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Fatigue life of girders with trapezoidally corrugated webs: An experimental study

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ABSTRACT

Corrugated steel plate has been increasingly used in the last 20 years for beam webs in hybrid and composite bridges. Girders with corrugated webs have many advantages over traditional structures with flat webs, but due to the new structural layout, there are still many design questions that need to be solved. In cases with girders with trapezoidally corrugated webs, the determination of the fatigue life is rather difficult because of the complex stress field in the flanges, and the fatigue detail category has also not been elucidated. This topic has gained importance in Hungary related to a highway bridge on the Tisza River designed and constructed between 2006 and 2011. There are only a small number of investigations dealing with the fatigue behaviour of corrugated web girders in the literature. The aim of the current tests published in this paper is the analysis of the fatigue behaviour of the corrugated web girders under pure bending and combined bending and shear. Furthermore, a proposal for the fatigue detail category is developed based on the test results to support the bridge design. The tests were completed to study the effect of the corrugation profile, the normal stress ratio, the effect of the combined normal and shear stresses and the weld size on the fatigue life.

1. Introduction

Corrugated steel plate has been used in many fields for a long time because of its favourable properties. For the last 20 years, it has been increasingly used as a beam web. This structural layout has spread also spread to bridge construction, especially in hybrid and composite bridges. The first hybrid bridge with trapezoidally corrugated webs was built in France in 1986 (Pont de Cognac bridge). Because of the great number of advantages of this structural layout, it has quickly spread, especially in Japan [1], where numerous hybrid bridges have been built or are still under construction with corrugated webs. Because of the features of corrugation, the application of corrugated steel webs has numerous advantages. Because of the corrugation profile, the normal stiffness of the web in the longitudinal direction is smaller than in the case of the usual I-girders with flat webs. Therefore, the prestressing of the flanges can be more efficient. The resistance against buckling – locally and globally – increases, so the number of stiffeners or diaphragms may be significantly reduced. In comparison to flat webs, there is a high bending stiffness in the transverse direction, which allows reduction of the number of cross frames in box girder bridges. Because of the increased stiffness, the web thickness may be reduced. Therefore, the dead load of the structure may be smaller, leading to easier and faster building processes especially in cases of incremental launching. The economical design of bridges requires the usage of slender structures. To avoid local or global plate buckling, numerous stiffeners are used, which are relatively expensive, and they may reduce the fatigue life of the structure. Corrugated webs increase the buckling strength of the structure. Therefore, the number of the stiffeners can be reduced, which can have a positive effect on the fatigue behaviour of the structure.

The Móra Ferenc bridge at the M43 highway over the Tisza River was designed and constructed with corrugated steel webs in Hungary between 2006–2011. The completed bridge can be seen in Fig. 1. It is an extradosed highway bridge with three spans (90 m + 180 m + 90 m). The bridge has a hybrid superstructure with prestressed reinforced concrete flanges and corrugated steel webs. The bridge superstructure is a box cross-section with 3 cells and varying web depth. The bridge erection was started in 2008 and finished in 2011. Despite this girder type often being used in bridges in the last 20 years, there are only a few investigations available in the literature dealing with the fatigue behaviour of these structures.

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Fig. 1. Móra Ferenc M43 highway bridge on the Tisza river [2].

The existing experimental, analytical and numerical investigations were analysed, and it was concluded that the applicability of the previous experiments are strictly limited because the test results can be used only for special corrugation profiles and the stress ratios analysed in the previous experiments. Given the lack of research results on the fatigue life of corrugated web girders, there are no recommendations in the standards [3]. Because of these facts, an experimental research program was designed and executed at the Budapest University of Technology and Economics, Department of Structural Engineering on six large-scale test specimens to investigate the fatigue life of girders with the same corrugation profile as used in the Móra Ferenc highway bridge. The current paper investigates the experimental research program and the test results.

2. Review of previous research

2.1. Experimental investigations

The first experiments on the fatigue life of steel girders with sinusoidal corrugated webs were completed by several researchers. Harrison (1965) tested two I-girders with sinusoidal corrugated webs under four-point-bending [4]. Korashy and Varga [5] investigated 11 I-girders with partial corrugated webs under four-point-bending in 1979. In the study, waves were placed at a defined distance from each other along the girder length. The study was not limited to homogeneous girders. It was also extended to hybrid girders as well. A comparison between hybrid and homogeneous beams revealed that there were no significant differences in the fatigue life between the two girder types. The wave-stiffened beams, in which conventional transverse stiffeners were replaced by the web corrugation, displayed 25% higher fatigue strength than the conventionally stiffened beams with transverse stiffeners welded to the web alone. The wave-stiffened beams displayed 47% higher fatigue strength than the conventionally stiffened beams with the stiffeners welded to the tension flange transversely. They displayed 56% higher fatigue strength than beams with stiffeners welded to the tension flange longitudinally.

In 2005, Machacek and Tuma [6] performed numerous experimental investigations on sinusoidally corrugated girders to analyse the fatigue behaviour due to shear force, patch load and moving loads of crane girders. For all test specimens, the web was sinusoidally corrugated, with a wave amplitude ±20 mm. Three series of specimens were produced with different web thicknesses (t_w = 2 mm, t_w = 2.5 mm and t_w = 3 mm). Under shear loading, the fatigue cracks initiated from the weld toes at web-flange or web-stiffener connections and propagated quickly to the fracture of the girder. Based on the test results, the fatigue detail categories were recommended for design of girders with sinusoidally corrugated webs under shear and transverse loading.

The first fatigue analysis of girders with trapezoidally corrugated webs was completed by Ibrahim in 2001 [7]. In the experimental program, 6 specimens were tested under four-point bending. A web depth of the girder was 500 mm and the thickness 3.18 mm. The flange size was for all specimens was 150 × 12 mm, the corrugation depth 75 mm and the wavelength 434 mm. The bend radius between the inclined fold and the longitudinal fold was 27 mm, and the corrugation angle was 36.9°. The size of the web-to-flange fillet welds was 5 mm. The calculated stress range on the top of the bottom flange varied between 64.7 MPa and 131 MPa. All six girders failed from fatigue cracks, and failure initiated at the web-to-flange weld toe along an inclined fold and propagated in the bottom flange within the constant moment region. The point of the crack initiation was generally at the end of an inclined fold where the bend region began.

Eight large-scale fatigue specimens were tested at Lehigh University in 2004 by Sause et al. [8–10]. The test girders were made of A709 HPS 485W steel and loaded under four-point-bending. The web depth of the analysed girders were 1200 mm, and the web thickness was 6 mm. The flange size was for all specimens 225 × 20 mm. The corrugation angle was 36.9°, and the radius of the corrugated plate was 120 mm. The inclined folds had a slope of 3:4 with 200 mm projection parallel to the flange edges and 150 mm depth of corrugation. The web to flange weld size was 8 mm. The total length of the girder was 7400 mm, and the distance between the two end supports was 7000 mm. The nominal stress range varied from 103 to 138 MPa. Each girder failed from a fatigue crack propagated in the bottom flange from the web-to-flange fillet weld toe within the constant moment region. The results of the study demonstrated that I-girders with corrugated webs exhibit a fatigue life that is generally longer than that of conventional I-girders with transverse stiffeners but shorter than I-girders with unstiffened flat webs. The fatigue life of the robotically welded girders was 42% higher than the fatigue life of similar girders welded using semiautomatic GMAW.

In 2006, a total of 6 specimens with trapezoidally corrugated steel webs were tested by Ibrahim et al. [11–13]. A simple