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Shear buckling behaviour of welded stainless steel plate girders with transverse stiffeners

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ABSTRACT

The shear buckling behaviour of welded stainless steel plate girders with transverse stiffeners has been experimentally and numerically investigated in this paper. A total of seven plate girders with rigid/non-rigid end posts were fabricated from hot-rolled stainless steel plates, and each of the plate girders was subjected to a concentrated load at mid-span. The shear buckling characteristics and postbuckling behaviour were observed. Prior to testing, the initial local geometric imperfections and the material properties were accurately measured. The critical shear buckling strengths of the web plates were determined from the recorded surface strains and out-of-plane deflections, which were further compared with theoretically predicted values from elastic and inelastic assumptions. By using the general finite element (FE) software package ABAQUS, elaborated FE models were developed and validated against the obtained test results and other available existing test data. Upon validation of the FE models, parametric studies were subsequently carried out to explore the influences of initial local geometric imperfections, web aspect ratios, end post conditions, and material properties over a wide range of web slendernesses. The obtained test/FE results, together with other existing test data, were summarised to evaluate the current codified provisions in GB 50017, EN 1993-1-5, EN 1993-1-4, EN 1993-1-4 + A1 and the design proposals from Estrada et al. Based on the test and numerical results, an alternative design approach that could account for the material non-linearity and rigid and non-rigid end posts has been proposed, which provides accurate and reasonable strength predictions for stainless steel plate girder with transverse stiffeners.

1. Introduction

Due to the typical configuration of relatively slender web panels, the failure mode of shear buckling is of prominent importance in structural design of plate girders. Web stiffeners, including transverse and longitudinal stiffeners and occasionally inclined stiffeners, have been used to reinforce the web panel and therefore, significant increase of critical shear buckling strength can be achieved. Previous studies have been conducted to develop improved method for the prediction of shear buckling resistances [1–6], from which, it is well recognised that the critical shear buckling strength, postbuckling strength and frame action of the flanges and transverse stiffeners would contribute to the ultimate shear resistance of transversely stiffened plate girders. The existing design methods that applied to ordinary carbon steels are based primarily on the assumption of an idealised elastic, perfectly-plastic material behaviour. However, this idealisation may lead to inaccurate design of plate girders made of nonlinear metallic materials, including aluminium alloy and stainless steel [7]. Since the material properties of stainless steels vary significantly from those of carbon steels in terms of characteristics such as absence of yielding plateau and continuous strain hardening capacity, significant progress has been achieved in investigating the structural behaviour of stainless steel members under various loading conditions, and efficient design approaches have been proposed by many researchers [8–14].

The design and buckling behaviour of stainless steel plate girders subjected to shear failure have attracted attentions in recent years. Olsson [15] conducted eight tests on austenitic and duplex stainless steel plate girders and established new design expressions for the calculation of shear resistance, which were later incorporated into the design code of EN 1993-1-4 [16]. Real et al. [17] presented an experimental programme of nine plate girders made of austenitic stainless steels. Their tests demonstrated the effect of material non-linearity on the shear strength. Meanwhile, Estrada et al. [18–20] performed comprehensive studies on austenitic stainless steel plate girders with transverse and longitudinal stiffeners. New design methods to determine the ultimate shear resistance of stainless steel plate girders

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were proposed subjected to complex boundary conditions. More recently, Saliba and Gardner [21,22] carried out nine tests on lean duplex stainless steel plate girders with rigid end posts, with a revised design approach for predicting the ultimate shear resistance presented. Numerical studies on shear buckling behaviour of stainless steel plate girders were also conducted by Hassanein [23,24], revealing the influences of the imperfections and the characteristics of failure mechanism. Despite the existence of experimental data, it may still be far from adequate to verify design approaches with reasonable accuracy due to the relatively high scatter in available test data. This is mainly due to the large family of stainless steel alloys pre-defined in various design codes. Therefore, the main aim of this paper is to investigate shear buckling and postbuckling behaviour and develop a uniform method for the design of welded stainless steel plate girders with transverse stiffener, crossing a wide variety of stainless steel alloys.

A total of seven transversely stiffened stainless steel plate girders were tested. The test specimens were loaded with concentrated load in the mid-span using simply-supported boundary conditions and they failed by shear buckling of the web. Based on the experimental results, numerical modelling on the shear buckling behaviour of the tested plate girders were performed in ABAQUS considering the measured imperfection and material nonlinearity, and the developed FE models were further validated against other available tests. A parametric study was carried out subsequently to examine the major factors affecting the ultimate shear resistance. The generated test and numerical results were used to assess the adequacy of design provisions in GB 50017 [25], EN 1993-1-5 [26], EN 1993-1-4 [16] and EN 1993-1-4 + A1 [27] and the design expressions presented by Estrada et al. [19]. Finally, an alternative design approach taking into account the material non-linearity and rigid and non-rigid end posts were proposed, enabling a reasonably accurate and efficient prediction for ultimate shear resistances of stainless steel plate girders with transverse stiffeners. The research work presented in this study provides supplementary test data on stainless steel plate girders, and also contributes to the development of design recommendations for improvement on the first edition of Chinese design standard for structural stainless steel [28].

