Engineering Structures 85 (2015) 234–248

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Harmonic analysis of measured initial geometric imperfections in large spiral welded carbon steel tubes

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ARTICLE INFO

Article history:
Received 13 September 2014
Revised 11 December 2014
Accepted 12 December 2014
Available online 2 January 2015

Keywords:
Spiral-welded tubes
Thick tubes
Geometric imperfections
Harmonic analysis
Imperfection characterisation

ABSTRACT

Geometric imperfections have long been known to play an important role in determining the buckling resistance of metal cylindrical shells and tubes. Though the effect is more important in thin shells rather than thicker tubular members, it may still have a significant impact on the strength of tubulars where buckling occurs in the plastic range.

Spiral welded carbon steel tubes with D/t ratios in the approximate range 50–150 are often used as primary load-bearing members together with sheet piling in deep retaining walls. A recent European study on such tubes aimed to devise improved and more economical design guidelines for their use. As a central part of this project, a representative selection of 18 tubes was subject to a laser survey to obtain detailed scans of the initial imperfections found on their outer surfaces, in addition to careful wall thickness measurements. The resulting high quality data set is considered to be the first of its kind.

The surface imperfections of the full set of 18 tubes were collectively analysed using a combination of single and double Fourier series to assess the dominant imperfection modes and their amplitudes. It was found that the spiral welding process results in a very unique pattern of surface imperfections which is here characterised algebraically. The systematic peak geometric deviations of the tube surfaces were found to be modest and consistent with the imperfection amplitudes defined by EN 1993-1-6 for this D/t range.

1. Introduction

Spiral welded cylindrical carbon steel tubes are often used as piles and with sheet pile walls where they offer a significantly increased resistance against flexure [1]. The practical range of diameter to thickness ratios (D/t) of such tubes is approximately 50–150. These may be designed either as a 'thin tube' using beam theory and a global stress resultant criterion [2] or as a 'thick shell' using shell theory and a local stress criterion [3]. Unfortunately, the differences in the design philosophy between these two standards have resulted in a substantial and unnecessary discrepancy between the provisions of both standards for tubes in this D/t range.

This discrepancy is the *raison d'être* of the RFCS-funded Combitube project [4], performed in partnership with the Universities of Edinburgh (UK), Delft (Netherlands) and Thessaly (Greece), the Karlsruhe Institute of Technology (Germany), ArcelorMittal (Luxembourg) and BAM Infraconsult (Netherlands) and recently completed in the summer of 2014. The aim of the project is to draw up safe and economical design rules for tubes in bending based on an extensive programme of experimental and numerical studies. A major part of the project consists of the testing of several full-scale specimens under global bending, performed simultaneously at the Delft University of Technology (TU Delft) and the Karlsruhe Institute of Technology (KIT), in each case preceded by detailed laser surveys of the exterior surfaces of these tubes which are the focus of this paper. The resulting very high quality data set of initial geometric imperfections associated with the spiral welding process is believed to be the first of its kind.

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http://dx.doi.org/10.1016/j.engstruct.2014.12.033

2. Background to the interpretation of imperfection measurements

This study of the measured imperfections in spiral welded tubulars exploits the numerous studies undertaken since the 1960s to characterise imperfections for accurate prediction of the buckling resistance of shell structures. Full-scale imperfection surveys that mapped the shell surface deviations may be traced to the work of Arbocz, Babcock and Singer [5–9] for the aerospace industry. This early work led to the proposed "Imperfection Data Bank" [10–16] to permit realistic imperfection shapes to be related to the fabrication process. More recently, similar full-scale surveys were made of aluminium shells for the Ariane space programme [17,18], composite cylinders for aerospace and marine applications [19–22] and spherical LNG storage tanks [23,24].

Surveys of large-scale civil engineering shells are relatively recent, but it was recognised that geometric imperfections found in such shells are significantly different to those in aerospace shells due to the widely different manufacturing processes and difference in scale, making them worthy of study in their own right [25]. Clarke and Rotter [26] may have been the first to survey geometric imperfections in a thin-walled cylindrical steel silo, while Coleman et al. [27] and Ding et al. [28–30] devised an improved measuring technique for large-scale silos and tanks involving a moving measuring trolley with biaxial degrees of freedom. Together with careful later studies by Berry et al. [31–33], Pircher et al. [34] and Teng et al. [35], it was shown definitively that measured imperfections in most civil engineering shells are dominated by axisymmetric depressions caused by the welding of curved circumferential panels. This contrasted with the asymmetric imperfections typically found in aerospace and laboratory shells which often have longitudinal seams (e.g. [5,8,18]). Previous analytical studies had already established that axisymmetric imperfections generally lead to the most dramatic strength reductions in cylindrical shells (e.g. [36,37]) and computational studies have since confirmed that the imperfections caused by circumferential welding are the most damaging for cylindrical civil engineering shells [33,38,39].

