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Environmentally friendly joining of tubes by their ends

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ABSTRACT

This paper proposes an environmentally friendly joining process for connecting tubes by their ends that has the potential to replace current solutions based on fastened, crimped, welded, brazed or adhesive bonded joints. The process is based on a new type of tubular lap joint produced by local plastic instability and compression beading that has a substantial overlap with the counterfacing surfaces of the mating tubes to be joined. The presentation combines independent characterization of the materials, experimentation and numerical simulation of the process in order to identify the modes of deformation and the process feasibility window, and destructive testing to establish the working limits of tubular lap joints under different type of loading conditions. Results demonstrate that the proposed joining process is a flexible and cost-effective technology for connecting tubes by their ends with a better performance than current environmentally friendly alternatives based on tubular butt joints produced by plastic deformation.

1. Introduction

Modern lightweight structures employed in architecture, engineering and building construction make use of tubular trusses. Tubes are also essential elements in air-conditioning, refrigeration, heat-exchangers, supply lines and pipelines to convey fluids from one location to another.

The design process of tubular trusses and piping systems may be divided into three different stages: (i) selection of the most appropriate framing system or piping layout, (ii) design of the member sections (tubular profiles) to be used and (iii) design of the connections and their fabrication processes taking into account the overall requirements given by the framing system, the piping layout or the member sections.

Structural engineers optimize the design of tubular structures and piping by improving the layout and the geometry of the member sections and by choosing high strength materials but, according to Girardier (1991), these improvements will rather alter the overall weight and cost of a lightweight structure by more than 10%. In contrast there is a much larger scope for weight and cost savings by revising the existing connections and their fabrication processes. This is very important in case of lightweight structures made from tubular trusses because up to 60% of the total costs, after subtracting direct material costs, are related to the design, fabrication and installation of the connections (Tizani et al., 1993).

Besides the importance of developing lighter and cheaper solutions for connecting tubes, there are growing environmental requirements that also need to be considered. For example, in case of joining tubes by their ends, the existing solutions based on welding (Fig. 1a), brazing and adhesive bonding (Fig. 1b) make use of shielding gases, hazardous materials or chemical reactions that may not be appropriate to use in applications for home or commercial buildings. Moreover, the welding of tubes made from dissimilar materials may even require coating the weld seams by painting or the utilization of transition inserts in order to avoid bimetallic corrosion of the weld seam in moist environments (Olson et al., 1993).

The utilization of brazing and adhesive bonding for connecting two tubes by their ends is also not recommended in case of tubes made from dissimilar materials or exposed to high service temperatures due to the differences in mechanical strength and thermal expansion rates of the tubes and fillers.

Alternative solutions for connecting two tubes by their ends based on flanges or bulkhead joints (Fig. 1c) are simple to design, easy to assemble and disassemble and capable of avoiding the above mentioned environmental drawbacks associated to welding, brazing and adhesive bonding. However, they are generally limited by aesthetic and geometric constraints plus additional tube end preparation requirements (e.g. threaded tube ends) that may

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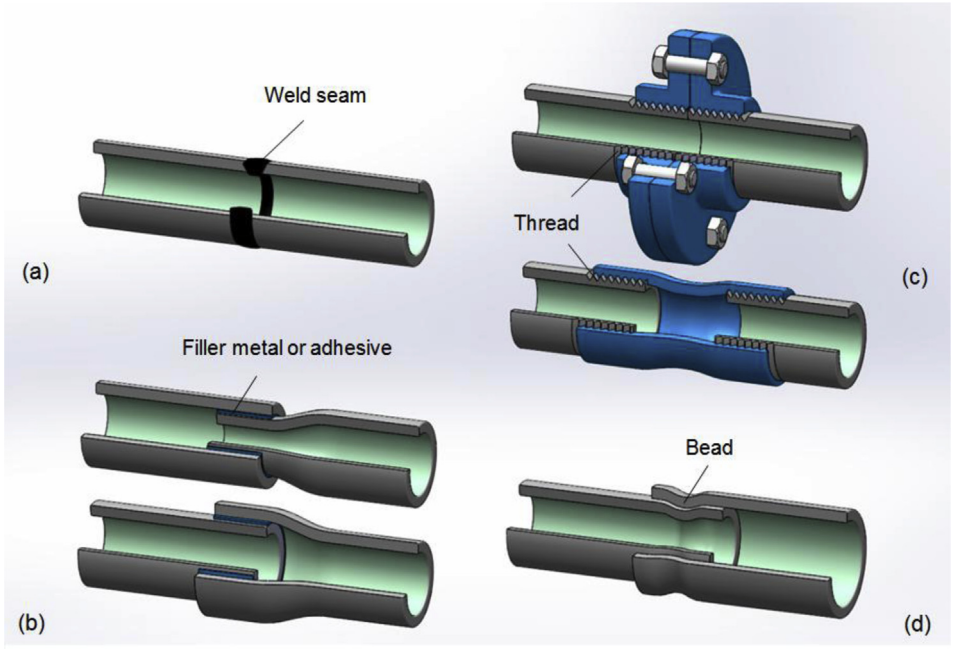

