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Review of Research on Corrugated Web Steel Beams

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Abstract: Wave-shaped web plate steel replaces the traditional flat web plate in order to achieve greater planar stiffness and higher shear buckling capacity with a thinner web plate thickness. Additionally, the local compressive load-bearing capacity and fatigue resistance are also improved, resulting in higher load-carrying capacity and economic advantages for this type of steel. This translation summarizes the research conducted by domestic and international scholars on wave-shaped web plate steel, focusing on its stability performance, shear buckling, fatigue resistance, and stress concentration. Finally, it concludes by discussing the factors influencing these four performance aspects and proposes improvement methods.

1. Introduction

The corrugated web plate has been widely used for a considerable period of time. Initially, it found extensive applications in the aerospace and marine sectors, and later expanded to industrial and civil construction. In the early 1980s, the Northeast Heavy Machinery Institute of China conducted pioneering research and successfully produced the world's first fully corrugated web H-beam in 1985 [1]. Corrugated web plate steel beams exhibit good out-of-plane stiffness even without the addition of stiffeners. Compared to beams with flat web plates, they demonstrate better overall stability, allowing for the use of thinner web plate thickness to withstand shear buckling capacity. Due to the corrugated shape of the web plate, the load characteristics differ from those of conventional flat web plates. Extensive research has been conducted both domestically and internationally on the stability performance, shear strength, stress concentration, and fatigue resistance of corrugated web H-beams.

2. The main characteristics of corrugated web plate

2.1 Stability Performance

Huang Haiyang [2] had conducted elastic-plastic nonlinear analysis on steel beams with the same steel volume but different wave-shaped web plate designs, including piecewise, trapezoidal, and sinusoidal wave profiles, using finite element analysis software. The analysis considered geometric initial defects, geometric nonlinearity, and material nonlinearity. The study also comprehensively examined the influence of geometric parameters such as web plate thickness, beam height, and wave period on the elastic-plastic overall stability performance of the steel beams. Through nonlinear buckling analysis, a comparative analysis was performed on the elastic-plastic overall stability critical load, load-lateral displacement curves, and stress distribution on the upper flange of the beams at

critical load for the three types of wave-shaped web plate steel beams with the same steel volume. The results indicate that the piecewise wave-shaped web plate steel beam has a higher elastic-plastic overall stability load-bearing capacity compared to the trapezoidal and sinusoidal wave profiles.

A study conducted by Yu Luhan [3] and his team analyzed the factors affecting the overall stability performance of cantilever steel beams with uniformly distributed load on the upper flange and investigated the calculation methods for the elastic flexural-torsional buckling load of the components. By utilizing finite element analysis software, they compared the critical buckling loads under different conditions and identified the influencing factors and their magnitudes. The results indicated that the wavelength of the web had the greatest impact on the overall stability performance of the corrugated web cantilever steel beams. Reducing the dimensions of the flanges highlighted the advantages of the corrugated web cantilever steel beams. However, there were several issues with the existing theoretical calculations for the overall stability of the sinusoidal corrugated web cantilever steel beams.

2.2 Shear Performance

Hu Jinmu [4] and his colleagues have pointed out that there is some debate regarding the selection of the parameter n in the formula. In order to address this issue, they have developed a finite element analysis model to simulate and analyze the elastic shear buckling strength of corrugated steel webs. By comparing the results obtained from the calculated elastic shear buckling strength formula with numerical results for different values of n, they have determined the optimal value for n. The findings demonstrate that the theoretical formula for the elastic shear buckling strength of corrugated steel webs, which takes into account three shear buckling modes, is highly accurate and can serve as a valuable reference in engineering design.

Elgaally [5] et al. conducted experimental and computational analysis on the shear strength of corrugated steel web beams. The results showed that the shear force in the beam is solely carried by the steel web, and the shear capacity of the beam is controlled by the buckling strength of the web. The shear strength of the corrugated steel web is mainly influenced by the thickness, height, geometric shape, material properties, and initial geometric defects of the web.

