International Journal of Steel Structures
September 2012, Vol 12, No 3, 321-338
DOI 10.1007/s13296-012-3003-9

International Journal of
STEEL
STRUCTURES

www.springer.com/journal/13296

Mechanical Behavior and Analysis of Composite Bridges with Corrugated Steel Webs: State-of-the-Art

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Abstract

The composite bridges with corrugated steel webs have excellent properties, such as lightness of girders, efficiency of introducing prestress forces, short construction period, optimum force distribution, good seismic performance, and aesthetics appearance etc., which have greatly promoted the application of such bridges. The objective of this paper is to provide and summarize important references related to the analysis, design and construction of composite bridges with corrugated steel webs. Subjects discussed in this review include (1) structural configuration and application; (2) shear behavior; (3) bending behavior; (4) torsional behavior; (5) patch loading resistance; (6) dynamic behavior; (7) long-term behaviors including fatigue and creep; (8) component connections; (9) analysis method and theory; (10) new concept application. The literature survey presented herein mainly focuses on papers written in English, Japanese, German and Chinese in relation to composite bridges with corrugated steel webs.

Keywords: state of the art, composite bridges, corrugated steel webs, design and construction

1. Introduction

Prestressed concrete girders with corrugated steel webs are one of the promising concrete-steel hybrid structures applied to highway bridges, which include prestressed slabs, corrugated steel webs and internal or external tendons (Fig. 1). The way to substitute corrugated steel webs for concrete webs of a box girder bridge will result in no restraint among the upper or lower deck slab and webs of the bridge, which will alleviate influences on the structure due to concrete creep, drying shrinkage and temperature differences. Prestressing can be efficiently introduced into the top and bottom concrete slabs due to the so-called “accordion effect” of corrugated webs. The strength, stability of the structure, and material efficiency can be improved by concrete slabs combined with corrugated steel webs (Liu, 2005a; He *et al.*, 2007a).

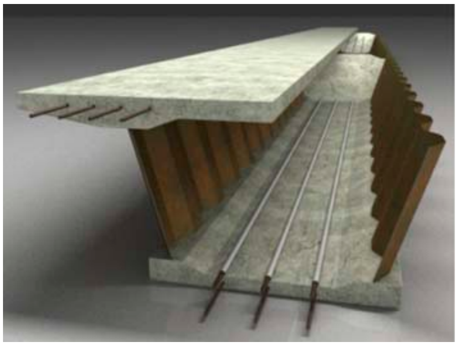

Figure 1. Prestressed concrete girders with corrugated steel webs.

Merits of replacing the conventional webs of box or I-girders with corrugated steel webs are summarized as follows: (1) the decreased dead weight of corrugated steel webs, compared to concrete webs, leads to reduced seismic forces and smaller substructures, which will result in lower construction cost and the ability to increase the girder’s length; (2) the corrugated steel webs without additional stiffeners have higher shear-buckling strength than that of flat plate steel webs; (3) the corrugated steel webs are more easily fabricated and constructed than concrete webs. Elimination of the need for concrete placement for the webs reduces field work and saves labor; (4) prestressing can be efficiently introduced into the top and bottom concrete slabs due to the so-called “accordion effect” of corrugated webs; (5) the external post-tensioned tendons is used for PC box girders with corrugated steel webs, which has many advantages over the internal bonded

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Note.-Discussion open until February 1, 2013. This manuscript for this paper was submitted for review and possible publication on November 21, 2011; approved on July 23, 2012.

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tendons in view of maintenance; (6) shear and bending forces can be distributed optimally into the corrugated steel webs and the concrete slabs respectively. However, a non-composite corrugated web girder will deflect and twist under in-plane bending. The costs associated with the extra lateral bracing may offset the advantage of corrugated steel webs.

In 1982, the advantages of using corrugated steel webs along with external prestressing for box or I-girder composite systems in bridge construction were recognized by Campenon Bernard BTP, France. The first highway bridge using corrugated webs was the Cognac Bridge, built in France as an experimental bridge in 1986. Over a period of time extending from 1987 to 1995, three more bridges with corrugated steel webs were built in France: Val de Maupre Viaduct, that was built over the river Charente in 1987; Parc Asterix Bridge was completed in 1989 and Dole Bridge was finished in 1995 (Combault, 1988; Cheyrezy and Combault, 1990; Virlogeux, 1992).

It appears that these French bridges inspired a number of similar structures in Japan which were built in the 1990s starting with the Shinkai Bridge in 1993 (Kondo *et al.*, 1994; Yoda *et al.*, 1994), followed by Matsunoki No. 7 Bridge in 1995, and Hondani Bridge in 1997 (Mizuguchi *et al.*, 1998). The research committee for hybrid structures with corrugated steel webs published the design manual to enhance the application of such bridges in 1998 (JSCE, 1998). Liu *et al.* (2002) and Tezuka *et al.* (2002) presented the structural characteristics of the PC box girder bridges consisting of corrugated steel webs with horizontal curvature (Nakano viaduct, and Shirasawa Bridge). Yasukawa (2003) and Maeda *et al.* (2005) introduced the design, construction and scaled model tests of the first extradosed bridge (Ritto Bridge) with corrugated steel webs in Japan. Yasuzato *et al.* (2005) first introduced the structural features of corrugated web girder as launching nose, outlined the design of the nose, and conducted some experiments to realize this new type of composite girder for Torisaki River Bridge. Fujioka and Kakuta (2006) introduced the characteristics and guidelines of Corru-T construction technique, and presented the design and construction details of the first PCT-girder bridge (Sou River Bridge) in Japan. Otani and Arai (2006) introduced the first cable-stayed bridge with corrugated steel webs (Toyota Arrows Bridge) in Japan.

Similar bridges were reported have been built or under construction in Sweden, Taiwan, USA, Korea and Germany (König *et al*., 1994). Novák *et al.* (2007) carried out a comprehensive research on general behavior and the detailing of bridges with corrugated steel webs based on Altwipfergrund Bridge in Germany. Jung *et al.* (2011) optimized the length of the steel launching nose, and analyzed the mechanical performance under construction stage to verify the safety of Ilsun Bridge in Korea. Beams with corrugated webs are more and more widely used in USA. Pennsylvania Department of Transportation (PennDOT) was sponsoring research adopting corrugated webs to realize additional benefits from high performance steel, and intended to construct a demonstration bridge with corrugated web I-girders (Abbas, 2003).

In China, Meng *et al.* (2006) analyzed the mechanical properties of the first footbridge with corrugated steel webs (Changzheng Bridge). He *et al.* (2007b, 2008a), and Li *et al.* (2009) introduced continuous prestressed composite box-girder bridges with corrugated steel webs (Kuandian Bridge, Juancheng Yellow River Bridge), design and construction experiences about these bridges were summarized and discussed.