It remains a formidable challenge to produce simplified characterisations of imperfection measurements suitable for use in the design of shell and tubular structures. A powerful method of data reduction practiced by the early aerospace engineers was harmonic analysis, appropriate for full 3D imperfection surveys and simple enough to be programmed on early computers. The result was a complete spectrum of Fourier harmonics which allowed possible critical imperfections to be identified by their relative amplitude and characterised by their wave number (see references by Arbocz and Singer). Though widely used to analyse measured imperfections in civil engineering shells (e.g. [30,35,40–43]), for design purposes the focus has generally shifted towards finding idealised mathematical representations of characteristic imperfections caused by specific manufacturing processes or construction details [38,44–48]. These include the circumferential weld depression [38], lap-joints [49,50], misfits of curved panels [51,52], local foundation settlement [53], global out-of-roundness [3,54] and local wall flattening [55], amongst many others.

The authors do not know of any previous 3D surveys or characterisations of geometric imperfections in spiral welded cylindrical tubes. This paper presents a detailed summary, harmonic analysis, interpretation and characterisation of 'as measured' patterns of initial geometric imperfections found in sixteen spiral welded and two longitudinally-welded 'control' tubes with D/t ratios ranging from 67 to 119. Though the influence of imperfections is often more dramatic in thin shells that buckle elastically, they may still significantly reduce the strength of thicker tubular members where buckling under global bending occurs in the plastic range. From a structural perspective, the critical terms in the harmonic analysis are usually not those with the largest amplitudes (typically low harmonics), but those whose wavelength is close to that of the critical buckling mode (typically a high harmonic). However, the structural consequences of the imperfections described here is beyond the scope of the paper.

3. Experimental procedure for measuring initial surface imperfections

3.1. Introduction

This paper explores the initial geometric imperfections in spiral welded tubes based on careful laser surveys performed at TU Delft and KIT. A detailed account of the two different surveying procedures is presented here. The processing and analysis of the data were performed within the 64-bit Matlab R2013a [56] programming environment.

A total of 16 spiral welded tubes were surveyed for this study together with 2 longitudinally-welded 'control' specimens, summarised in Table 1. Fifteen of these were surveyed at TU Delft (T1–T13 as well as the two control specimens T17 and T18) while three were surveyed at KIT (T14–T16). The nominal steel grade of the tubes ranged from X52 or $f_y = 355$ MPa to X70 or $f_y = 450$ MPa, representative of such tubes used in practice. A statistical analysis of characterised tensile tests from similar tubes was performed by Sadowski et al. [57], offering bounds on post-yield material properties and suggesting that the spiral welded tubes may be effectively treated as isotropic. Since the forces required to deform the steel sheet from the coil into the helical tubular form depend linearly on the yield stress, one might also suppose that the amplitudes of the imperfections caused by those forces are also linearly related to the yield stress. However, as the spread of steel grades is small it is assumed here that all specimens can be treated as part of the same population for the imperfection assessment. A number of the spiral welded specimens contained either a girth weld (where two segments of spiral welded tube were welded together to form a single specimen), a coil weld (joining the ends of two steel coils as the tube is spirally rolled) or both. Each of these welds leads to an additional systematic imperfection pattern caused by the manufacturing process.

3.2. Surveying procedure at TU Delft

The measurements of the initial surface imperfections of the fifteen specimens at TU Delft were performed with a Sensopart FT50 RLA-40-F [58] laser scanner mounted on a specially designed mobile trolley. The specimen was placed on two stiff supports while the trolley slowly travelled along the designated survey length of the tube (approximately 7630 mm) and scanned the underside of the specimen (Fig. 1). The laser scanner was also used to scan along a trough containing an opaque liquid positioned parallel to the specimen. The measurements of the tube surface were then related to the flat surface of the liquid to provide a truly horizontal reference. The specimen was then successively rotated about its axis through a fixed increment and the scan repeated. A first group of specimens were scanned using only 8 generators (angular increment = 45°), but all others used 16 generators (increment = 22.5°) to detect more detail. The meridional resolution of all scans was very high with approximately one observation per mm. The position of the trolley was identified from the total rotation of one of the wheels using an angular displacement transducer, and the net outer surface deviation was thus expressed in terms of the relative position of the trolley. A floating average filter