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Modelling and behaviour of cylindrical shell structures with helical features

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A B S T R A C T

Spiral welding or bonding is a particularly efficient and cost-effective method of constructing continuous tubes. However the understanding of the mechanics of such structures is not yet well developed. This is in no small part due to the difficulties involved in their computational analysis.

Cylindrical shells are traditionally modelled using rectangular finite elements oriented parallel to the meridional and circumferential axes. However, spiral features are particularly challenging to model because such features are not orthogonal to the axes of the cylinder. Commercial finite element pre-processors often struggle to mesh these with anything other than a free triangulation. A superior mesh would consist of well-conditioned rectangular elements oriented orthogonally with respect to the axes of the helix, termed a 'helical mesh', but this requires significant programming effort. A helical mesh is particularly important if features of the shell such as geometric imperfections, residual stresses, weld material and heat affected zones, and bonding in systems using adhesives are required to follow the helical form. Helically wound structural forms are widely used in different applications that demand continuous cylindrical forms. The most common uses in structural engineering are in spiral wound tubes, piles, chimneys and pipelines.

This paper describes a powerful computational procedure developed by the authors to generate high quality helical meshes. Special emphasis is placed on the modelling of geometric deviations defined relative to the helix, appropriate for the analysis of spiral welded and stiffened tubes. The effect of helical meshing is illustrated using benchmark examples of perfect and imperfect cylinders under axial compression.

1. Introduction

The most common structural application of a cylindrical shell with helical features is the spiral formed tube, first used at the end of the 19th century in water transmission pipelines [1,2]. Spiral formed pipes were initially constructed by riveting together appropriately bent plates [3] until advances in welding technology allowed for efficient tandem arc welding [1] (Fig. 1). Spiral welded tubes are now widely used in applications such as water, gas and oil pipelines under both low and high pressure [4] as well as for foundation piles and primary load-bearing members in Combi-walls [5].

Spiral welded tubes offer certain advantages over traditional longitudinal and butt-welded tubes. In particular, continuous or very long tubular members may be constructed efficiently both in a factory and on-site from compact coils of metal strip, eliminating the need for costly transport of long structural members. The material coil is usually produced to very tight tolerances which results in a consistent wall thickness in the finished tube [6]. Further, under certain conditions spiral welded tubes have been found to exhibit a superior performance in fatigue tests to that of tubes with longitudinal seams [7]. They also exhibit a comparable resistance to ductile crack propagation [8]. However, the diameter and wall thickness of spiral welded tubes are currently limited to approximately 3 m and 30 mm, respectively [9] which generally makes them unsuitable for offshore and deep-water applications [10].

Not every helical feature produces a detrimental imperfection. For example, tall slender chimneys are often fitted with continuous spiral fins, known as 'helical spoilers', to protect against alternating vortex shedding that can cause large oscillations under wind [11]. Other structures include screw conveyor shafts [12], pre-stressed concrete and plastic pipes with helical wire reinforcement [13,14] and specialist thin-walled cylindrical tanks constructed using either the LIPP® Dual-Seam or similar spiral folding systems.

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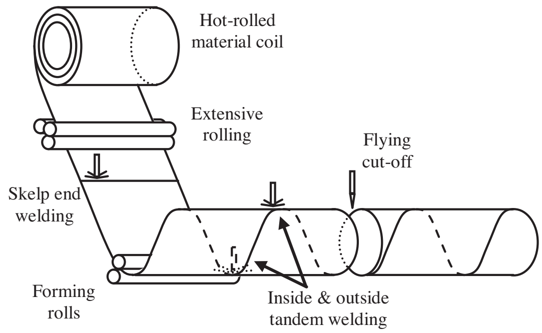

Fig. 1. Generic illustration of key features of the spiral welding process.

2. Current computer modelling of cylinders with helical features

Spiral welded and helically wound cylindrical structures represent a fast growth area in several industries due to the above advantages. However, very little scientific study has so far been undertaken to gain an understanding of the nonlinear behaviour and mechanics of such structures, so the field is still in its infancy. The limited literature that does exist is based largely on empirical studies rather than analytical ones. This is in no small part due to the mathematical complexity of helical geometries which precluded their consideration in the development of thin-walled shell theory when the first hand solutions were being developed [15–19].