Based on the design and construction data of all completed composite bridges with corrugated steel webs, the structural configuration for such bridges can be divided into simply supported bridges, continuous bridges, rigid frame bridges, and cable-stayed bridges (Liu, 2005a,b). According to the cross section, there are two general type: box girders (trapezoid or triangle) and I-girders. As for the construction methods, besides conventional full scaffold construction, balanced cantilever construction and incremental launching construction, a construction method by incremental launching the corrugated steel webs as nose was proposed to shorten construction period (Yasuzato *et al.*, 2005; Okusumi, 2008; He *et al.*, 2008b). Figure 2 shows the relationship between the maximum span and structural configuration. The maximum span for the simply supported bridges, continuous bridges, T-type rigid frame bridges, continuous rigid frame bridges and cable-stayed bridges is 51, 142, 95, 150, and 235 m respectively. Figure 3 shows the number and proportion of each structural configuration. Continuous and rigid frame bridges with the main span length from 50 to 150 m account for about 80% of the total number, which indicates these two kinds of structural configurations are suitable for composite bridges with corrugated steel webs.

The objective of this paper is to present highlights of references pertaining to composite bridges with corrugated steel webs that have been published prior to 2012. Such papers will complement previously published literature survey articles that (1) would provide the theoretical

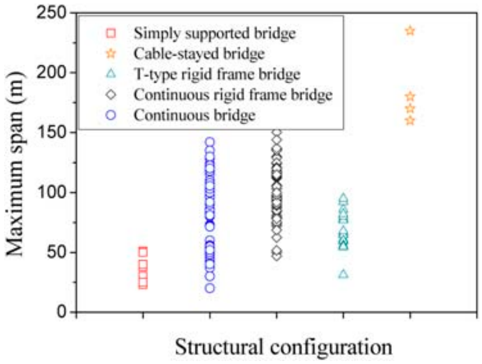


Figure 2. Relation between maximum span and structural configuration.

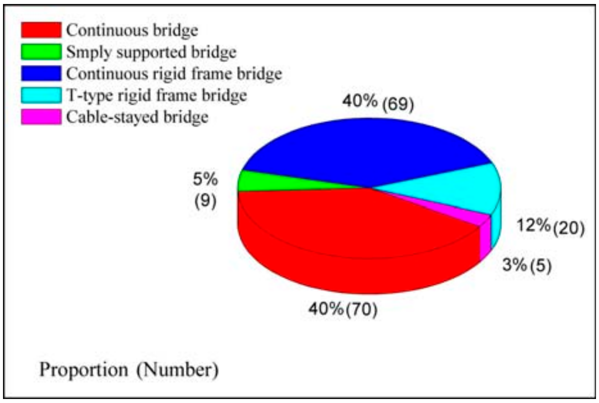


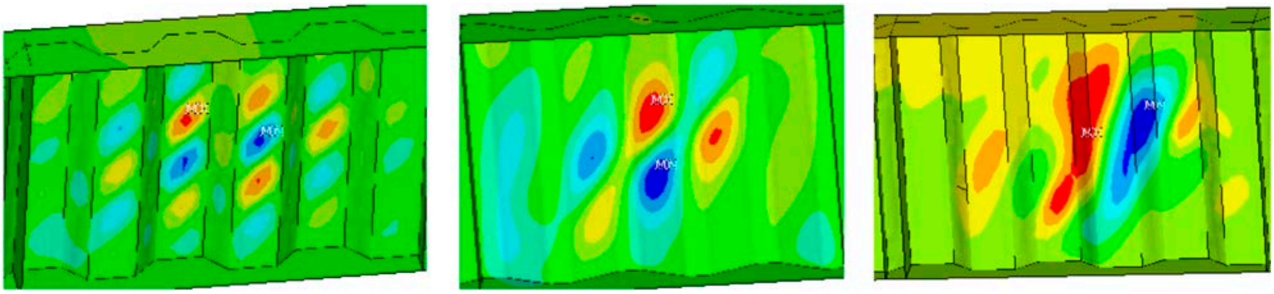
Figure 3. Number and proportion of each structural configuration.

foundation or play an important role in the development of composite bridges with corrugated steel webs in terms of the analysis, design and construction specifications; (2) would represent the levels and hotspots of current research of such bridges; and (3) would facilitate continued research efforts.

2. Shear Behavior

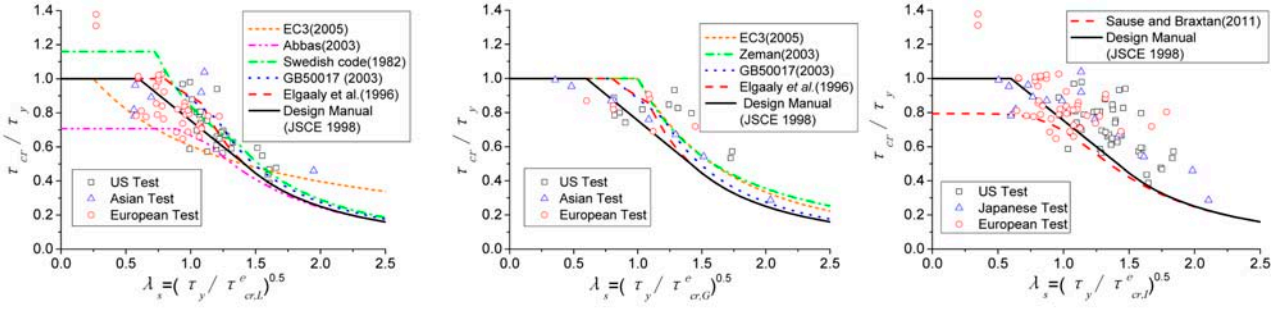
Shimada (1965) was the first researcher who studied the shear strength of steel plate girders with folded web. Then, shear strength of trapezoidal corrugated steel webs has been studied extensively. Easley and McFarland (1969) proposed the global shear buckling equation of corrugated web by treating it as an orthotropic flat web. The corrugated steel web is assumed to provide the shear capacity of the girder where the shear strength is controlled by buckling and/or shear yielding of the web (Bergfelt and Leiva-Aravena, 1984; Leiva-Aravena and Edlund, 1987; Metwally, 1998; Sayed-Ahmed, 2001, 2007; Abbas, 2003). Lindner and Aschinger (1988) presented test results for the shear strength of steel trapezoidal corrugated webs and suggested using 70% of the shear buckling stress as the nominal shear strength for design. Luo and Edlund (1994, 1996a) analyzed the buckling of trapezoidally corrugated panels under in-plane loading by spline finite strip method and finite element method. The influence on the elastic buckling load of various parameters, such as geometry, loading patterns and boundary conditions, etc., was studied. Elgaaly *et al.* (1996) presented experimental and analytical results for steel beams with trapezoidal corrugated webs loaded predominantly in shear, and proposed the bucking formulas of corrugated steel webs which were based on the local buckling of the corrugation folds as isotropic flat plates or the global buckling of the entire web panel as an orthotropic plate. Metwally and Loov (2003) investigated the behavior of composite girders with steel trapezoidal corrugated webs and prestressed concrete flanges, and developed a formula for predicting the nominal shear strength. Yamazaki (2001) described some formulas for estimating buckling strength of corrugated steel webs, and compared to the test results of 6 full-scale models for bridge girder webs. Machimdamrong *et al.* (2002) presented an estimation of global elastic shear buckling strength of corrugated plates considering the influence of elastically rotational restraints on the boundary edges. Driver *et al.* (2006) tested full-scale corrugated web girders made of HPS 485W steel, assessed the effect of web initial geometric imperfections through measurements of the out-of-plane displacements, and proposed a lower bound equation for design which accounts for both local and global buckling of the web in the elastic and inelastic domains. Liew *et al.* (2007) and Peng *et al.* (2007) presented an elastic buckling analysis and a geometrically nonlinear analysis of stiffened and un-stiffened corrugated plates using a mesh-free Galerkin method. Watanabe *et al.* (2007), Watanabe and Kubo (2009) presented the test results using four different trapezoidal corrugation configurations to study the shear capacity with and without local heating history. Yi *et al.* (2008) studied the nature of the interactive shear buckling of corrugated webs, and concluded that the first order interactive shear buckling equation not considering material inelasticity and material yielding provides a good estimation of the shear strength of corrugated steel webs by comparison with 15 tests and FEA results. Shitou *et al.* (2008) carried out experimental studies using full scale and half size models of actual box girders to solve the shear behavior of corrugated steel webs which were constrained by concrete. The results revealed that the contribution of corrugated steel webs for shear increases accompanying with the progress of cracking in concrete member, but the contribution decreases gradually after the corrugated steel webs reaching to shear yield stress. Moon *et al.* (2009a) presented 3 test results, described the shear strength formula previously presented by Yi *et al.* (2008), and compared the proposed formula and several other formulas with results from 17 tests. Sause and Braxtan (2011) summarized previously developed formulas for predicting the shear strength of steel trapezoidal corrugated webs, along with the corresponding theory, and a new formula was developed.

