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Cantilever welded wide-flange beams with sinusoidal corrugations in webs: Full-scale tests and design implications

Zhe Zhang [a], Sheng Pei [a], Bing Qu [b,*]

[a] School of Civil Engineering, Zhengzhou University, Zhengzhou, Henan Province 450001, China
[b] Dept. of Civil and Environmental Engineering, California Polytechnic State University, San Luis Obispo, CA 93407, USA

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ABSTRACT

Wide-flange members with sinusoidal corrugations in webs are recently developed and gradually accepted as alternatives to wide-flange members with flat webs and trapezoidally corrugated webs. However, limited knowledge is available regarding flexural behavior of such members. This research investigates flexural behavior of the cantilever wide-flange members with sinusoidal corrugations in webs. First, four cantilever specimens were constructed. Each specimen was tested using a monotonically increased point load applied at the free end. Test results show that the specimens overall exhibited the flexural torsional buckling behavior, which is similar to that of the conventional wide-flange members with the flat webs and subjected to the same loading and boundary conditions. Next, computer models were developed for the tested specimens. Both eigenvalue analyses and nonlinear static analyses were conducted to glean the buckling strength of each specimen. It was found that the nonlinear static analyses can provide reasonable predictions of the strengths of the tested specimens. Based on the validated computer models, parametric analyses were conducted to investigate the influence of initial geometrical imperfection on strength of the cantilever wide-flange members with corrugations in webs. In addition, the flexural performances of the cantilever wide-flange members with sinusoidally corrugated webs were compared with those of the corresponding wide-flange members with the flat webs based on the computer simulations. The computer models were further analyzed to assess adequacy of some existing models for calculating strength of the wide-flange members with sinusoidal corrugations in webs.

1. Introduction

A conventional wide-flange member (either hot-rolled or welded) consists of two parallel flanges supported by a flat web plate along the longitudinal direction. When such a wide-flange member is used as a beam subjected to strong-axis bending, the bending moment resistance and shear resistance are primarily provided by the flanges and the web, respectively. In typical building structures, flexural demands often govern over shear demands in design of wide-flange beams. Accordingly, thicknesses of the webs of wide-flange beams determined from strength design alone are normally thinner than those of flanges. Using a wide-flange beam with a thinner web, although helps achieve a lighter design, may trigger local buckling of the web, consequently causing a premature failure of the beam. To enhance local stability of the thin web, transverse stiffeners are often used. However, welding transverse stiffeners to a wide-flange member can be costly and more importantly it may introduce significant residual stresses and heat affected zones to the beam, consequently compromising performance of the beam.

As an alternative and more favorable solution to the transverse stiffeners, the corrugated thin webs have recently been proposed for the welded wide-flange beams. The benefit of corrugation in thin steel plates in increasing its strength against buckling has been long recognized. For example, thin steel corrugated plates have been widely used in composite slabs of building floors and bridge decks [1–15]. In addition, steel corrugated plates have been recently proposed to be installed in structural building frames to increase the system seismic force resistances [16]. Investigation on welded wide-flange members consisting of corrugated webs started in 1970s [9]. Past researchers have revealed that to achieve the same strength wide-flange members consisting of corrugated webs can be much lighter than these consisting of stiffened flat webs [11,12,14,15]. Beyond savings in materials, it is reported that erection cost associated with the wide-flange beams consisting of corrugated webs can also be lower since the corrugations in the web provides the member with higher resistance against bending

* Corresponding author.
E-mail address: bqu@calpoly.edu (B. Qu).

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about its weak axis and the auxiliary lifting equipment may be unnecessary in many cases. To date, applications of wide-flange beams consisting of corrugated webs have been seen in France, Germany, Sweden, Austria, Japan, the United States and many other countries [1–5]. Design recommendations for such members are currently available [17,18]. Nevertheless, it should be mentioned that most of the existing knowledge on the wide-flange beams with corrugated webs is limited to those with trapezoidal corrugations in the webs [4,12,13].

The latest-generation machines are able to produce web plates with sinusoidal corrugations and subsequently weld the profiled web plates to the flanges through a fully automated process. The beams with sinusoidal corrugations in their webs are more attractive than those with trapezoidal corrugations in the webs primarily for the following three reasons. First, the sinusoidal corrugation has a better stability than the trapezoidal profiling since it eliminates local buckling of the flat plate strips included in the trapezoidal corrugation. Moreover, the webs with sinusoidal corrugations have less severe stress concentrations than those with trapezoidal corrugations. Furthermore, the members with sinusoidal corrugations in the webs can be architecturally more attractive in some cases. Fig. 1 compares a conventional wide-flange beam with two wide-flange beams having sinusoidal and trapezoidal corrugations in their webs, respectively.