These difficulties have persisted into the computer era. Helical features in cylindrical structures represent a significant challenge for finite element modelling because they are not orthogonal to the principal axes of the structure and are consequently difficult to mesh, though several attempts have been made in the past decade. For example, Dong et al. [20] analysed a cylindrical spiral welded steel tube with ABAQUS [21] using a 'double-helix' mesh of inclined quadrilateral shell elements (Fig. 2). The welding process was modelled using a thermo-mechanical material model applied directly to the elements defined as the 'weld', and the tube was given no geometric deviations. Wirth [22] used ANSYS [23] to perform nonlinear buckling analyses of axially-compressed thin-walled cylinders with explicitly-modelled spiral LIPP® folds using a 'single-helix' mesh (Fig. 2) of slightly distorted shell elements. As the helical incline angle was very shallow, the mesh distortion was minimal and the analyses were in close agreement with experiments. Arif et al. [24] used ANSYS [23] to perform a thermal stress analysis of a laser-welded spiral tube with solid continuum elements. They employed a user subroutine to generate a 'single-helix' partition of the tube to trace the outline of the spiral weld for the purposes of defining an appropriate region for load introduction and material properties. However the perfect geometry of the structure itself was meshed freely with tetrahedral elements. Ohnishi et al. [25] analysed spiral fabricated steel pipes under cyclic loading using a 'double-helix' mesh of shell finite elements and the CYNAS [26,27] finite element program, though the choice of mesh and its consequences were not discussed. In their study of predicted residual stress patterns in arc-welded spiral pipes, Forouzan et al. [28] used ANSYS [23] to model the spiral pipe with a 'single-helix' mesh of distorted shell elements. Rather than employing a partitioning procedure, the authors used external scripts to generate nodal coordinates of the perfect shell directly. No mention is made of the effect of element distortion on the accuracy of the solution, though the authors reported a good agreement with experiment.

Sadowski and Rotter [29] described a detailed procedure according to which a commercial finite element pre-processor may be used to model a cylindrical shell with a regular mesh of well-defined, helical, quadrilateral shell elements. As always, however, the user must be sufficiently proficient as a programmer to manually create helical partitions on the cylinder. These in turn force the intrinsic meshing algorithm of the pre-processor to generate quadrilateral elements which conform to the axis of the helix rather than to that of the cylinder. The procedure is general enough to be applied using any finite element pre-processor with an external scripting functionality (e.g., ABAQUS, ANSYS, COMSOL). This manner of 'helical meshing' is central to the material presented in this paper, so a brief outline is appropriate here.

The procedure of [29] proposes two partition configurations (Fig. 2), the 'single-helix' and 'double-helix', each leading to a distinctly different type of inclined finite element mesh. In the first type (Fig. 2a), a family of equally-spaced adjacent helices is generated on the cylinder surface, each helix forming an angle of α with the transverse axis and partitioning the cylinder face accordingly. The pre-processor then generates a regular mesh of curved parallelogram elements where one pair of opposing sides lie parallel to the horizontal axis and the other pair is parallel to the helices. Though relatively simple to code, elements generated in this manner become increasingly distorted with the helical angle α which may result in inferior performance [30,31]. The second, superior, type of partitioning involves generating regularly-spaced pairs of orthogonal helices. The pre-processor then creates a regular mesh of well-conditioned curved rectangular elements that all share the same angle of inclination everywhere (Fig. 2b), except near the ends of the cylinder where some local triangulation is necessary to enforce a circular diametral boundary.

With appropriate scripting, helical partitioning clearly works very well to model *perfect* cylindrical geometries. Indeed, all the computational studies referenced above used partitioning on a perfect shell to model the effects of spiral welds. However, the meshing algorithm of a typical commercial pre-processor usually struggles to mesh helically partitioned cylinders with all but the most trivial spiral geometric imperfections using any method other than a free triangulation. The more geometrically versatile triangular elements can certainly be used to mesh deep spiral imperfections, but

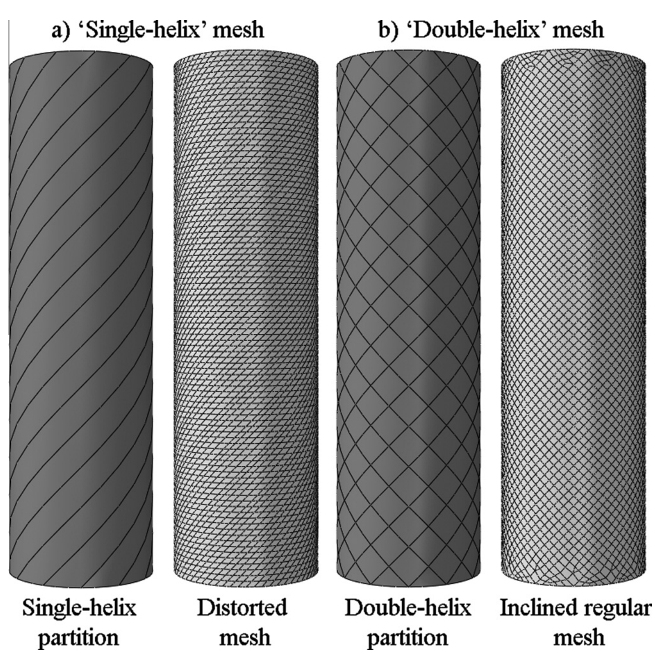

Fig. 2. Illustration of helical partitioning and meshing in ABAQUS CAE, after [29].