On the basis of experimental and numerical studies of shear behavior for corrugated web girders, it can be found that shear buckling of corrugated webs is often classified as either local buckling (Fig. 4a) or global buckling (Fig. 4c). The interactive shear buckling mode (Fig. 4b) is attributed to the interaction between local and global shear buckling modes. Global buckling involves multiple folds and the buckled shape extends diagonally over the height of the web. Local buckling is controlled by deformations within a single flat panel or "fold" of the web. Corrugated steel plates can ensure higher resistance against shear buckling, leading to elimination of stiffeners. Generally, local buckling is considered to be controlled by the slenderness of the individual folds of the web, and global buckling is considered to be controlled by the



(a) Local buckling (b) Interactive buckling (c) Global buckling

Figure 4. Shear buckling modes.



(a) Local buckling (b) Global buckling (c) Interactive buckling

Figure 5. Comparison of experimental and predicted shear strength.

slenderness of the entire web. He (2011) carried out parametric analysis on the shear strength of corrugated web girders by pertinent FE Models and compared with other researcher's works, found that: (1) the web initial geometric imperfection can be simulated by consistent mode imperfection through the first order mode of eigenvalue buckling analysis if the measured out-of-plane displacements were not obtained; (2) when the corrugation is dense, global buckling of the whole web is in control. As the corrugation becomes coarse, the capacity of web will be controlled by local buckling of single folds; (3) with the increase of corrugation depth, the buckling mode changes from global buckling to a more localized buckling mode; (4) the ultimate shear capacity increases with the thickness and strength of the web.

Based on experimental results of shear strength for corrugated web girders in Europe (Elgaaly *et al.*, 1996; Lindner and Aschinge, 1988), USA (Abbas, 2003; Sause and Braxtan, 2011) and Asia (Yamazaki, 2001; Watanabe *et al.*, 2007; Moon *et al.*, 2009a), the evaluation of predicted equations from specifications and related researchers was conducted (He, 2011). It was found that the elastic local or global buckling equations overestimate the shear capacity. Considering material nonlinearity, residual stress and initial geometric imperfections, inelastic equations of shear strength were provided by Elgaaly *et al.* (1996), Design Manual (JSCE, 1998), Zeman (2003), EN 1993-1-5 (2005), Abbas (2003), Swedish code (SISC, 1982), and GB 50017 (2003).

Figure 5 shows the comparison of experimental and predicted shear strength based on the relation between nominal shear stress (critical buckling stress τ_{cr}/yield shear stress τ_y) and λ_s. For the specimens failed by local buckling, Abbas (2003) underestimates the test results; on the contrary, Swedish code (SISC, 1982) overestimates the test results; the predicted value by Design Manual (JSCE, 1998) is almost the average of the test results, while the calculated value by EN 1993-1-5 (2005) is approximate the low limit of the test results which can be used in the design stage for safety consideration. For the specimens failed by global buckling, the predicted value by EN 1993-1-5 (2005) is almost the same as that by Zeman (2003), and the calculated value by Design Manual (JSCE, 1998) is around the low limit of the test results which can be used in the design stage, the divergence mostly appears in the non-elastic region ($0.7<\lambda_s<1.0$), that may be caused by the residual stress and initial geometric imperfection of corrugated web, further studies should be carried out to modify the predicted equations.

In order to verify the applicability of the idea of interactive buckling (Yi *et al.*, 2008), the test results were compared with Design Manual (JSCE, 1998) and the formula provided by Sause and Braxtan (2011). All the critical buckling stress in the test was calculated as interactive buckling ($\tau_{cr,I}$). Although the calculated value by Sause and Braxtan (2011) is the low limit of the test results, some of the specimens are too underestimated.

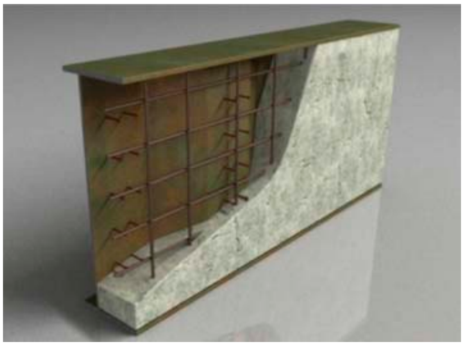


Figure 6. Partially encased composite girder with corrugated web.

With the aim of improving shear behavior of composite bridge with corrugated webs under hogging moment, concrete is poured in the area surrounded by the upper flange, lower flange and web around the intermediate supports especially the section of large height. The encased-concrete is expected to prevent buckling of the web in compression and the concrete itself also contributes to the shear strength, as shown in Fig. 6. The shear performance of partially encased composite girder with corrugated web was investigated experimentally and numerically by the authors (He, 2011; He *et al*., 2012a,b). Experimental results showed that the partially encased composite girders have superior shear strength since shear bucking of steel web is restricted by concrete encasement. Moreover, the predicted shear stiffness and strength were proposed and verified by experimental and numerical results.

3. Bending Behavior

Flexural strength of steel girders with corrugated steel webs is provided by the flanges with almost no contribution from the webs due to its “accordion effect”. Huang *et al.* (2004), Egaaly *et al.* (1997), Khalid *et al.* (2004), Oh *et al.* (2012) conducted experiments, finite element and theoretical analysis on the accordion effect of steel beams with corrugated webs. Furthermore, there is no interaction between flexure and shear behaviors of these girders. Thus, the ultimate moment capacity of a steel girder with a corrugated steel web can be based on the flange yield strength (Leiva-Aravena, 1987; Protte, 1993; Elgaaly *et al*., 1997; Johnson and Cafolla, 1997; Sayed-Ahmed, 2007). The flexural capacity of composite girders with corrugated steel webs was also investigated and the same aspects defined for steel girders were found to be applicable to composite girders (Metwally and Loov, 2003).

