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Finite element investigation of shear failure of lean duplex stainless steel plate girders

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ABSTRACT

The use of duplex stainless steel material has gained popularity in the last two decades thanks to its nature that combines well the advantages of both austenitics and carbon steel materials. The duplex grades offer a combination of higher strength than austenitics in addition to a great majority of carbon steels with similar or superior corrosion resistance. However, high nickel prices have more recently led to a demand for lean duplexes with low nickel content, such as grade EN 1.4162. Wide-ranging work is needed to include the lean duplex grade EN 1.4162, into design standards such as EN 1993-1-4. Accordingly, a finite element modelling for full-size lean duplex stainless steel plate girders of non-rigid end stiffeners of Grade EN 1.4162 is presented in this paper. The paper is principally concerned with shear failure mechanism characteristics of this type of plate girders, which is not yet investigated. The ABAQUS 6.6 programme, as a finite element package, is used in the current work. The lean duplex stainless steel material is simulated here based on an accepted stainless steel material model available in the literature. A number of transversely stiffened I-section plate girders having equal depth of 1000 mm in span of 4 m is considered and parametric studies regarding flange width-to-web depth ratio, flange-to-web thickness ratio and web plate slenderness are carried out. However, new conclusions on shear strength of lean duplex stainless steel plate girders are presented.

1. Introduction

Over the last 20 years, significant developments have occurred in materials processing, providing a range of stainless steel materials characteristics to suit the demands of various engineering applications. This is due to the aesthetic appearance, high corrosion resistance, ease of maintenance, smooth and uniform surface, high fire resistance, high ductility and impact resistance, reuse and recycling capability, as well as ease of construction of stainless steel structural members. Generally, the austenitic grades feature most prominently within the constructional industry. The most commonly employed grades of austenitic stainless steel are EN 1.4301/1.4307 and EN 1.4401/1.4404, which contain around 8–11% nickel. Nickel stabilises the austenitic microstructure and therefore contributes to the associated favourable characteristics such as formability, weldability, toughness and high temperature properties. However, nickel also represents a significant portion of the cost of austenitic stainless steel. Therefore, high nickel prices have more recently led to a demand for lean duplexes with low nickel content, such as grade EN 1.4162 [1–3].

Despite early applications of lean duplex stainless steel, its structural properties remain to some extent unverified as limited test data on structural components have been reported. A research project is underway at Imperial College London to address these shortcomings, focusing initially on cold-formed hollow section columns and beams [4,5], respectively. Paper [4] examined the compressive behaviour of lean duplex stainless steel square and rectangular hollow section columns through experimental tests. The test results were used to validate finite element (FE) models, which were thereafter employed in parametric studies, to expand the range of available structural performance data, studying the influence, in particular, of the cross-section and member slenderness. It is important to note that the compound Ramberg–Osgood material model [6–8], which is a two-stage version of the basic Ramberg–Osgood model [9,10], was used during the numerical part of these papers [4,5]. The results of the study showed that a good agreement between experimental and FE results for cold-rolled stainless steel hollow sections was obtained.

Hence, the generated stress–strain curve based on the available models, as used in Ref. [4], may be used to represent the actual behaviour of the lean duplex stainless steel material. At the same time, extensive work is still needed to include the lean duplex 1.4162, into design standards such as EN 1993-1-4 [11]. One of these works is to investigate the behaviour of the lean

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duplex stainless steel plate girders under shear, which is not yet investigated, as presented in the current paper.

Commonly, plate girders are fabricated by welding together two flanges, a web and a series of transverse stiffeners. Flanges resist the applied moment, while web plates maintain the relative distance between the top and bottom flanges and resist the induced shearing force. In most practical ranges of span lengths of plate girder, the induced shearing force is relatively lower than the axial forces in the flanges. Accordingly, the thickness of the web plate is generally much smaller than that of the flanges. Thus, the web panel buckles at a relatively low value of the applied shear force. Therefore, the webs are often reinforced with transversal stiffeners along their spans to increase the buckling strength. However, the web design involves finding a combination of an optimum plate thickness and stiffener spacing that provides economy in terms of the material and fabrication cost [12].

Until the 1960s, the elastic buckling concept was basically used in the design of plate girders despite the fact that post-buckling behaviour was discovered by Wilson [13] as early as 1886 and diagonal *tension field theory* was firstly developed later by Wagner [14]. By that time, different theories had been developed to analyse the ultimate shear capacity of carbon steel plate girders, leading to some being used in current design codes. These theories have been reviewed in Refs. [15,16]. The fundamental assumption that compressive stresses that develop in the direction perpendicular to the tension diagonal do not increase any further once elastic buckling, which was first assumed by Wagner [14], has taken place is common in all of these theories although they assume different yield zone patterns. The application of this fundamental assumption to the whole web panel led to the well-known theory that the tension field action in plate girders with transverse stiffeners needs to be anchored by flanges and stiffeners in order for the webs to develop their full post-buckling strength.

