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Behaviour and design of hollow and concrete-filled spiral welded steel tube columns subjected to axial compression

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ABSTRACT

Spiral welded tube (SWT) structures have found worldwide application in pipeline construction, wind turbine towers, foundation piles, and columns in tall buildings. However, the understanding of their fundamental behaviour is still insufficient and efficient analysis and design methods have not been precisely developed owing to the lack of experimental and numerical research on these types of structures. A distinct advantage of SWT is their streamlined manufacturing process, so that today large diameter SWT can be economically produced. Due to the application of SWT as structural members being relatively new, this paper presents an investigation into the behaviour of hollow and concrete-filled steel SWT columns when subjected to axial compressive loading. Parameters of particular interest affecting the strength and failure modes include the weld's spiral geometry and initial imperfections from the production process. To evaluate the behaviour of SWT columns, an accurately developed finite element model (FEM) which incorporates the effects of initial local imperfections and residual stresses using the commercial finite element program ABAQUS has been prepared. The FEM buckling behaviour of SWT is compared with that of longitudinally welded tubes (LWTs). Experimental laboratory testing is carried out on twenty columns under displacement-controlled loading conditions in order to calibrate and verify the accuracy of the model results. Furthermore, a design model is proposed for circular concrete-filled steel tube columns. In addition, comparisons with the prediction of axial load capacity using the proposed design model, Australian Standards, Eurocode, and American Institute of Steel Construction code provisions for hollow and concrete-filled SWT and LWT columns is also carried out.

1. Introduction

Steel tubes are widely used in many industrial applications, and are usually distinguished by their method of production. They can be produced either seamless (with diameter from 21 to 406 mm) or with seam method by longitudinal welding (with diameter from 10 to 1630 mm) or spiral welding (with diameter from 160 to 3000 mm) from rolled strip or thick plate [1]. Welded tubes are produced by bending metal strips (skelp) or plates into the form of a tube by roll forming and welding the seam by various welding processes. Currently around two thirds of the steel tubes produced in the world are accounted for by welding processes. There are two types of welded tubes, longitudinally welded tube (LWT) and spirally welded tube (SWT) [2]. LWTs are manufactured from steel plate with only one weld seam joining the two edges of the rolled plate. SWTs are manufactured by helical rolling of the steel coils. In contrast to LWT production where each tube diameter requires a certain plate width, spiral tube production is characterised by the fact that various tube diameters can be manufactured from a single strip or plate width [3]. Total global SWT and LWT production distribution was 37% and 63% in 2007, respectively, as shown in Fig. 1 [4].

The most common structural application of a cylindrical shell with helical features is the SWT, first used at the end of the 19th century in water transmission pipelines [5–6]. SWTs were originally manufactured by riveting together properly bent plates until progress in welding technology allowed for the efficient tandem arc welding process [5] (see Fig. 2). The process of producing SWT has been progressively improved, so that today large diameter SWTs can be economically produced. These tubes are used for pipeline construction, wind turbine towers, foundation piles, load-bearing members in combined walls, and columns in tall buildings [2,7].

SWTs provide significant benefits over traditional longitudinal and butt-welded tubes, for the following reasons: (a) SWTs are a cost-effective solution compared with other manufacturing processes, (b) SWTs can be manufactured in 30 m lengths with outside diameters from 160 to 3000 mm and wall thicknesses ranging from 2 to 30 mm [8],

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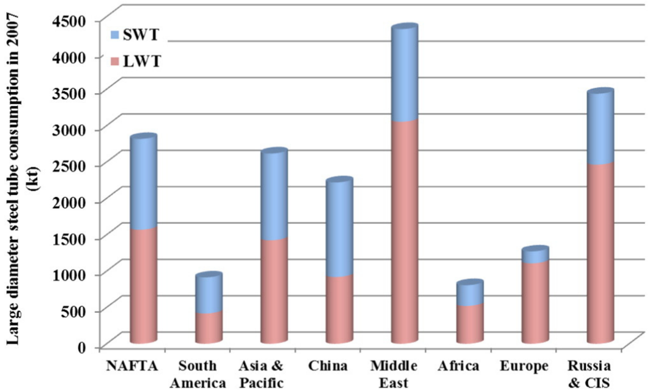

Fig. 1. SWTs and LWTs consumption [4].

and (c) continuous or very long tubular members may be constructed efficiently both in a factory and onsite from compact coils of metal strip, reducing the need for costly transport of long structural members [9].

SWTs can be used as structural columns in buildings. These SWT columns will be more effective especially if they are filled with concrete. Concrete filled steel tubes (CFSTs) are stiff and strong in axial compression, and have substantial bending resistance which has been proven in previous studies [10]. The combined action between the steel tube and the concrete infill provides a higher resistance in tension (steel tube), compression (concrete filled), and reduces local and global instabilities. These properties make them ideal for bridge piers, foundation caissons and piles, as well as columns in multi-storey buildings subjected to both gravity and extreme loadings, such as earthquake, impact, and blast [11].