Lindner (1992), Aschinger and Lindner (1997) studied the elastic flexural behavior of corrugated web I-girders under in-plane loads. In their analyses, they assumed that the flanges carry only the moment and the web carries only the shear. Elgaaly *et al.* (1997) carried out experimental and analytical studies on bending strength of steel beams with corrugated webs. Parametric analytical studies were performed to examine the effect of the ratio between the thicknesses of flange and web, the corrugation configuration, the panel aspect ratio, and the stress-strain relationship to the ultimate bending moment capacity of steel beams with corrugated webs. Chan *et al*. (2002), Khalid *et al*. (2004) studied the influence of web corrugation on the bending capacity of the beam using finite element method. Beams with flat web, horizontally corrugated web and vertically corrugated web were studied. Watanabe and Kubo (2006) presented test and numerical analysis results of corrugated web girders with four different trapezoidal corrugation configurations under pure bending. A predicting method of the ultimate strength considering local flange buckling was also proposed based on the parametric analysis of corrugated web girders. As for the non-composite steel I-girder with corrugated web, local buckling of the compression flange affects bending strength. Generally, the limitation on the flange outstand-to-thickness ratio should be satisfied to prevent local flange buckling before yielding. Based on a previous investigation (Johnson and Cafolla, 1997), it was argued that the average flange outstand b_{av} may only be used if a ratio R is less than 0.14, where R is the ratio of area EFGH to area ABCD defined in Fig. 7. If R is greater than 0.14, it is recommended to be conservative using the large flange outstand b_{cmax}. However, a considerable uncertainty still exists regarding the correct value which should be used for the flange outstand of corrugated web girders.

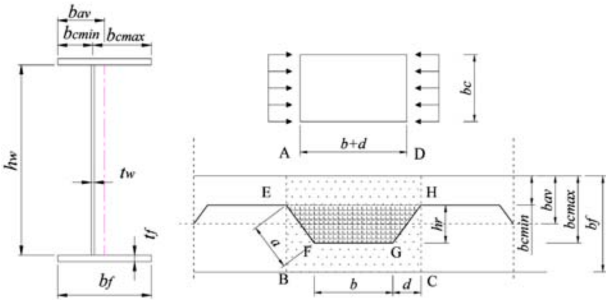


Figure 7. Outstands of compressive flange for corrugated web girder.

For the composite girders with corrugated webs, Mo *et al.* (2003) presented the experimental and analytical results of four scaled prestressed concrete box girders with corrugated steel webs. It was found that both the thickness of end diaphragms and the location of prestressing strands at both ends of the specimens are insignificant when the specimens failed in the mid-span due to concrete crushing. He *et al*. (2008c) analyzed the mechanical behaviors of corrugated steel web box girders with different parameters of internal and external tendons under flexural load, including the arrangement and prestressing force of the internal and external tendons, the position of the anchorage points and the distance of the diversion devices. Song (2003), Li *et al*. (2009a) developed a nonlinear program based on the quasi-plane assumption (Wu, 2002) of flexural strain distribution and axial force-bending moment-curvature relationship at cross-section to investigate the ultimate flexural capacity of the external prestressed composite box girder with corrugated steel webs. On the basis of the experimental and analytical results mentioned above, the ultimate flexural capacity of composite girders with corrugated steel webs can be depended on the strength of concrete slabs and prestressing forces of the internal and external tendons without the contribution from the web for the safety reason and conservative predication.

4. Torsional Behavior

Generally, the lateral-torsional buckling is a major design aspect of thin-walled beams. When a slender I-girder is subjected to flexure about its strong axis with insufficient lateral bracing, out-of-plane bending and twisting may occur as the applied load approaches its critical value. Previous researches (Lindner, 1990, 1992; Lindner and Aschinger, 1990; Aschinger and Lindner, 1997) have shown that a corrugated web I-girder under in-plane moment and shear will deflect in-plane and twist out-of-plane simultaneously. Lindner (1990), Lindner and Aschinger (1990) revealed that the torsional section constant for an I-girder with trapezoidal web corrugations does not differ from those of a beam with flat web; however, the warping section constant is different. Ibrahim (2001) calculated the lateral-torsional buckling strength of corrugated web I-girders using the design formulas for conventional I-girders from the AISC Specifications with the modified warping torsion constant. Abbas *et al.* (2006, 2007a,b) presented the theoretical, experimental, and finite element analysis results for the linear elastic behavior of corrugated web steel I-girders under in-plane loads. A rigorous theoretical formulation and a simplified analysis method for flange transverse bending of corrugated web I-girders under in-plane moment and shear in the elastic range were developed. Sayed-Ahmed (2005, 2007) performed a series of finite element analyses and concluded that the equations used to calculate the critical lateral-torsional buckling strength of the I-girder with flat web would underestimate the capacity of the I-girder with corrugated web. An equivalent moment factor concept was proposed for the corrugated web girders to improve the validity. Yu (2006) addressed the lateral-torsional buckling strength of steel corrugated web I-girders for highway bridges. The resistance of corrugated web I-girders under uniform torsion, uniform bending and moment gradient bending were investigated respectively. Design formulas were proposed and compared with AASHTO LRFD Bridge Design specifications (AASHTO, 2004). Kubo and Watanabe (2007) tested lateral-torsional behavior of corrugated steel web girders with four different trapezoidal corrugation configurations under a mid-span concentrated loading. It was found that the contributions of the corrugated web to lateral buckling load are pronounced for the longer girders with large wave height. Moon *et al.* (2009b), Nguyen *et al.* (2010) presented theoretical and finite element analytical results of the lateral-torsional buckling strength of I-girders with corrugated webs under uniform bending. Approximated methods for locating its shear center and calculating the warping constant were proposed. Based on the proposed methods, the lateral-torsional buckling strength of I-girders with corrugated webs under uniform bending can be calculated easily. Nguyen *et al.* (2011, 2012) investigated the moment modification factors of an I-girder with trapezoidal web corrugations under moment gradient and various end restraint conditions. And the moment modification factors were proposed and verified to improve the accuracy of lateral-torsional buckling strength. Hamid (2010) developed a 3D FEM for the lateral-torsional buckling analysis of I-girders with corrugated webs and investigated the effects of elastic lateral bracing stiffness on the critical moment of simply supported I-girders with corrugated webs under pure bending. It was revealed that the effect of bracing depends not only on the stiffness of the restraint but also on the modified slenderness of the I-girder. A general equation was put forward to determine the value of optimum stiffness in terms of the I-girder's slenderness.

