangement irregularity.

(2) Internal force of main girder

The seismic internal forces of the main girder at the five check sections when the height of piers is identical under longitudinal seismic excitation are shown in Table12.

Table 12–Internal forces of the main girder under longitudinal seismic excitation

section / response	1-1 Bending moment (kN•m)	2-2 Shear force (kN)	2-2 Bending moment (kN•m)	3-3 Bending moment (kN•m)	4-4 Shear force (kN)	4-4 Bending moment (kN•m)	5-5 Bending moment (kN•m)
Corrugated steel web	5444.6	378.2	14257.2	1981.1	336.3	8099.0	7900.3
Concrete web	7264.6	398.3	15409.6	2019.6	395.4	10961.3	9818.0

As can be seen from Table 12, the internal forces of the main girder of the bridge with corrugated steel webs are all smaller than these of the bridge with concrete webs, his is same to the bridge arrangement irregularity.

(3) Internal force of pier

The seismic internal forces of the piers at the five check sections when the height of piers is identical under longitudinal seismic excitation are shown in Table13.

Table 13–Internal forces of the pier under longitudinal seismic excitation

Internal force			Shear force (kN)	Bending moment (kN•m)
1#pier	Corrugated Steel web	top of pier	1976.6	17629.2
		bottom of pier	2702.2	52394.3
	Concrete web	top of pier	2051.2	21622.3
		bottom of pier	2826.4	53588.5
2#pier	Corrugated Steel web	top of pier	1602.2	12716.3
		bottom of pier	2231.6	47704.6

Concrete web	top of pier	1914.7	17950.7
	bottom of pier	2577.1	48758.7

As can be seen from Table 13, the internal forces of the bridge with corrugated steel webs are all smaller than these of the bridge with concrete webs. Compared to the irregularity of bridge arranged, the situation of internal force of 2 # pier is improved.

6. Conclusions

(1) The displacements response of the rigid frame bridge with corrugated steel webs are larger than the bridge with concrete webs, indicating that the influence of reduced stiffness to the displacements of structure is bigger than the seismic action reduction effect caused by decrease of the dead weight of the girder..

(2) The internal force of the rigid frame bridge with corrugated steel webs are basically smaller than the bridge with concrete webs, but the internal force of higher piers are greater than these of the bridge with concrete webs because of the irregularity of the bridge layout scheme. The situations are improved when the regularity of the pier arrangement. So the decrease of the dead weight of the rigid frame bridge with corrugated steel webs is advantageous to the seismic responses. But the adverse effects caused by irregularity of pier arrange should be paid more attention in the design of a specific real bridge.

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References

[1] Yin Hang, Liu Bao-dong, Ren Hong-wei. Analysis of the dynamic characteristic of concrete box-girders with corrugated steel webs[J]. Earthquake Resistant Engineering and Retrofitting, 2008,30(2):29-32.

[2] Li Ming-yuan. Study on construction and dynamic characteristic of Po-he bridge[J]. Transportation standardization. 2006(4): 135-138.

[3] Dai Ben-liang. Research on structural dynamic performance of Po-he bridge [J]. Transportation standardization. 2008 (9): 216-218.

[4] Zhang Yong-jian, Huang Ping-ming, Di Jin, Zhou Xu-hong. Free vibration characteristics and experiment study of composite box-girder with corrugated steel webs [J]. Journal of traffic and transportation engineering , 2008,10(5): 76-80.

[5] Wang Chao, Chen Hua-li, Wan Shui. Analysis on the anti-seismic performance of the prestressed composite box-girder viaduct with corrugated steel webs [J]. Shanxi Architecture, 2009,35(29): 291-292.

[6] Zhang Chang-qing, An Yong-ri, An Li-peng. Analysis of seismic response of continuous rigid-frame bridge with corrugated steel webs[J]. Bridge Construction, 2011(3):17-21.

[7] Li Dong-yi. Dynamic behaviours research of continuous bridge with variable cross-section box girder combined with the corrugated steel webs [D]. Xi an: Chang An University, 2010.

[8] Chen Hai-bo. Research on dynamic characteristic of concrete box-girder with corrugated steel webs [D]. Beijing: Beijing Jiao tong University,2006.

[9] Chen Yi-yan, Wang Zhong-yong. Study on Construction and Design of Prestressed Concrete Composite Box Girder with Corrugated Steel Webs [M]. Beijing: People’s Communications Press, 2009.

[10] The People’s Republic of China national standard. (2009). Guidelines for Seismic Design of Highway Bridges (GB50111-2006). Beijing, China: China Standard Press.