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Reliability-based design recommendations for sinusoidal-web beams subjected to lateral-torsional buckling

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ABSTRACT

Developments and advances in fabrication technology have led to a new generation of structural shapes, among them, the sinusoidal-web girder. Due to easy execution and potential for structural efficiency, the use of sinusoidal-web girder has been increasing significantly in several segments of civil engineering construction such as bridges, pedestrian walkways, hangars and industrial buildings. In spite of the advantages this type of structural component may offer, there are no design standards or specifications dealing with all the phenomena involved in the behavior of such beams, such as the resistance against lateral-torsional buckling (LTB). As a result, there is a need to develop design recommendations that properly address the flexural capacity of these elements. Following the current trend of semi-probabilistic codes (e.g. load and resistance factor design format), these recommendations shall be developed within the concepts and methods of Structural Reliability. In this paper, reliability-based design recommendations for sinusoidal-web beams for the limit state of LTB are presented. To this end: (i) an experimental investigation on the resistance of sinusoidal-web beams has been performed, (ii) a finite-element model has been developed and validated by experimental results, (iii) a theoretical model for the sinusoidal-web beam resistance prediction is proposed, (iv) a comprehensive program was established toward the assessment of both physical and epistemic uncertainties related to the basic variables, (v) reliability analyses are performed using First Order Reliability Method (FORM), and (vi) resulting implicit reliability levels are checked against current practice. It is shown that the implicit safety levels in the proposed recommendations are in agreement with current trends in structural engineering practice.

1. Introduction

Developments and advances in fabrication technology have led to a new generation of structural shapes, among them, the sinusoidal-web girder. A sinusoidal-web girder is a built-up I-girder with a thin-walled corrugated web (with a sinusoidal profile) and flat plate flanges. Although used since the early 1960s, further developments in fabrication technologies – especially the computer numerical control process and robotics – were needed before the large-scale and economical production of corrugated-web beams was made possible.

The corrugated web considerably increases the rigidity and the resistance to shear forces and local effects, thus reducing the occurrence of local and shear buckling. Additionally, compared to trapezoidal corrugation, the sinusoidal corrugation presents the advantage of reducing, or even eliminating, the local buckling of flat parts that exist in the trapezoidal corrugation. Therefore, it allows for thinner web sheets without the need for transverse stiffeners; it also allows for reduced self-weight and increased load capacity, as compared to conventional flat-web I-girders [25]. Due to easy execution and potential for structural efficiency [27], the use of sinusoidal-web girders has been increasing significantly in several segments of civil engineering construction such as bridges, pedestrian walkways, hangars and industrial buildings (Fig. 1) [20].

In spite of the advantages this type of composite construction may offer, there are no design standards or specifications dealing with all the attendant phenomena defining the structural performance of such elements. For instance, lateral-torsional buckling (LTB) is an important limit state for these girders, especially during construction. Additionally, LTB is a complex problem depending on many parameters which are not well defined at the time of design [17]. European code EN 1993-1-5 [11] uses the same procedure as EN 1993-1-1 [10] to determine the moment that causes LTB in steel beams, that requires calculation of the elastic critical moment

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for LTB. However, these codes do not provide information on the calculation of the critical moment of corrugated-web beams. Other codes, such as ANSI/AISC 360-05 [1] and the Canadian CSA S-16 [8], do not provide any recommendations concerning corrugated-web girders. Consequently, there is a need to develop design recommendations that properly address the flexural capacity of these elements, and their connections to adjacent members. Following the current trend of using semi-probabilistic codes, these design recommendations shall be developed within the concepts and methods of Structural Reliability [21].

The investigation reported herein is part of a major research program developed at the Federal University of Minas Gerais, Brazil, addressing the structural behavior of sinusoidal-web beams and composite systems, as well as, the requisite reliability-based design (RBD) recommendations. RBD recommendations for composite corrugated-web beams and connections have been reported in Pimenta et al. [25]. In this paper, RBD recommendations for sinusoidal-web beams for the limit state of LTB are presented. To this end: (i) an experimental investigation on the resistance of sinusoidal-web beams has been performed; (ii) a finite-element model has been developed and validated by experimental results, (iii) a theoretical model for the sinusoidal-web beam resistance prediction is proposed, (iv) a comprehensive program was established toward the assessment of both physical and epistemic uncertainties related to the basic variables, (v) reliability analyses are performed, and (vi) the resulting implicit reliability levels are checked against current practice.