As for composite box girders with corrugated steel webs, Yoda and Ohura (1993), Yoda and Shoda (1994) analyzed the torsional behavior experimentally and theoretically. Mo *et al.* (2000), Mo and Fan (2006) performed a series of systematic tests on hybrid concrete box girders subjected to torsion. According to the test results, an analytical model was developed, and a step-by-step procedure for torsional design of such bridges was presented. Based on the test specimens (Mo *et al.*, 2000), Ding *et al.* (2012) carried out parametric analysis of PC box-girders with corrugated webs under pure torsion. It was found that the shear flow in concrete top or bottom flange is not equal to that in corrugated steel webs; the ultimate torsional strength is in linear proportion to shear modulus, thickness of corrugated steel webs and compressive strength of concrete. Li (2003) analyzed the torsion and distortion effect of box girders with corrugated steel webs, calculated the restrained torsion using the second theory of A.A. Umanskii and evaluated the distortion by B.E.F. analogy method. Kato *et al.* (2004) proposed cross sectional distortion theory for PC box beams with corrugated steel web by the matrix method. Distortion effect in box girders with corrugated steel webs under eccentric loading is more evident than that in conventional box girders with concrete webs (Li, 2003; Di *et al.*, 2009). Thus diaphragms are essential to decrease warping normal stresses. Li (2003), He (2011) analyzed the effect of diaphragms on warping normal stress under eccentric loading considering different ratio of height to span, different distances of diaphragms. And empirical equations for diaphragm distances were obtained based on parametric analyses. In regard to the horizontal curved composite box-girder bridges with corrugated webs, diaphragms should be arranged reasonably to reduce torsional and distortion effect for safety and stability, due to the coupling effect of bending and torsion and reduced bending stiffness in horizontal direction caused by corrugated steel webs. He (2011) conducted extensive parametric studies (including central angle, the aspect ratio of the box section, the spacing of the intermediate diaphragms) to obtain the design suggestions for the maximum spacing of the intermediate diaphragms. It was found that the curved bridge can be simplified as straight one when the central angle is less than 5 degree, more intermediate diaphragms should be arranged in curved bridges with corrugated webs than straight ones when the central angle is more than 5 degree, model test and detailed simulation analysis must be carried out when the central angle designed more than 20 degree.

5. Patch Loading Resistance

From the modern bridge erection methods, the incremental launching technique is one of the most competitive. This construction process, however, involves a problem with buckling of the thin steel web under patch loading. Experimental research on the patch loading resistance of girders with trapezoidally corrugated webs was initiated by Leiva-Aravena and Edlund (1987). Six tests were conducted considering patch loading width and location, as well the web thickness. Kähönen (1988) made six tests on different girders, where the web crippling was analyzed under patch loading. A design model based on the four plastic hinge failure mechanism was developed to determine the patch loading resistance. Elgaaly and Seshadri (1997) performed five tests on a simply supported beam by varying the position of the applied load. Numerical investigations were made based on their experiments. Further numerical investigations were conducted by Luo and Edlund (1996b). The ultimate strength of steel plate girders with trapezoidally corrugated webs under patch loading was studied using nonlinear finite element analysis, considering the material nonlinearity, initial imperfections, “corner effect” of corrugation corners, loading position and distribution length. Also, an empirical design formula was proposed. Kovesdi *et al.* (2010) carried out numerical investigations for the determination of the patch loading resistance. The geometric parameters which influence the patch loading resistance and the structural behavior were determined and analyzed. Design formulas from the view point of bridges are enhanced according to the numerical results and the existing experiments.

Actually, when such a bridge is incrementally launched, the girder is subjected to combined bending moment, shear and transverse forces, resulting in complex stress field and interacting instability phenomena. Elgaaly and Seshadri (1997) investigated the shear and patch loading, bending and patch loading interaction of girders with corrugated webs. Based on a limited number of test results and the numerical calculations, the interaction equations were proposed. However, the previous investigations focused on typical building structures, where the analyzed loading length was very short. Kovesdi (2010) extended the previously analyzed parameter range to bridge application, investigated the interaction behavior of the girders with corrugated webs and finally developed interaction proposals for both interaction types (shear and patch loading, bending and patch loading) through experimental and numerical studies.

6. Dynamic Behavior

The dynamic properties of the structure are the fundamentals of seismic and wind resistant analysis. Tategami *et al.* (1999) investigated the dynamic increment factor and the dynamic behavior of external tendon and corrugated steel webs subjected to running vehicle experimentally. From the test results, it was verified that external tendon was not resonant with the bridge and the vehicle. Also, the dynamic increment factors of the bridges with corrugated steel webs were larger than the design impact coefficient of prestressed concrete bridges. Kadotani *et al.* (2003a,b) studied the vibration characteristics of composite bridges with corrugated steel webs extensively by model tests, field dynamic load tests and finite element analysis. It was found that shear deformation should be considered in natural frequency analysis. Takaki *et al.* (2004) conducted vibration tests to identify the dynamic characteristics of the extradosed bridge (Himi Yume Bridge) with corrugated steel webs. The results showed that both the fundamental natural frequency and damping ratio are equivalent to those of existing extradosed bridges and PC cable-stayed bridges of similar sizes. Chen *et al.* (2007) analyzed the influence of structural parameters including thickness, inclination of corrugated steel webs and the effect of external tendons on dynamic characteristic by model tests and FEM simulation. Manko and Beben (2008) presented the results and conclusions of dynamic load tests that were conducted on a corrugated steel arch bridge in Sweden. The critical speed magnitudes, dynamic coefficients, and vibration frequency were determined. Zhang *et al.* (2008) deduced natural frequencies formulas of the composite box girders with corrugated steel webs considering the effects of shear lag and shear deformation by the method of energy variational principle. Based on the results of field load tests in previous dynamic studies for such type bridges, it was obtained that first order natural frequency (generally flexural mode) of composite bridges with corrugated steel webs is slightly smaller than that of conventional PC bridges. However, the dynamic increment factor is larger that of conventional PC bridge.

While the damping ratio of composite girder bridges with corrugated webs is between that of the steel bridges and the PC bridges.

7. Long-Term Behavior

The aforementioned researches regard the instantaneous behavior of composite bridges with corrugated steel webs, the investigations used to predict the long-term structural response under sustained loads and repeated loads are also necessary.

