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Research on Fatigue Property of Composite Box Girder with Corrugated Steel Webs

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Abstract: Corrugated steel web composite box girder is a new type of steel-concrete composite structures, and it replaces the traditional one with corrugated steel webs and has the characteristics of both concrete and steel webs. The thesis summarizes the research status and results of fatigue property of composite box girder with corrugated steel webs and finds a number of structural fatigue properties that have a significant impact on the factors. Through analysis, this paper presents the prospects of further research of fatigue property in composite box girder with corrugated steel webs and applications of fatigue characteristic analysis in the construction of composite box girder with corrugated steel webs in future. The results show that the fatigue life evaluation method of corrugated steel web composite beam based on fatigue reliability theory should be developed, and the anti-fatigue design of bridge suitable for our national actual situation should be explored, suggesting for bridge construction.

1. Introduction

In 1975, the French CB company firstly proposed the ideas of adopting corrugated steel web as the web of the box girder and the prestressed steel bars in the box girder at the same time, and constructed the world's first corrugated steel web PC composite box girder bridge-Cognac viaduct in 1986, which marks that the corrugated steel web composite structure in the construction of modern bridges in the application of steel web composite box girder have been into depth study.

The early study of the corrugated steel web combined box girder in the United States, Japan and other European developed countries [1] mainly begins with the study of bending, torsion, shear stability and geometrical parameters of corrugated steel webs. With the continuous development of corrugated steel webs and the continuous application of the box girder bridge, the mechanical properties of the whole box girder [2, 3] have been studied, including the static characteristics of box girder bending, torsion, deflection; frequency, vibration mode, damping ratio and other dynamic characteristics study; prestressed configuration, shear connections, steering devices and other research. The research is getting closer to the research level of traditional prestressed concrete box girder, and the whole theoretical system tends to be perfect. The results show that the corrugated steel web combined box girder has better mechanical properties than the prestressed concrete composite box girder, and the composite structure is reasonable and has great application prospect.

China's research on corrugated steel web composite box girders has been relatively late, but universities and other scientific research institutions that have carried out research work have also achieved some results. Some colleges and universities such as Tongji University, Southeast University and Harbin Institute of Technology have carried out a series of studies on the box girder [4,5], and the basic understanding of the corrugated steel composite box girder mechanical properties has been conducted, including corrugated steel web, the shear lag effect of the composite box girder, the pseudo-flat section assumption, the influence of the shear deformation on the deflection and the distortion and torsion, the mechanical properties under the eccentric load and the ultimate bearing capacity [6, 7]. The research results of many scholars and experts have laid a foundation for the establishment and perfection of corrugated steel web composite box girder bridge theory system and its application in practical engineering.

Based on the research results of many domestic and foreign scholars, this paper analyzes the excellent performance of the corrugated steel web composite box girder structure, summarizes the many factors that influence the structural fatigue properties, and analyzes how to improve the fatigue performance of the structure.

2. An overview of corrugated steel web combined box girder

Corrugated steel composite box girder with corrugated steel web has replaced the traditional concrete web, which consists of concrete roof, concrete floor, corrugated steel web, prestressed cable and diaphragm. Concrete plate has compressive strength; corrugated steel web can effectively resist the shear force; the external prestressed cable and the body prestressed cable can enhance the strength and durability of the concrete plate; the diaphragm is set into every interval, in order to improve the components torsion capability, and effectively reduce the warping normal stress; the shear connection is set between the corrugated steel web and concrete as well as corrugated steel web and the end of the

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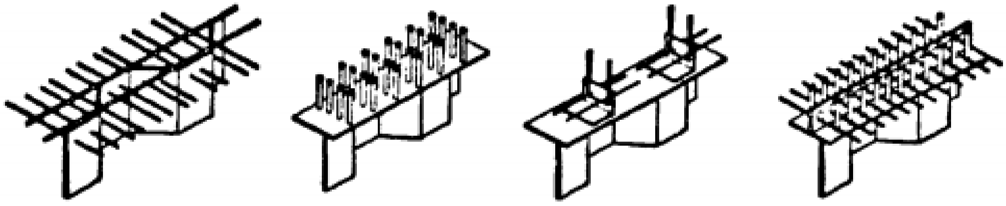
beam between, which can effectively transfer vertical horizontal shear, so that the various materials characteristics can be used. There are four common types of shear connections as shown in Figure 1.