While the beams with sinusoidal corrugations in the webs have aroused a wide range of interests in the market, the follow-up investigations, particularly the experimental studies on large-scale specimens, are very limited. To achieve a better understanding on flexural behavior the wide-flange beams with sinusoidal corrugations in the webs and promote the use of such members in future designs, this research team conducted tests on four cantilever specimens. Based on the test results, computer models of the tested specimens were developed and validated. Based on the validated computer model, the influence of initial geometrical imperfection on flexural resistance of such beams were discussed. Moreover, flexural performances of the wide-flange beams with sinusoidal corrugations in the webs were compared with the corresponding wide-flange beams with flat webs. Further, the research team discussed if the existing knowledge for wide-flange beams with flat webs and trapezoidally corrugated webs can be applied to the wide-flange beams with sinusoidally corrugated webs. The following presents in detail the specimen information, test setup, experimental observations, test results, development and validation of computer models, and the follow-up analyses and evaluations conducted.

2. Tests of full-scale specimens

2.1. Specimen design and fabrication

A total of four specimens, designated as Specimens A to D, were considered in this investigation. All specimens are cantilever beams consisting of sinusoidal corrugations in their webs. Among these specimens, the web thickness, the flange width and the geometries related to web corrugations (including amplitude of the sinusoidal corrugation, a, and the wavelength of sinusoid, q, as shown in Fig. 2) were kept constant while beam depth, flange thickness and beam length were varied. Note that the geometries of the specimens were selected to represent full-scale beams in conventional building structures. Detailed dimensions of each specimen are listed in Table 1. Note in the table that b_f, t_f, t_w, d and L represent flange width, flange thickness, web thickness, depth of the cross-section (measured from the top and bottom faces of the beam) and length of the beam, respectively.

The plate elements used in each specimen were cut, profiled (if appropriate) and assembled in factory through a fully automated process. All specimens were made of Q235 steel which has a nominal yield strength of 235 MPa. Coupon tests conducted according to the Chinese guideline [19] indicated that the actual strength of the steel varies from 285.9 MPa and 320.3 MPa with an average of 301.3 MPa.

2.2. Test setup and instrumentation

Each specimen was loaded as a cantilever with a point load acting at its free end. Note that the cantilever boundary condition was adopted for testing the specimens since stability of a beam under such a boundary condition is inferior to the same beam under the other boundary conditions with both ends restrained (e.g., that for a simply supported beam). Fig. 3 shows the test setup. As shown, a 10-mm thick end plate together with a 10-mm thick vertical stiffening plate was attached at the loading end of each specimen. Moreover, each specimen was fixed to the strong wall. Note that the point load on each specimen can be exerted by actuators. However, this loading application plan was not adopted in this investigation to avoid any unexpected displacement restraints or accidental loading eccentricities potentially exerted from the actuators. Alternatively, a steel cage (1-m long, 1-m wide and 0.7-m high) was hung through steel cables to the free end. During the tests, standard weights of 20 kg each were gradually added to the cage to load each cantilever specimen. The standard weights were arranged in the cage so that their center of gravity and the center of gravity of the cage alone were in the same vertical plane. Fig. 4 shows the steel cage and standard weights used in the tests. The point load applied as such remains vertical. In each test, a preliminary load equal to 30% of a pre-calculated strength was first applied to and then removed from the specimen to confirm that the instrumentation facility functioned as expected. Next, the load was monotonically increased. The load increment varied from 20 kg to 100 kg during the tests. The interval of each loading step was set to be 5 min. The tests were concluded when a specimen became unstable or its lateral deformation became too excessive to allow further loading applications.

Uniaxial Strain Gauges (USGs) and Linearly Variable Displacement Transformers (LVDTs) were used to record the strain and deflection quantities, respectively. The instrumented locations of

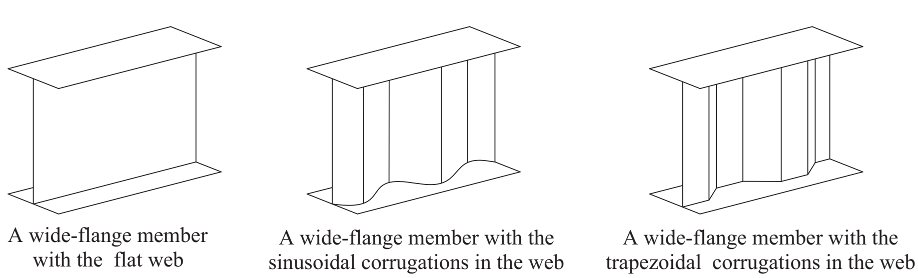

Fig. 1. Comparison of wide-flange members with flat web and webs with trapezoidal and sinusoidal corrugations.