The finite element results of different simple-span carbon steel plate girders indicate that the formation of plastic hinges in flanges may either have a flexural or shear basis. In the bending-initiated mechanism, plastic hinges form at mid-spans; while in the shear-initiated mechanism, plastic hinges only occur in the end panels. If flange plates are not rigid enough to resist bending-induced normal stresses, plastic hinges appear at the position of maximum-bending moment. After buckling of web plate occurs, the plate cannot carry further compressive stresses and a new load carrying mechanism develops, whereby any additional shear loading is supported by an inclined tensile stress field. As the applied loading increases, the tensile membrane stress grows until it reaches the yield stress of the material. When the web has yielded, final collapse will occur when plastic hinges are formed in the flanges that permit a shear sway failure mechanism [16,17].

The design of stainless steel members is more complex than that of carbon steels, due to the differences in the mechanical behaviour of stainless steels as compared to carbon steels. It is noted that stainless steels have gradually yielding type of stress–strain curves with relatively low proportional limits.

In the research carried by Real et al. [17], it was noted that stainless steel structures' shear buckling is always developed in the nonlinear path and its post-critical behaviour is clearly influenced by the material nonlinearity, which results in a loss of resistant capacity. It was also concluded that *the numerical model provides a good approximation to the actual behaviour of stainless steel structural elements*. Consequently, it could be used as a useful analysis tool in order to develop and establish new design rules to incorporate into codes.

However, although there has been a great deal of work carried out on carbon steel plate buckling and post-buckling behaviours, there is still a new amount to be learnt in the case of lean duplex stainless steel plate girders.

Recently, theoretical series of models to investigate the shear behaviour and strength of austenitic stainless steel plate girders of grade EN 1.4301 (304) were reported by the current author [18,19]. I-section plate girders with non-rigid stiffeners were considered in them. The principal aim was to improve the current knowledge of the structural behaviour of both austenitic stainless steel plate girders, leading to more efficient relationships between the key parameters that affect this type of girders. It was concluded, generally, that the behaviour of the austenitic stainless steel plate girders in shear to some extent differs from that of carbon steel ones. It was also stated in the conclusion of Refs. [18,19] that the work done may extend to study the effect of stiffener thickness, other end stiffener types, value of the initial imperfection of the stainless steel plate girders, different stainless steel material grades and different design methods.

Hence, the work done in Refs. [18,19] is expanded here for different stainless steel material grades; the lean duplex stainless steel grade EN 1.4162. Accordingly, the current paper reports a theoretical series of models to investigate the shear behaviour and strength of I-shaped lean duplex grade EN 1.4162 stainless steel plate girders of non-rigid end stiffeners. This work seeks to build a basis for the structural behaviour of lean duplex stainless steel plate girders. Hence, the effect of different parameters such as the flange width-to-web depth ratio (b_f/h_w), flange-to-web thickness ratio (t_f/t_w), web plate slenderness (h_w/t_w) and the initial imperfection amplitude are taken into consideration.

2. Current finite element model

2.1. General

A web plate is bound to have some bending moments due to lateral loadings, the true behaviour of flange-web junction is neither simply supported nor clamped, a free or restrained in-plane movement of panel edges cannot represent the real behaviour of web plates and the number of sub-plates created by intermediate transverse stiffeners and conditions of end-posts (end stiffeners) has considerable effects on the behaviour of plate girders [16]. Therefore, an isolated web panel simulation model, a simply supported web plate in shear and even single-panel experimental tests cannot accurately represent the behaviour of plate girder web plates. For these reasons, in order to analyse the shear behaviour of the nonlinear lean duplex stainless steel plated girders, a numerical analysis on full-size plate girders was conducted here. The finite element analysis programme conducted in case of austenitic stainless steel plated girders with square web panels, as presented in Ref. [19] is considered in the current modelling to allow for a comparison between both types of steels.

Finite element models, using the ABAQUS [20] computer package, are performed on one hundred and fourteen lean duplex stainless steel plate girders covering the following parameters:

1. flange width-to-web depth ratio (b_f/h_w); (0.25, 0.30 and 0.35),
2. flange-to-web thickness ratio (t_f/t_w); (0.5 to 4),
3. web plate slenderness (h_w/t_w); (125, 167, 200 and 250) and
4. initial imperfection; (h_w/100, h_w/500 and h_w/100000).

The span of the girders and the web depth are fixed to 4000 and 1000 mm, respectively, for the whole finite element models. The aspect ratio of the web panel (a/h_w) is fixed to one, i.e. only square panels are considered. The webs of the girders are stiffened transversely to avoid them from deflecting and prevent the flanges from coming nearer to each other at the stiffeners. Out-standing plate stiffeners extending to the edge of the flanges of the plate girder are considered and the thickness of them is