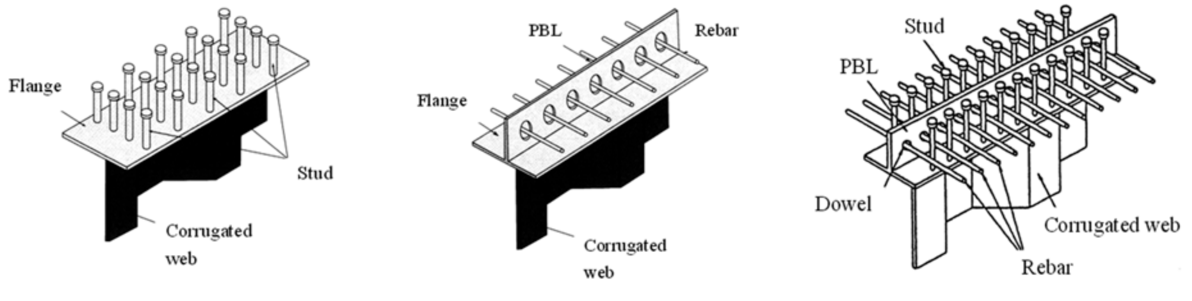
7.1. Fatigue behavior

An initial attempt to explore the fatigue strength of I-girders with corrugated webs was made by Harrison (1965) in the UK. He tested two I-girders with sinusoidal corrugated webs to investigate possible fatigue life improvements over conventional I-girders with stiffeners. In Hungary, Korashy and Varga (1979) conducted a series of fatigue tests on eighteen stiffened steel girders (Eleven girders were stiffened using discrete corrugated webs). The girders stiffened by discrete corrugated webs showed an increase of approximately 25% in fatigue strength compared to traditionally stiffened girders. Cracks initiated at the web-to-flange weld toe within the corrugated regions and propagated into the flange leading to fracture. In USA, Elgaaly *et al.* (2000) and coworkers (Rodriguez, 2000; Ibrahim, 2001) at Drexel university investigated the fatigue behavior of I-girders with trapezoidal corrugated webs. Ibrahim *et al.* (2006a,b) carried out an experimental program on plate girders with corrugated webs under both monotonic and repeated loading. Fatigue cracks initiated at the web-to-flange fillet weld toe where the web was inclined and then propagated in the flange leading to failure. A comprehensive nonlinear finite element analysis was conducted to study the effects of the different geometrical parameters on the stress concentration at different locations, and to explain the findings of earlier experimental study (Ibrahim, 2006c). Anami *et al.* (2005), Anami and Sause (2005) examined the fatigue performance of the web-flange weld of steel girders with trapezoidal corrugated webs experimentally using large-scale girder specimens, and analyzed the crack propagation by the finite element method. Parametric FEM analysis indicated that the corrugation angle and the bend radius at the fold lines of the corrugations are the parameters that influence the stress at the web-flange weld toe most. Sause *et al.* (2006) presented fatigue tests on large-scale girder specimens with full-scale trapezoidal webs. The results demonstrated that steel corrugated web I-girders exhibit a fatigue life that is longer than that of conventional steel I-girders with transverse stiffeners. For the design of corrugated web I-girders, the Category B' design curve of the AASHTO LRFD specifications (2004) was recommended for finite life fatigue design calculations. All the previous researches indicated that steel corrugated web I-girders has better fatigue performance than that of conventional steel I-girders, and cracks initiated at the web-to-flange weld toe then propagated into the flange leading to fracture.

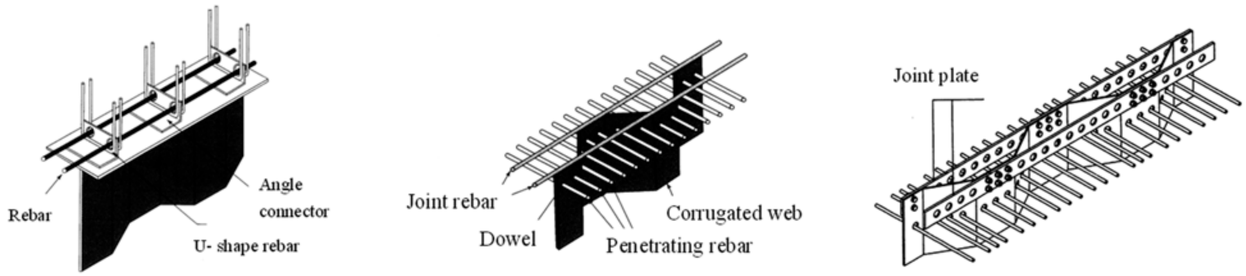
In Japan, many researchers paid attention to the fatigue behavior of welding joints and component connections in such bridges. Yamada *et al.* (2001a,b), Yamada *et al.* (2003) investigated the fatigue behavior of inclined non-load-carrying fillet welded joints experimentally and numerically using fracture mechanics. They reported that multiple fatigue cracks initiated typically at the fillet weld toe for all cases, even when the steel flange is embedded in the concrete slab. Takeshita *et al.* (2001) conducted fatigue tests of composite girders with corrugated webs in a simply supported condition under dynamic load, three types of shear connectors including studs, holes with penetrating reinforcement, the holes with penetrating reinforcement and wire net were adopted. Experimental results revealed that holes with penetrating reinforcement are more effective than studs for composite girders with corrugated webs. Shito *et al.* (2002), Sakai *et al.* (2002) carried out model tests from the aspect of fatigue behavior with respect to the shape of the scallops used for lap and fillet welding in the joints of steel plates in corrugated steel web bridges. Sugimoto *et al.* (2002) investigated the fatigue durability of joints connecting a corrugated steel web with a concrete slab. It was verified that two different embedded joints with the reinforced bars or the tie plates have sufficient fatigue durability. Mori *et al.* (2004) aimed at making clear of fatigue and stress properties of the PC box girder bridges with corrugated steel webs through fatigue tests, stress measurements and 3D FEM analyses. From the aspect of fatigue life, fillet welded joints with the scallops of rational shape should be selected, and less welding or good welding quality are recommended in component connections.

7.2. Creep and durability

The long-term structural responses such as creep behavior under sustained loads and lifetime durability performance for composite bridges with corrugated steel webs are unknown since only a limited number of publications are available on this important design aspect. Maeda *et al.* (2003) suggested that it is necessary to analyze the creep deflection in consideration of shear deformation. Li *et al.* (2008) conducted two reduced scale models to study the creep behavior of the externally prestressed composite box girders with corrugated steel webs under 205 days successive observation. The results indicated that the camber of the composite box girder with corrugated steel webs is less than that of the concrete box girder. Shan and Ling (2011) analyzed the cross-section internal force and stress redistribution of a box-girder with corrugated steel webs under the influence of concrete creep. As the long-term behaviors are not



(a) Stud (b) PBL (c) Stud and PBL Combined



(d) Angle (e) Embedded connector with joint rebar (f) Embedded connector with joint plate

Figure 8. Conventional joint structures of composite bridges with corrugated steel webs.

investigated sufficiently, the creep behavior and prestressing loss under sustained loads need to be determined based on the model tests and field monitoring. In addition, durability performance (corrosion and degradation) of corrugated steel webs as well as the joint structures should be paid more attention and further studied.

8. Component Connections

The connections between the concrete slabs and the corrugated steel webs play an important role to the structural safety and durability for such composite bridges. The studs, PBLs and angle shear connectors welded on the flanges or the corrugated steel webs embedded directly into the concrete slabs are commonly used for the joint parts (Fig. 8). Studs were adopted mostly for the composite bridges with corrugated webs in the early time, such as Shinkai Bridge (Kondo *et al.*, 1994) in Japan and Altwipfergrund Bridge (Novák *et al.*, 2007) in Germany. The PBL connectors were developed in 1980s by the German company for the design of the third bridge over the Caroni River in Venezuela (Leonhardt *et al.*, 1987). Push out test results showed that PBL shear connectors are advantageous from the viewpoint of fatigue strength (Hosaka *et al.*, 2002). Ebina *et al.* (2003, 2004) conducted an extensive research using normal and high-performance lightweight aggregates concrete to obtain the mechanical characteristics (shear and out-plane bending behaviors) of twin perforbond ribs connectors. From the test results and related FEM analysis, shear strength equations were proposed considering the influence of distance from the concrete edge to the ribs. In addition, the force transmission mechanism and fatigue characteristics under out-plane bending moments caused by transverse deflection of concrete slab were discussed.