2. Test specimens

2.1. Specimen geometry

The test specimens include a group of seven girders, which were designed and fabricated from hot-rolled stainless steel plates. Both the austenitic grade EN 1.4301 (ASTM 304, GB/T S30408) and duplex grade EN 1.4462 (ASTM 2205, GB/T S22253) [29] were adopted in this study. By means of the laser cutting technique, the constitutive plates of each test specimen were cut in parallel to the longitudinal direction of hot-rolled coil. Compared to the water jet cutting, wire cutting and plasma arc cutting methods, the laser cutting technique provides a much more satisfactory cutting speed, quality and precision. Moreover, a relatively smaller amount of heat is introduced into the plates, resulting in negligible thermal distortions of flat plates during the operation process. Shielded metal arc welding (SMAW) using covered electrodes were performed to fabricate the I-section, where type E308 electrodes corresponded to the EN 1.4301 alloy and type E2209 electrodes to the EN 1.4462 alloy were used and all the electrodes were dried at 350 °C for one hour prior to welding [30]. Subsequent to welding, a hydraulic press with specially designed clamping apparatus successfully applied for fabricating built-up sections in the previous study [13], was also used to alleviate the residual distortions in the cross-sections.

Among the seven test specimens, five of them were designed with non-rigid end posts, while the other two with rigid end posts, as illustrated in Fig. 1. The average measured geometric dimensions are listed in Table 1, where $\overline{\lambda}_w$ is the web slenderness parameter defined in EN 1993-1-5, w_0 is the local imperfection amplitude measured with specially designed setup, and other symbols are defined with reference to Fig. 1. The specimens were labelled such that the material grade, cross-section dimensions and the end post condition can be readily recognised. For example, the label V-2205-R500ad1 defines a plate girder specimen made of EN 1.4462 alloy having rigid end posts, with nominal web 500 mm in depth and aspect ratio $a/h_w = 1.0$. It is worth noting that all test specimens were designed to be slender cross-sections with Class 4 webs subject to bending stipulated in EN 1993-1-4 + A1 [27].

2.2. Local geometric imperfections

Prior to member testing, the initial local geometric imperfections of the test specimens were measured. The adopted device and procedures for determining the geometric imperfections were similar to those presented by Yuan et al. [13], which were successfully applied for measurement of local imperfections in stainless steel built-up sections [31] and extruded aluminium alloy I-sections [32]. Furthermore, the digital linearly varying displacement transducer (LVDT) was replaced with a specially designed laser displacement sensor (LDS) to eliminate the possible frictional effects between the translational LVDT and the plate surface, as shown in Fig. 2. The LDS attached to the slide block of the guideway was driven by a magnetic stepping motor at a uniform translational speed of 20 mm/s along a specified path. Meanwhile, a constant data sampling rate of 20 Hz was used to generate one reading per millimeter. The measuring procedure was accomplished at three representative cross-sections of both panels for each specimen, as illustrated in Fig. 3, and the maximum value among the six cross-sections was taken as the local imperfection amplitude w_0 for the specimen. The measured imperfection distributions of the six cross-sections from specimen V-2205-500ad1.5 are plotted in Fig. 4, and the local imperfection amplitudes w_0 for all test specimens are summarised in Table 1. It can be seen from Table 1 that the maximum value of the local imperfection amplitude among all the specimens is 3.60 mm (h_w/139) for specimen V-304-500ad1.5.

2.3. Material properties

A series of tensile coupon tests were performed to obtain the material properties of the two stainless steel alloys. By using the wire-cutting technique, the standard tensile coupons of each alloy and each thickness were machined from the same hot-rolled stainless coil plates used to fabricate the specimens. Tensile coupons were cut from three directions, including the longitudinal (rolling direction), diagonal and transverse direction. Therefore, a total of forty-five tensile coupons involving fifteen different cases (as listed in Table 2) were tested, since three repeated coupons were prepared for each case. All tensile coupon tests were carried out by means of a 1000 kN capacity universal testing machine. The initial loading rate was set to be 0.5 mm/min until reaching the 0.6% strain limit, and it was gradually increased to 5 mm/min afterwards. Two orthogonal strain gauges and an extensometer were used to record the full stress-strain curves. The average measured material properties from the tested coupons are summarised in Table 2, where E_0 is the Young's modulus, ν is the Poisson's ratio, $\sigma_{0.01}$, $\sigma_{0.2}$ and $\sigma_{1.0}$ are the 0.01%, 0.2% and 1.0% proof stresses, respectively. σ_u is the ultimate tensile stress. ε_u is the strain at the ultimate tensile stress (not obtained for EN 1.4301 coupons due to the limited range of the extensometer) and ε_f is the plastic strain at fracture based on elongation over the standard gauge length. n and m are the first and second strain hardening exponents, respectively, according to Annex C of EN 1993-1-4 + A1 [27]. $n'_{0.2,1.0}$ is the strain hardening exponent from the modified two-stage Ramberg-Osgood model proposed by Gardner and Ashraf [7]. The ratios of 0.2% proof stresses (i.e., DT/LT and TT/LT) are also presented in Table 2, indicating the relatively small degree of anisotropy for the two stainless steel alloys. Specifically, the 0.2% proof stresses from the transverse coupons are generally higher than those