2. Experimental investigation

The experimental program consisted of four tests on two sets of simply supported sinusoidal-web beams, with 5.0 m (EX5) and 6.0 m spans (EX6). Tests on specimens EX5S and EX6S were carried out with lateral restraints at the supports only. Two shapes WT155x39.5 were welded to the beam ends, provided with slotted holes in the web, allowing for the installation of rods to prevent lateral displacements of the supports. In the tests of specimens EX5C and EX6C, the same lateral restraints were added at the center of the span. The test apparatus is shown in Fig. 2; details of the apparatus are schematically shown in Fig. 3.

In the tests of beams without lateral support, a system consisting of rollers over a steel cylinder, between the hydraulic actuator and the beam, was used (see Fig. 2(a)). Additionally, in order to keep the load vertically at the center of the compression flange, the hydraulic actuator could displace horizontally by means of a translation mechanism, represented by the system indicated as "9" in Fig. 3(a). The ability of the apparatus in keeping the load vertically at the center of the compression flange can be seen from Fig. 4 that shows Specimen EX6S after collapse.

Fig. 1. Roof supported by sinusoidal-web girders.

The girders were manufactured by a Brazilian steel fabricator, Codeme Engenharia S.A., at present, the only local producer of sinusoidal-web shapes in Brazil. The beam flanges and web were made from proprietary steels USICIVIL 350 and USICIVIL 300, respectively. USICIVIL 350 is similar to ASTM A-572 grade 50 with yield strength, f_y, of 350 MPa and ultimate strength, f_u, of 500 MPa, and USICIVIL 300 is similar to ASTM A-572 grade 42, $f_y = 300$ MPa and $f_u = 410$ MPa. The steel has been supplied by USIMINAS, the Brazilian largest steel producer. The actual dimensions of the tested beams are shown in Table 1. The specimens showed initial bow imperfections of 1.9 mm and 13.2 mm, for girders EX5 and EX6, respectively. The actual yield strength and ultimate strength, have been obtained by tensile tests of coupon samples from the flange plate and the web sheet ($f_y = 455$ MPa and $f_u = 601$ MPa for the flange; $f_y = 343$ MPa and $f_u = 440$ MPa for the web coupons).

Two failure modes were observed: lateral-torsional buckling (LTB) for specimens without central restraint, and flange local buckling (FLB) for specimens with central restraint. The failure modes for test specimens EX6S and EX6C are shown in Figs. 4 and 5, respectively. The information regarding the plastic moment, M_p, the ultimate load, P_u, the corresponding ultimate moment, M_u, and the failure mode is summarized in Table 2. The plastic moment was calculated using the measured yield stress adjusted according to the procedure recommended by the Technical Memorandum #7 and #8 of the Structural Stability Research Council – SSRC [17]. Based on preliminary calculations, it was expected that fully plastic condition of the flanges would occur in the specimens with central restraint (EX5C and EX6C). However, as shown in Table 2, specimens EX5C and EX6C failed by LBF at ultimate moments, M_u, below the plastic moment, M_p. The direct application of the load on the top flange, by means of a rigid plate, may have caused the early onset of local buckling of the compressed flange.

3. Numerical model

A finite element (FE) model, using the software Ansys (2004) version 9.0, was developed to simulate the behavior of the test specimens. In order to model the sinusoidal-web beam and the end plates, four-node elements *SHELL 181* were used, except for the sinusoidal web and flange junction where triangular elements were necessary (Fig. 6).

The assumed steel constitutive relationship was elastic, perfectly plastic, following the *von Mises* yield criterion. Actual dimensions and boundary conditions as well as measured material properties were used in the analysis, except the modulus of elasticity, taken as the nominal value given by the ANSI/AISC 360-05 [1]. The position of the load relative to the beam shear center and the initial bow imperfections play an important role in the behavior of the beams and were also taken into account.

In models corresponding to beams without central restraint, the vertical load was applied to nodes located at the mid-span section of the beam at a height of 162 mm from the top flange. For the models of beams with central restraint, different loading conditions were tested. The best results were obtained for loads applied directly on the 63 nodes of the top flange, representing a $100 \times 150\ \mathrm{mm}^2$ area (area of the rigid plate between the load actuator and the beam, see Fig. 2(b)). It should be reminded that due to the geometry of the sinusoidal-web cross-section there is an inevitable eccentricity of the load with respect to the shear-center.

In order to incorporate initial geometric imperfections in the numerical model, an eigenvalue analysis was performed and buckling modes were determined. The first buckling modes (lateral