The performance of composite girders depends largely on the effectiveness of shear connections at the interface of concrete and steel. Corrugated steel webs have very low axial rigidity, which requires relatively flexible shear connectors. A new type of shear connectors without using a top steel flange was proposed. No top steel flange may improve cost performance of composite girders with corrugated steel webs. Corrugated steel webs embedded in the concrete as shear connectors were initiated in Hondani Bridge. Nakajima *et al.* (1995) and Takeshita *et al.* (2001) carried out two points bending and fatigue tests of composite girders with different shear connectors (studs and embedded connectors). Experimental results revealed that holes with transverse and shear steel bars are effective as shear connectors. Nakasu *et al.* (2000) performed experiments and FEM analysis for several types of specimens changing plate thicknesses and embedded depths of corrugated steel webs to investigate static and fatigue behavior of embedded connectors under out-of-plane bending. Sugimoto *et al.* (2002) conducted static and fatigue loading tests with a full-scale model simulating a real railway bridge under out-of-plane cyclic bending to confirm fatigue durability of the joint parts. As a result, it was clarified that both of two different joints types, called constraint reinforced bar type (Fig. 8e) and flat plate type (Fig. 8f), have enough fatigue durability. Kosa *et al.* (2006) presented experimental and analytical investigations on flexural and shear behaviors of composite girders with corrugated steel webs to make clear ultimate

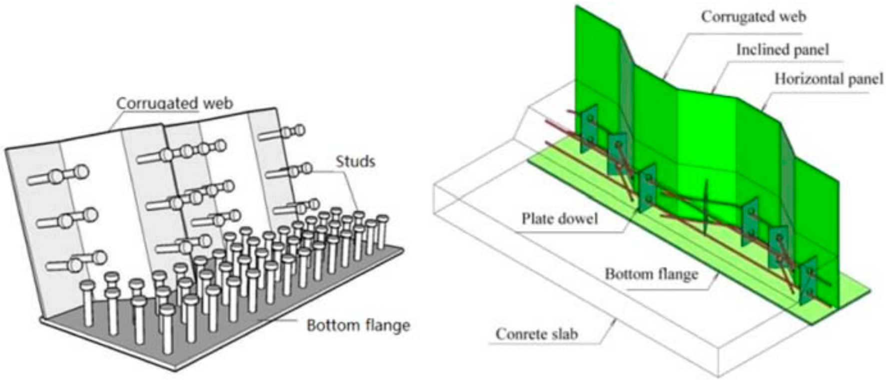


Figure 9. Joint structure beween lower slab and corrugated web.

behavior and failure mechanism of embedded connection. In consideration of damage of the connection, the harmful gap phenomenon in the connection was confirmed. A simple analysis model was proposed base on the assumed mechanism to analyze the quantity of the harmful gap. Taira *et al*. (2009) investigated the stress distribution in embedded connection zone by finite element method considering the effects of embedded depth, thickness of corrugated steel plate, and the direction of wedding joint. Novák and Röhm (2009), Röhm and Novák (2010) studied the load bearing behavior of an embedded corrugated steel web in combination with concrete dowels under longitudinal shear and transverse bending respectively. On the basis of these studies, simple design rules for shear connection in the ultimate limit state were developed. Ahn *et al*. (2011) carried out push-out tests of corrugated perfobond rib shear connectors. Test results showed that the failure was determined by concrete bearing with small deformations of inclined panel, and shear strength increased much than standard perfobond rib connector due to the shear resistance of the inclined rib panel.

When studs or embedded connections used for the joints between corrugated steel webs and lower concrete slab, care must be taken into the inverted construction of concrete and water proofing of the joints. With a view to these problems, Ono *et al*. (2006) prepared some specimens modeled the embedded connections and carried out accelerated corrosion tests of the specimens. The results showed that durability of the embedded connection was increased by sealing the border between steel and concrete and by embedding paint in concrete. Shiji *et al*. (2008), He (2011) presented the application of the joint structures as shown in Fig. 9, and the validity of placing lower slab on the inner side of corrugated steel webs was confirmed. In addition, punching shear tests were conducted to investigate the properties of shear slip at the joints. It was proved that the bottom flange is beneficial for the concrete quality and slab construction, as well as the durability of the interface between concrete slab and corrugate web.

In comparison of all the mentioned connection types for such composite bridge, the workability of construction, durability and maintenance performance of the connections with flange are superior to that of the embedded connection without flange, but the economic performance is in inferior position in comparison with embedded connection. Therefore, comprehensive influencing factors such as shear capacity, construction, durability, maintenance and economic performance should be considered when the connection is chosen.

9. Analytical Method and Theory

9.1. Shear deformation theory

In the study of deflection and stress of the PC girders with corrugated steel webs, the classical Euler-Bernoulli and Timoshenko beam theories are found not to be applicable as shear deformation in the corrugated steel webs becomes large (Machimdamrong *et al*., 2004; He *et al.*, 2009a,b). Taniguchi and Yoda (1997) assumed that a composite girder with I-section consists of three parallel beams bonded together, each beam is divided into thin laminas, and displacements and stress within each lamina are linearly changed. Nonlinear analysis and comparison to experimental results were also included in their work. Shirozu *et al*. (2000) provided another numerical method based on the so-called “constant shear flow panels”. The girder is divided into a number of small sections and the assumption on constant shear flow is postulated on each panel. This method has an advantage when the depth of the girder is varied. Noda and Ohtoi (2000) presented a calculation method for sectional deformation of box girder with corrugated steel webs based on folded plate theory. Kato *et al*. (2002), Kato and Nishimura (2003) developed an elastic equation extending beam bending theory considering shear deformation. The dual three-moment method and the corrugated web beam matrix displacements method were formularized. Then, analytical methods were applied in continuous girder and cable-stayed bridges with corrugated webs. Machimdamrong *et al*. (2004) derived an elastic shear deformable beam theory(G3 theory) which is based on three displacement fields and is similar to the classical Timoshenko beam theory for analysis of PC girders with corrugated steel webs. Bariant *et al*. (2006) proposed an extension of the G3 theory by taking into account the inelastic properties of corrugated steel webs. FEM analysis was used as a benchmark and the FEM results were very close to the prediction of the elasto-plastic G3 theory. He *et al*. (2009a,b) presented the elastic bending theory taking shear deformation into consideration for composite bridges with corrugated steel webs. A limit ratio of depth to span (1/30) was suggested for considering influence of shear deformation or not.

