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Mechanical Behavior of a Partially Encased Composite Girder with Corrugated Steel Web: Interaction of Shear and Bending

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ABSTRACT

The synergistic use of partially encased concrete and composite girders with corrugated steel webs (CGCSWs) has been proposed to avoid the buckling of corrugated steel webs and compression steel flanges under large combined shear force and bending moment in the hogging area. First, model tests were carried out on two specimens with different shear spans to investigate the mechanical behavior, including the load-carrying capacity, failure modes, flexural and shear stress distribution, and development of concrete cracking. Experimental results show that the interaction of shear force and bending moment causes the failure of specimens. The bending-to-shear ratio does not affect the shear stiffness of a composite girder in the elastic stage when concrete cracking does not exist, but significantly influences the shear stiffness after concrete cracking. In addition, composite sections in the elastic stage satisfy the assumption of the plane section under combined shear force and bending moment. However, after concrete cracking in the tension field, the normal stresses of a corrugated web in the tension area become small due to the "accordion effect," with almost zero stress at the flat panels but recognizable stress at the inclined panels. Second, three-dimensional finite-element (FE) models considering material and geometric nonlinearity were built and validated by experiments, and parametric analyses were conducted on composite girders with different lengths and heights to determine their load-carrying capacity when subjected to combined loads. Finally, an interaction formula with respect to shear and flexural strength is offered on the basis of experimental and numerical results in order to evaluate the load-carrying capacity of such composite structures, thereby providing a reference for the design of partially encased composite girders with corrugated steel webs (PECGCSWs) under combined flexural and shear loads.

1. Introduction

Composite girders with corrugated steel webs (CGCSWs), as shown in Fig. 1, which include prestressed concrete slabs, corrugated steel webs, or internal or external tendons, have been applied to highway and railway bridges as a promising steel-concrete hybrid structure. No restraint exists between the slabs and webs due to the use of corrugated steel webs, which can alleviate structural responses due to shrinkage, creep of concrete, and temperature differences between slabs and webs. The "accordion effect" of corrugated webs efficiently introduces prestressing into the concrete slabs, while the combination of concrete slabs and corrugated steel webs improves the structures' strength, stability, and material efficiency [1–3].

Since the construction of the first highway bridge using corrugated webs, which occurred in France in 1986 (Cognac Bridge), numerous composite bridges with corrugated steel webs have been erected around the world [2–4]. In addition, a considerable number of experimental and theoretical studies have been carried out on such bridges, including studies on their bending behavior [5–15], shear behavior [16–24], torsional behavior [25–27], and dynamic behavior [28,29].

Experimental, numerical, and theoretical studies have been carried out by Elgaaly et al. [5], Huang et al. [6], and Oh et al. [7] on the "accordion effect" of steel girders with corrugated webs. Due to this effect, the corrugated steel web makes almost no contribution to the section flexural strength. Thus, the ultimate bending

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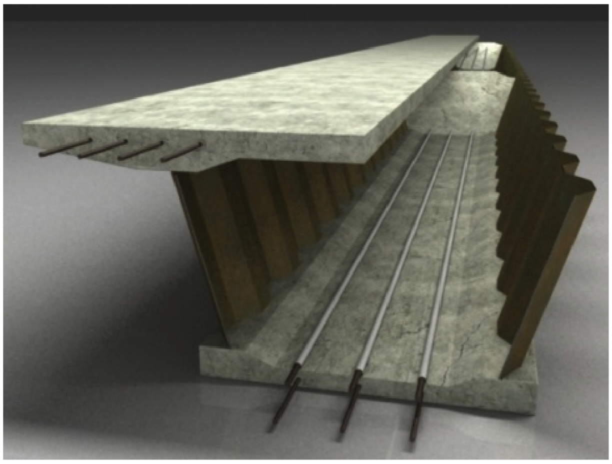

Fig. 1. Layout of a CGCSW.

moment capacity of the girder depends on the flange yield strength [5,8–11]. This conclusion was found to be applicable to composite girders after several investigations on the flexural capacity of CGCSWs [12–15].

The shear behavior and shear bucking of corrugated steel webs have been extensively studied both experimentally and theoretically, and the results show that corrugated steel webs can resist almost all of the shear forces [16,17]. Therefore, the effective shear modulus of the corrugated steel web, which is determined while taking the shear deformation and web corrugation into account, is a key parameter in predicting the shear force resistance accurately [9]. Moreover, the shear yielding of the corrugated steel web and the buckling properties, including global buckling, local buckling, and interactive buckling, controls the calculation of shear strength [18–21]. Based on experimental results on the shear performance of steel or composite girders with corrugated steel webs in Europe, the United States, and Asia, an assessment of predicted equations was conducted [22]. It was found that the elastic global or local buckling equations overestimate the shear strength. Considering material nonlinearity, residual stress, and initial geometric imperfections, inelastic equations for shear stress were provided in design codes [23,24].