(a) Inserted connector (b) Stud connector (c) Steel connection (d) Combination connection

Fig. 1 Connection form betweencorrugated steel webs and roof, floor

3. Application of corrugated steel web combined box girder bridge

3.1 The unique advantages of corrugated steel webs

Corrugated steel web has the most notable features of the small vertical stiffness and lighter weight. Corrugated steel web combined box girder has a great advantage over traditional prestressed concrete box girder, including the following aspects [8, 9]:

1) The structure of corrugated steel web instead of concrete web can reduce heavy weight and overall stiffness; increase the vibration cycle to improve the seismic performance.

2) The structure has advantages of steel web and concrete material combined, of which corrugated steel web shear ability can avoid the problem of web cracking, and achieve the pretty durability. The longitudinal stiffness of the web is small, which reduces the prestress loss due to factors such as shrinkage creep and temperature change, and improves the prestressing efficiency. The concrete slabs bear most moment, and the radius of the cross section increases.

3) Prestressed layout is reasonable, to avoid the complex process of concreting web embedded pipe; prestressed cable can be replaced in time, conducive to bridge maintenance and reinforcement.

4) Structural economy is strong, the use of corrugated steel web can reduce the upper structure weight. The lower structure's force requirement is lower, and the lower engineering quantity is directly reduced, which can shorten the construction period and reduce the total cost of the project.

5) The diverse patterns of corrugated steel make the corrugated steel composite box girder bridge colorful and has a strong structure beauty. The structure is preferred by the scenic area or overpasses and other bridges having the requirements of beauty.

3.2 Application overview

In 1978, the first corrugated steel web composite box girder bridge was built in France-the Corign bridge. Since then, the corrugated steel composite box girder is widely used in bridge construction (especially France and Japan). Table 1 gives domestic and foreign more typical corrugated steel composite box girder bridges :

Table 1 Typical example of composite box girder with corrugated steel webs bridge

No.	Nation	Bridge Name	Structure
01	France	Cognac bridge	3 span continuous beam
02	France	Maupre Bridge	7 span continuous beam
03	France	Asterix Bridge	2 span continuous beam
04	Japan	New bridge	Simple beam
05	France	Dole Bridge	7 span continuous beam
06	Japan	Japan Yinshan Yu Xingqiao	5 span continuous beam
07	Japan	Japan Ben Valley Bridge	3 span continuous steel structure
09	Japan	Japan pot field viaduct	3 span continuous beam
09	Japan	Under the bridge	3 span continuous steel structure
10	China	Long March Pedestrian Bridge	3 span continuous beam
11	China	Guangshan pull river bridge	3 span continuous beam
12	China	Juancheng Yellow River Highway Bridge	13 cross-beam
13	China	Oasis Bridge	3 span continuous steel structure

4. Research on fatigue behavior of corrugated steel web combined box girder

As early as 1965, foreign scholars carried out research on the corrugated steel I-beam and corrugated steel composite box girder fatigue performance from all aspects. China's research on the fatigue research is later, but the foreign advanced theoretical experience and domestic early research on the steel composite beam fatigue performance

[10] undoubtedly provide an important theoretical basis and reference for the study about the fatigue performance of corrugated steel web combined box girder.

4.1 Fatigue Performance Comparison between Corrugated Steel Webs and Flat Steel Webs

In order to verify that corrugated steel webs are more advantageous than flat steel beams in practical applications, foreign scholars compared their fatigue strength and fatigue life.

In 1965, the British Harrison [11] professor first conducted two corrugated steel web I type steel beam fatigue performance test. In this test, a sinusoidal corrugated steel web is used in the bearing and loading point position set vertical stiffener, which supports the full height, the loading point for the half-web height. The thickness of the first beam is longer than that of the second root, and two beams are tested at 50.8 mm fracture. After analyzing the data, the fatigue strength of the I-beam of the steel plate of the corrugated steel web is improved by at least 25% compared with that of the stiffened ribs. A predictive analysis for the fatigue properties of the I-beam of corrugated steel web is also provided.