Mozhdeh Amani [6] et al. conducted a study on the shear strength of corrugated steel web beams made of EN 1.4162/LDX 2101 stainless steel. Shear tests were performed on four full-scale trapezoidal corrugated web beams. Prior to testing, Digital Image Correlation (DIC) was used to measure the actual geometric defects of the web. Supplementary finite element analysis was carried out to evaluate the sensitivity of shear strength to initial defects. The test results showed that all beams reached the shear yield strength when the local slenderness ratio was $\lambda = 0.7$. Subsequently, strain hardening occurred, and the strain hardening strength was 8-18% higher than the yield strength. This indicates that the limit $\lambda = 0.25$ specified in the European code for achieving plastic shear strength in corrugated webs is quite conservative for stainless steel. Based on the sensitivity study of defects, the maximum amplitude was estimated to be amax/200, where amax represents the maximum wavelength of the corrugation folds, and the resulting limit strength was within 3% of the experimental results. When the amplitude increased to hw/200 (hw being the height of the web), the estimated limit strength decreased by an average of 25%. Among the three beams studied, it was found that other forms of initial defects were more severe than the first buckling mode. Furthermore, the study revealed that regardless of the number of modes, the higher the extent of mode extension on the web, the greater the degradation of the final shear strength.

2.3 Fatigue Resistance

Ibrahim S A [7] discovered that the fatigue life of a flat web beam is reduced when transverse

stiffeners are welded due to stress concentration. By evaluating the fatigue life of a trapezoidal corrugated web beam under different stress ranges, the performance of the trapezoidal corrugated web beam under fatigue loading was studied. The test beams failed due to fatigue cracks, which initiated at the welds between the web and the tension flange near the corrugations of the web. The relationship between the stress range "Fr" and the number of failure cycles "N" was established for the trapezoidal corrugated web beam. The fatigue life of the tested trapezoidal corrugated web beam was compared with other types of beams, and the test results were found to be consistent with the current AASHTO specifications.

In the past 20 years, B. Kövesdi [8] finds that corrugated steel plates have been increasingly used as web plates for hybrid and composite bridge girders. Compared to traditional flat web structures, corrugated web girders have many advantages, but there are still many design issues that need to be addressed due to the adoption of new structural arrangements. Determining the fatigue life of trapezoidal corrugated web girders is quite challenging, as the flanges have complex stress fields and the fatigue detail categories have not been clarified. This topic has received attention in Hungary because a highway bridge was designed and constructed over the Tisza River between 2006 and 2011. In the literature, only a small amount of research has been conducted on the fatigue performance of corrugated web girders. Therefore, experiments were conducted to analyze the fatigue performance of corrugated web girders under pure bending and combined bending-shear actions. Additionally, based on the experimental results, suggestions for fatigue detail categories were proposed to support bridge design. The influence of corrugation shape, normal stress ratio, combination of normal and tangential stresses, and weld size on fatigue life was investigated through experimental research.

The application of trapezoidal corrugated web beams in hybrid and composite bridge structures has been increasing. However, there are still many design issues that need to be addressed due to the adoption of new structural arrangements. This study focuses on the fatigue performance of trapezoidal corrugated web beam and conducts experimental research to analyze its performance under pure bending and bending-shear combined actions. The experimental results provide suggestions for determining the fatigue detail category and investigate the effects of corrugation shape, stress ratio, stress combination, and weld size on fatigue life. It is found that trapezoidal corrugated web beams are prone to fatigue under repetitive and large traffic loads. Jun Xu [9] conducted large-scale fatigue tests on trapezoidal corrugated web beams with inclined I-section. The test results show that the critical crack initiates in the bending-shear combined region, while multiple cracks occur at the weld toe of the web-flange connection detail in the constant moment region. When the critical crack extends along the thickness of the flange plate to one side of the flange plate edge, the test beam almost fails simultaneously. The other two less critical cracks in the constant moment region approach failure in the final stage of crack propagation. Therefore, the fatigue failure criterion of the test beam is conservatively recommended as the worst-case scenario in two situations: when the critical crack length reaches 1.6 times the thickness of the flange plate or extends along the thickness of the flange plate. The influence of corrugation parameters on the stress condition of the fatigue-sensitive point was studied through parameterized finite element analysis. The finite element analysis results show that shear action causes the critical crack position to shift from the constant moment region to the bending-shear combined region, resulting in a 11.3% reduction in the fatigue life of the test beam.