In this study, SWTs have been used in CFST columns and the research has been conducted with an eye towards characterising the engineering properties of SWTs and resulting design recommendations. Available code provisions do not currently address the design of CFST incorporating SWTs and this study attempts to remedy this situation.

Moreover, a finite element model (FEM) which includes the effects of initial local imperfections and residual stresses using the commercial program ABAQUS has been implemented to evaluate the behaviour of SWT and LWT columns. Experimental laboratory tests are carried out on ten hollow SWT and LWT columns and ten concrete-filled SWT and LWT columns under axial compression loading conditions in order to calibrate and verify the accuracy of the model results. Moreover, a design model incorporating a concrete confining pressure approach is proposed for predicting the ultimate axial strength of circular CFST columns. Furthermore, comparisons with the prediction of axial load capacity by using the Australian Standards, Eurocodes, American Institute of Steel Construction code provisions, and the proposed design model for hollow and concrete-filled SWT and LWT columns is also carried out.

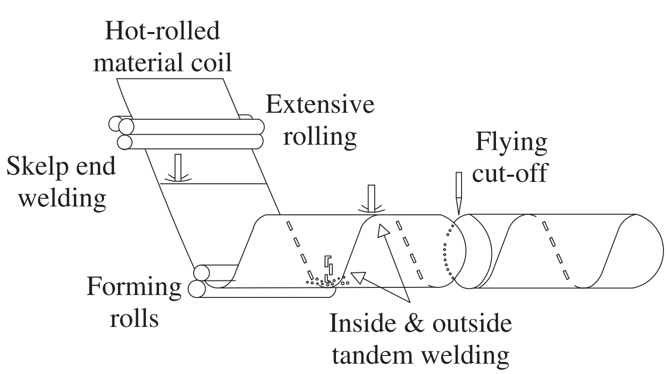

Fig. 2. Schematic illustration of the SWT forming process.

2. Experiments

This section outlines the test program undertaken which consists of hollow and concrete-filled SWT and LWT column tests and associated material property tests. The test set-up for the columns will be described and the results will then be presented. A general review and description of the failure modes will then be presented.

2.1. Material properties

2.1.1. Tensile coupon tests

One of the crucial concerns for the SWT is the possible influence of material anisotropy on the bending resistance of the resulting fabricated tube. The rolling process used to form the SWT causes the steel to develop anisotropic characteristics [12]. The longitudinal yield strength is generally lower than in the transverse direction of the steel. For LWT, the orientation of anisotropy remains the same as that of the steel plate from which it is formed. As a result, the highest yield strength occurs in the direction around the circumference of the cylinder, which is termed the hoop strength. This also means that LWTs are weaker along the longitudinal axis. However, this situation is not the same for SWT. The longitudinal strength follows the spiral with the transverse yield strength perpendicular the weld. Thus, the axial direction along the length of the cylinder is stronger compared with that of a LWT. On the basis of material anisotropy directions, SWT has the potential to outperform LWT when subject to axial compressive loading. Heiberg et al. [12] presented findings of bending stiffness being greater in SWT than LWT, and proposed that this might also be attributed to SWTs having a higher Young's modulus in the axial direction. Also, Sadowski et al. [13] have conducted tensile tests on four SWTs with outer diameters of 820 mm (two had a nominal thickness of 8 mm and two of 11 mm) at four different orientations parallel to the tube axis, transverse to the tube axis, parallel to the strip axis and transverse to the strip axis. They have concluded that SWTs exhibit no significant differences for different orientations, and therefore the stress-strain characteristics of a SWT may thus be treated as isotropic.

In this study, two tensile coupon test scenarios have been considered. To determine the stress-strain characteristics of the SWT and LWT steel plate in tension, six 400 mm tensile coupons were produced from the virgin SWT and LWT steel plate and six 400 mm tensile coupons were extracted from SWT in three different orientations relative to the tube axes and the spiral directions (Parallel to the tube axis (denoted V), transverse to the tube axis (S), parallel to the weld axis (P)) and tested in an Instron uniaxial testing machine. Pertinent data for these test coupons is provided in Table 1.

Six tests were conducted for virgin SWT and LWT steel plates with a mean value of yield stress of 288 N/mm^2 and 277 N/mm^2 being established, respectively. The tests revealed an increase in stress after yielding and the mean ultimate stress of the SWT and LWT steel plate in tension was determined to be 298 N/mm^2 and 308 N/mm^2, respectively. Stress-strain diagrams are provided in Fig. 3 and the failure mode of the tensile coupons is illustrated in Fig. 4. The ductility can also be observed both by the pronounced necking of the specimens, which resulted in ultimate strains in excess of 1441 and 1440 microstrain (με) for SWT and LWT, respectively.

Another six tests which were conducted for six 400 mm tensile coupons were extracted from SWT and the results show that there is no significant difference between the yield stress for the V, P, and S orientations. Furthermore, these results concur with the conclusions of Heiberg et al. [12] and Sadowski et al. [13].