On this basis, the Kotaki [12] of the Tokyo Institute of Technology conducted a fatigue test on high strength corrugated web girder in 2003. The test beam consists of two identical corrugated webs of steel, which are connected by three-point bending. The fatigue crack eventually spins near the intersection of the straight and inclined sections, and then extends to the lower flange. Experimental studies have shown that if the vertical stiffeners are replaced by corrugated webs, the fatigue strength can be increased by about 25%. The study confirms the results of Professor Harrison's experiments. However, the fatigue life of corrugated steel webs and conventional web beams still needs to be further studied.

On the basis of the research of Japanese scholars, the United States scholars also conducted a large number of experimental analysis on the fatigue performance of corrugated steel web composite box girder. In 2006, Sherif A.Ibrahim [13] analyzed the fatigue behavior of corrugated steel web combined box girders under different loads by assessing their fatigue life in different stress ranges. In the test, the test beam in the grid and the fold line near the fatigue crack showed welding failure. The results show that the shear deformation should be considered in the fatigue test, and it is pointed out that the corrugated steel web has longer fatigue life than the conventional web beam; the expression of the fatigue life and the applied stress range of the corrugated steel web algorithm. In the same year, Richard Sause [14] conducted the eight test beam trapezoidal wave mesh design, to obtain the trapezoidal corrugated steel web of fatigue crack propagation law. The results show that corrugated steel web I-beam exhibits a longer fatigue life than the general I-beam, and provide a logarithmic relationship between the fatigue life data and the stress (N) and the fatigue life (S_r):

$$\log N = 12.6758 - 3\log S_r \tag{1}$$

4.2 The Influence of Corrugated Steel Geometric Parameters on Its Fatigue Performance

On the basis of a large number of experiments, scholars have found that the geometrical parameters of corrugated steel have important influence on the fatigue performance of the corrugated steel, and the influence of different geometric parameters on the fatigue properties of the corrugated steel is studied. A series of methods that setting reasonable geometric parameters to improve fatigue properties of corrugated steel webs are provided.

In 1979, Korsshy and Varga [15] carried out fatigue tests on some corrugated steel web stiffeners. The stiffened ribs are sprouted at the break of the stiffener, and the corrugated web is cracked at the toe of the tilted portion of the wing. The main conclusions are as follows: with the inclination of the web and the vertical angle decreasing, the stress concentration coefficient at the weld part of the weld toe decreasing correspondingly; with the decrease of the inclination angle of the corrugated web, the fatigue strength of the web beam would increase. Korsshy analyzed the results of two beams testing, to present the logarithmic relationship between stress (N) and fatigue life (S_r):

$$\log N = 7.4274 - 0.05366 S_r \tag{2}$$

In 2001, the American scholar Ibrahim [16] carried out the single-load and periodic load test of the corrugated steel web beam under the four-point load arrangement, and analyzed the fatigue problem of the corrugated steel web beam by finite element method. The weld cracking between the tensioned flange and the web eventually leads to the construction failure, and the fatigue crack initiation occurs at the end of the corrugated steel longitudinal corrugation line. The experimental results are as follows: The fatigue life of the corrugated steel web beam is 50% to 80% higher than that of the full height stiffened web beam, 30% to 50% higher than that of the flat web beam that is not connected to the stiffener at the flange. The high stress zone at the weld between the webs should prevent large local stresses at the height of the 3/4 height of the inclined folds.

The fatigue properties of the web butt joint of corrugated steel web composite beams under shear force are studied in 2003. In this test, the diagonal butt welds and welds perpendicular to the direction of the test specimen are used. In the fatigue test of 9 mm thickness specimens, the fatigue life of the specimens with 0 ° and 15 ° are same, while the fatigue life of the 30 ° oblique butt welds is 1.5 times higher than that of two former. At the same time, the radius of the weld toe also has a great impact on fatigue performance.