Results from previous studies show that the shear force and bending moment are resisted by the corrugated steel webs and by flanges, respectively; no interaction takes place between the global flexure and the shear behavior of these girders [5,16]. However, Kuchta [30] investigated the mechanical performance of steel girders with corrugated steel webs subjected to combined shear force and bending moment. The results showed that there is a small reduction in the load-carrying capacity under combined loads, with a maximum reduction of 8.33% due to the interaction of shear and bending.

According to data from the design and construction of composite bridges with corrugated steel webs in China and Japan, continuous girders and rigid frames, which were used for about 80% of such bridges, are the two most popular typologies. However, the large shear force and bending moment caused by the hogging moment at the intermediate supports can lead to cracking on the concrete upper slab. After concrete cracking, the steel reinforcements in the tensile concrete slab resist tensile stress, whereas the lower parts of the webs and bottom flanges are vulnerable to lateral-torsional buckling resulting from the large compressive stress. In addition, local failure was observed in the vicinity of the diaphragms of specimens tested by Kosa et al. [31], Shitou et al. [32], and Chen [33] due to the interaction between web shear deformation and local bending of concrete slabs [33]. Thus, the middle support area is the weak area, having low durability and strength. Therefore, as shown in Fig. 2, concrete encasement in this area has been proposed in order to improve the structural performance, especially for structures with a large section depth. This concrete encasement, which is surrounded by corrugated steel webs and the upper and lower flanges, is expected to enhance the structural bending, shear strengths, and buckling resistance of the corrugated steel webs. Moreover, the shear stiffness of the encased corrugated steel web in the vicinity of the diaphragms is much larger than that of a pure corrugated steel web, so the concrete encasement greatly relieves the interaction between web shear deformation and the local bending of concrete slabs.

Few recent reports exist on design provisions for the partially encased composite girder with corrugated steel web (PECGCSW). We tested the flexural and shear behaviors of I-shaped steel and composite girders with a flat or corrugated web by means of parametric studies. These parameters include the thickness of the steel web and the level of composite action between the steel web and the encased concrete. Through comparison with experimental results, theoretical and numerical models were built and validated in order to predict the flexural and shear strength [34–36]. When the encased concrete was connected to the corrugated steel web by shear connectors, it was shown that the mechanical behavior of such a composite girder was totally different from that of a steel girder with a corrugated web under individual flexural or shear loading. However, PECGCSWs are recommended for application in the region of the intermediate supports of a continuous bridge, where a large shear force and bending moment exist. Referring to the continuous bridge, it is necessary to understand the mechanical performance of PECGCSWs under a combined shear force and bending moment. In addition, the interaction of the shear force and bending moment on a PECGCSW is different from that on a steel girder with a corrugated web, and has not yet been sufficiently studied.

This paper aims to understand the mechanical behavior of a PECGCSW that is subjected to combined loadings of shear and bending by means of model tests and numerical analyses. Two encased corrugated steel web girders with different ratios of bending moment to shear force were tested in order to investigate their load-carrying capacity and failure mechanism. Next, numerical finite-element (FE) models of test specimens that incorporated material and geometric nonlinearity were built and validated by experimental results. Parametric analyses were carried out using calibrated FE models in order to investigate the interaction of flexural and shear strength. On the basis of these experimental and numerical results, this paper proposes an interaction formula for the shear and flexural strength to assess the load-carrying capacity of such composite girders.

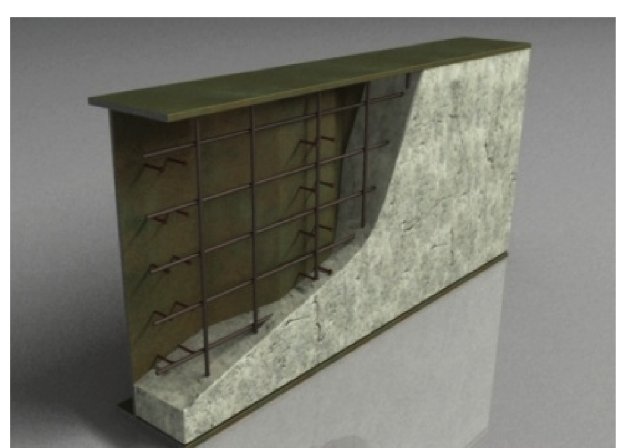

Fig. 2. Structural details of the PECGCSW.

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