9.2. Three-dimensional finite element analysis method

The finite element method (FEM) acts as a link between the experimental tests, the mechanical and analytical modeling, permitting better understanding of the experimental behavior and the simplified methods. Elgaaly and Seshadri (1998) performed nonlinear finite element analysis by ABAQUS considering both geometric and material nonlinearities to investigate the behavior of girders with corrugated webs under shear, uniform bending and local discrete compressive loads up to failure. Huang *et al*. (2004) presented a simple approach to account for three-dimensional phenomena of the accordion effect using link-type elements within a two-dimensional finite element model. Wu (2002) and Li *et al*. (2009b) investigated the shear lag effect by model test and FE analysis, and put forward the practical calculating formula and chart for calculation of the shear lag coefficient. Watanabe and Kubo (2006), Watanabe *et al*. (2007), Kubo and Watanabe (2007), Sayed-Ahmed (2007) analyzed in-plane capacity, shear buckling and lateral torsional buckling of steel I-girders with corrugated webs by 3D FE software. Xie *et al*. (2008) proposed a numerical method based on finite element theory with shell elements. The corrugated steel webs and the concrete flanges were simulated with orthotropic plate elements and isotropic plate elements respectively. On the basis of such type bridges built in China, He *et al*. (2007b, 2008a) and Li *et al*. (2009) established 3D FE models to analyze the mechanical behaviors of the structure, such as the stress distribution, deflection, the effects of internal and external prestressing. He *et al*. (2008b) and Jung *et al*. (2011) conducted detailed construction stage analysis by 3D FE models to verify the construction safety. The results revealed that essential design issues should be considered when constructing PC girders with corrugate steel webs using incremental launching method.

In summary, beam theories considering shear deformation are recommended to analyze the internal force and deflection of composite bridges with corrugated webs in the preliminary design stage. While 3D FE models should be established to investigate stress distribution of detailed structures such as component connections, anchorage blocks and so on.

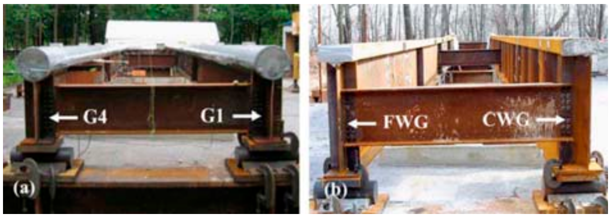


Figure 10. Tubular flange girders with flat webs or corrugated webs, Sause *et al*. (2008).

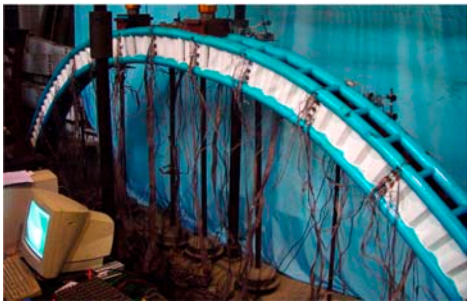


Figure 11. CFST arch with corrugated webs, Gao and Chen (2008).

10. New Concept Application

Plate girders or box girders with corrugated webs are not the olny application form for such composite bridges. Wang (2003) proposed the concept of corrugated web I-beams combined with tubular flanges to improve the stability and bending capacity. The behavior of innovative structures subjected to shear, bending, and axial compression was extensively investigated. Kim *et al*. (2005), Sause *et al*. (2008) performed the design of tubular flange girders with flat webs or corrugated webs (Fig. 10). An experimental study of these girders showed that the lateral torsional buckling capacity was improved by concrete-filled tubular flange, and these girders were capable to resist factored design loads under construction conditions and in the final constructed condition. Gao and Chen (2008), Chen and Gao (2008) presented concrete filled steel tubular (CFST) beam and arch with corrugated steel web (Fig. 11). Experimental results showed that the flexible rigidity and ultimate load-carrying capacity were improved considerably. And a trial design of arch bridge with corrugated steel webs was carried out based on the tests (Chen and Mou, 2008). Shao *et al*. (2010) conducted an experimental study to investigate the behavior of a new type multi-cantilever prestressed composite beam with corrugated steel webs, as shown in Fig. 12. The investigation focused on mechanical performance of the novel structure, such as efficiency of prestressing, creep and shrinkage of concrete slab, load distribution, and load-carrying capacity. Kim *et al*. (2011) proposed prestressed composite beam with corrugated web (Fig. 13), prestress is efficiently introduced to the top and bottom flanges due to the small axial rigidity of corrugated

Figure 12. Multi-cantilever prestressed composite beam with corrugated steel webs, Shao *et al*. (2010).

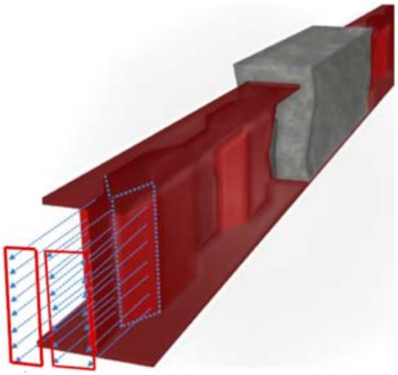


Figure 13. Prestressed composite beam with corrugated web, Kim *et al*. (2011).

web. In addition, corrugated web was encased by concrete after the introduction of prestressing force so that the local buckling of corrugated web can be avoided. The surrounding concrete also improves fire-resistance performance and durability of the member. On the other hand, as the prestressed steel beam is placed, no form or supporting posts are necessary for concrete casting, which leads to save construction cost.

Although only a few new concept application examples were introduced in this paper, we believe that innovative structure types and advanced technology making full use of corrugated plates may be proposed to prosper and develop the bridge construction in the future.

11. Concluding Remarks

From the published literature on the analysis, design and construction behaviors of composite bridges with corrugated steel webs, the following comments and recommendations deserving high priority are made:

(1) Apart from the Japanese design manual for PC bridges with corrugated steel webs, no other official design codes exist in the world for such bridges, which means many countries recommend few analytical methods for design or construction of this type bridges. Therefore, practical requirements in the design process necessitate a need for design codes of such bridges in respective countries.

(2) The current design specifications as well as the published literature do not provide enough information on the behavior of composite bridges with corrugated steel webs during the construction phase. Further research work is required using field tests and finite element analyses to investigate the behavior of composite girders with corrugated steel webs at the construction phase and to avoid possible failures.

(3) Current researches on the torsional and warping behavior of curved composite bridges with corrugated steel webs are still mainly based on straight composite girders. Actual torsional and warping behavior of such bridges through laboratory or field tests should be a research focal point.

(4) A non-composite corrugated web girder deflects and twists under in-plane bending. Depending upon the number of corrugations (even or odd), the twisting of the girder takes place in a half sine wave or a full sine wave. The costs associated with the extra lateral bracing may offset the advantage of corrugated steel webs.

(5) The long-term structural response under sustained loads and lifetime durability performance of composite bridges with corrugated steel webs are unknown since only a limited number of publications are available on this important design aspect. Thus, the creep behavior and prestressing loss needs to be determined based on the model tests and field monitoring, and durability performance (corrosion and degradation) of corrugated steel webs as well as the joint structures should be paid more attention.

(6) Further studies on force transmission and failure mechanism of complicated structural details such as joint structures and corrugated steel webs encased by concrete near support sections should be conducted to improve the design theories and methods for composite bridges with corrugated steel webs. In addition, innovative structure types and advanced construction technology need to be proposed to prosper and develop the application of composite bridges with corrugated steel webs.

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