In 2005, the Japanese scholar K. Namini [17] used the parametric finite element analysis method to carry out the fatigue test on high-performance corrugated web and high-performance steel girder, to find that most of the fatigue crack occurre in the oblique section of the corrugated web. K.Namini analyzes the geometrical parameters affecting the fatigue performance of the test beam, indicating that the geometrical parameters of the corrugated web have a certain degree of influence on the stress at the weld. The corrugation angle and the bending radius of the corrugated web have a particularly significant effect on the stress concentration factor, which also have a great influence on the fatigue performance.

In 2006, Professor Wang Chunsheng and Xu Yue [18] of Chang'an University conducted the geometric parameters finite element analysis based on the structure and mechanical properties of the corrugated steel web composite box girder. The results show that the stress concentration concentration of the steel web inclination angle θ and the line radius R of the curve are significant, and the stress concentration coefficient is positively correlated with θ and negatively correlated with R.

4.3 Influence of web-to-wing connection on fatigue properties of components

The connection between the corrugated steel web and the concrete wing is responsible for the shear stress of the transfer member, which is accompanied by a certain stress concentration, and it tends to be a weak link in the component. Its fatigue performance has also aroused widespread concern of scholars.

In 1997, Japan's Waseda University's scholar Touxian [19] reported the corrugated steel web composite beam fatigue test. Touxian made a fatigue test on the prestressed composite plate girder and corrugated steel web combined box girder. In the A and B-type test, the beam is used in the upper and the end of the corrugated web reserved hole, and in the C-type test, the beam is used in steel wings welded steel and connected concrete wing plate. The fatigue failure of the test beam of the A and B test beams is fatigue fracture of the lower wing; the fatigue failure of the C-type test beam is the collapse of the reinforced concrete wing plate or the buckling of the steel plate. The experimental results show that the design structure of the corrugated steel web has a great influence on the fatigue performance, and the stress concentration of the corrugated steel web should be improved.

In 2001, the fatigue performance of the web-connected welds of corrugated steel web composite beams was studied in Japan. In the upper and lower concrete vanes of corrugated steel web composite beams, four kinds of corrugated steel web joints are set in the form of four kinds of corrugated steel web joints: lap welded joint, lower than web height spliced welded joint, high splice welded joints, and web butt welds. The fatigue strength of corrugated steel webs with different welded joints was studied based on the fatigue test of corrugated steel webs combined with plate girder and box girder. The resistance of corrugated steel webs Fatigue design has a reference value.

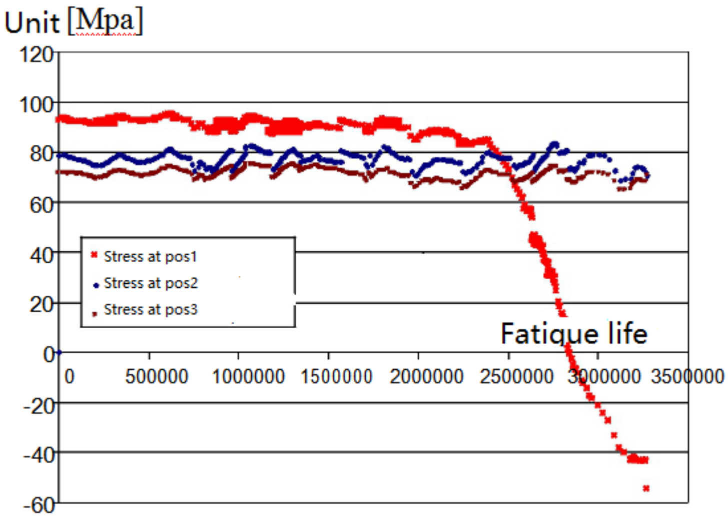


Fig. 2 Stress history at the characteristic points of specimen No. 5

In 2013, B. Kövesdi et.al. [20] analyzed the pure bending fatigue performance of corrugated steel web composite box girder, which is based on the bending and shearing behavior of corrugated steel web combined box girder. The strain gauge of crack initiation zone was studied (Figure 2 shows the stress change at the measuring point of the No. 5 test beam). At the same time, the influence of the weld size on the fatigue performance is analyzed and the importance of the size of the spot weld is emphasized, which provides basis for the anti-fatigue design of steel-web composite box girder bridge.