2.4 Stress Concentration

In order to analyze the effect of geometric dimensions on stress concentration in trapezoidal corrugated web I-section beams, Chen [10] et al. established the corresponding ABAQUS finite element analysis model and verified its accuracy by using existing experimental results of trapezoidal corrugated web I-section beams. A large number of nonlinear finite element analyses were conducted

on the trapezoidal corrugated web I-section beams using ABAQUS software, studying the influence and regularity of corrugation amplitude, thickness, parallel section length, corrugation angle, and radius of curvature on stress concentration in the web and flange. The results showed that the finite element analysis model for trapezoidal corrugated web I-section beams was reasonable. The variation of corrugation angle, radius of curvature, and web thickness had a significant influence on stress concentration in the trapezoidal corrugated web I-section beams, while the variation of corrugation amplitude and parallel section length had a relatively small influence on stress concentration in the steel beams.

3. Conclusions

Numerous studies both domestically and internationally have shown that corrugated web beams have been widely used in seismic design of structural steel beams in buildings. However, the initial defects and stress concentration phenomena in corrugated web beams affect their maximum effectiveness in building applications. Moreover, the existing theoretical calculations for the overall stability of corrugated web beams still have certain issues that impact their practical applications. Nevertheless, selecting the appropriate form of corrugated web beams in architectural design can effectively improve their overall stability. Properly choosing the geometric dimensions of the web and reducing the initial geometric defects can significantly enhance the buckling resistance and energy dissipation capacity of corrugated web steel beams, thus promoting the establishment of theoretical calculation methods.

Furthermore, the application of composite beams has become increasingly widespread in recent years, leading to a growing number of studies on the local bearing capacity, axial compression performance, and composite material corrugated web beams. Since the founding of the People's Republic of China, the country's infrastructure development has been rapidly progressing, expanding the potential applications of corrugated web beams. In order to keep up with the visual and sustainable development path of the construction industry, it is necessary to advance research on corrugated web beams.

References

[1] Cao Hongde, Cai Zhihua, Zhang Wenzhi. Hot rolling process for corrugated web H-beams: China, 86101365A [P], 1988, 03, 30

[2] Huang Haiyang, Zhu Puning, Huang Bingsheng, et al. Comparative analysis of elastic-plastic overall stability performance of steel beams with different corrugated web panels [J]. Steel Structures, 2017, 32(07): 60-66.

[3] Wang P, Liu C, Liu M. Large deflection behavior of restrained corrugated web steel beams in a fire[J]. Journal of Constructional Steel Research, 2016, 126:92-106.DOI:10.1016/j.jcsr.2016.07.017.

[4] Hu Jinmu, Wei, Xing, Feng Wenxian. Numerical Simulation Study on Elastic Shear Buckling Strength of Trapezoidal Corrugated Steel Web [J]. Development Orientation of Building Materials, 2017, 15(24): 42-45.

[5] Elgaaly M, Hamilton R W, Seshadri A. Shear Strength of Beams with Corrugated Webs [J]. Journal of Structures Engi-neering. 1996, 122(4):390-398.

[6] Mozhdeh Amani, Mohammad Al-Emrani, Mathias Flansbjer, Shear behavior of stainless steel girders with corrugated webs, Journal of Constructional Steel Research, Volume 210, 2023

[7] Ibrahim A S, El-Dakhakhni W W, Elgaaly M. Fatigue of Corrugated-Web Plate Girders: Experimental Study[J]. Journal of Structural Engineering, 2006, 132(9).

[8] Kövesdi B, Dunai L. Fatigue life of girders with trapezoidally corrugated webs: An experimental study[J]. International Journal of Fatigue, 2014, 64.

[9] Xu J, Sun H, Cai S, et al. Fatigue testing and analysis of I-girders with trapezoidal corrugated webs[J]. Engineering Structures, 2019, 196.

[10] Chen Liang, Zheng Yanyin. Influence of Changes in Web Geometry Dimensions on Stress Concentration of I-shaped Steel Beams with Trapezoidal Corrugated Web [J]. Journal of Nanjing University of Technology (Natural Science Edition), 2012, 34(04): 138-144.