4.4 Study on Fatigue Behavior of Components Based on Damage Mechanics and Reliability

In recent years, the emergence of damage mechanics and the development of fracture mechanics have provided a new theoretical basis and ideas for the traditional fatigue analysis based on the experience. In addition, fatigue life assessment based on reliability theory has also aroused the concern of scholars.

Li et.al. [21] studied the impact of the corrugated steel web box box fatigue damage on the bending capacity. Based on the production of two external prestressed corrugated PC beam steel webs, one of the beams is subjected to the static loading test, the other beam is subjected to the fatigue test until the static loading process is carried out after the fatigue failure, to derive the basic elastic-plastic mechanical properties, the typical fatigue damage characteristics and the bending strength of the two test beams. Based on the test results, the strength degradation law of concrete after fatigue damage and the constitutive relation of concrete material before and after fatigue damage (as shown in Figure 3 and Table 2) are deduced. The whole process of two kinds of test beams is analyzed by nonlinear process analysis program. The results show that the fatigue damage of the corrugated steel web has a slight effect on the flexural capacity of the composite box girder, but it significantly reduces the ductility of the whole structure.

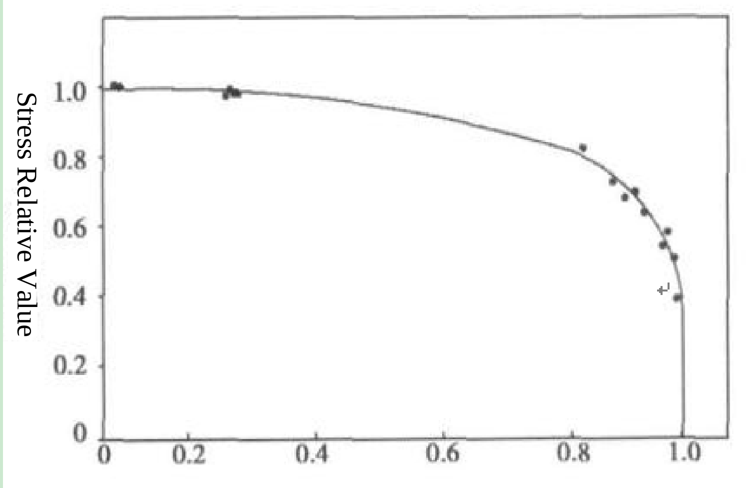


Fig. 3 Strength degradation curve for concrete suggested by this paper

Table 2 Comparasion of typical parameters of stress-strain relationship for concrete

Project	Axial Compressive Strength (Mpa)	Elastic Modulus (Mpa)	Peak Strain (με)	Limit strain (με)
Before injury ①	38.2	42.9	1793	3360
After injury ②	36.02	32.6	1755.4	2200
②/①	0.94	0.76	0.97	0.65

5. Conclusion

The research results of corrugated steel web composite box girder show that the fatigue performance of corrugated steel web composite box girder is mainly affected by the geometrical parameters of corrugated steel web and the connection of shear force. The optimized design can improve its structural mechanics performance, lay the foundation for anti-fatigue design. But the relative geometric parameters of different shear connections still need to be discussed step by step. It is necessary to study the diversity and complexity of the fatigue performance factors of the corrugated steel webs. At the same time, in order to promote the application of corrugated steel web composite box girder bridge better, it is necessary to study the fatigue life of the box girder structure and the fatigue damage during the later use further

With the rapid development of corrugated steel web combined box girder bridge, the fatigue durability requirement of bridge is gradually improved. This paper should take this as an opportunity to grasp the main direction of the future work of bridge fatigue research and develop fatigue life evaluation method based on fatigue reliability theory, and obtain the theoretical analysis method to simulate the development of fatigue failure process of corrugated steel web composite beam, to explore the practical situation of China's bridge anti-fatigue design specifications for the bridge construction of the proposed recommendations.

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