Fig. 1. Different types of conventional connections for the joining of tubes by their ends: (a) welded joints, (b) brazed or adhesive joints, (c) flanges or bulkhead joints and (d) crimped joints.

increase the overall weight and cost of tubular trusses and piping systems.

New solutions based on crimped joints (Fig. 1d) obtained by reduction, swaging (Zhang et al., 2014), dieless hydroforming (Marré et al., 2010) or electromagnetic forming (Psyk et al., 2011) are not constrained by aesthetics or by the availability of flanges or bulkhead unions in standard sizes but are generally limited by the required mechanical strength, the overall tightness of the connections and, in case of electromagnetic forming, by requirements of high electrical conductivity, which limit its applicability to tubes made from aluminium, copper and its alloys.

Recent developments in joining by forming that are comprehensively systematized in state-of-the-art reviews by Mori et al. (2013) and Groche et al. (2014) allow concluding that plastic deformation offers great potential to fabricate connections for tubular trusses and piping systems while combining the growing demands for high productivity, low fabrication costs and environmental friendliness with high performance and material versatility. Table 1 summarizes these features and compares with joining by welding.

Table 1
Summary of the main features of joining by forming and by welding.

	Joining by forming	Joining by welding
Mechanism	Plastic deformation	Melting with addition of filler materials
Shape of the connections	Arbitrary geometries	Limited to butt, lap, corner and edge joints
Operating temperature	Ambient	Melting point
Heat-affected zones	No	Yes
Shielding gases	No	Yes
Materials	Metals and polymers	Metals (similar)
Coated materials	Possible	Very difficult or impossible
Energy consumption	Less	More
Productivity	More	Less
Cost	Less	More
Environmental friendliness	More	Less

The present paper draws from the above mentioned advantages of joining by forming and from previous developments in joining of sheet panels to tubes (Alves et al., 2011) and joining of tubes by their ends (Alves et al., 2014), to propose a new type of connection for joining two tubes by their ends. In fact, contrary to what Alves et al. (2014) propose in Fig. 2a (and hereafter referred to as the 'tubular butt joint produced by plastic deformation', or simply as the 'butt joint'), the new proposed connection shown in Fig. 2b is based on a lap joint produced by plastic deformation that is capable of ensuring a significant overlap of the mating tubes to be joined. This new type of connection will be hereafter designated as the 'tubular lap joint produced by plastic deformation' (or simply as the 'lap joint') and the depth of insertion shown Fig. 2b is controlled by the tooling system.

The lap joint produced by plastic deformation greatly reduces the number of critical parameters of the connection of tubes by their ends. Compared to the butt joint produced by plastic deformation, which performs a similar function, the lap joint has the following main advantages:

a) Can easily accommodate tubes of different thicknesses, although the thinner tube should be placed at the outside region of the compression bead in order to guarantee that both tubes undergo plastic instability simultaneously. Otherwise, the thinner tube would trigger plastic instability during the expansion of the thicker tube;
b) Provides self-alignment of the tubes to be joined, thereby avoiding the use of additional fixtures to guarantee that the two tubes are properly aligned before joining;
c) Only one of the two tubes requires a chamfered end;
d) Ensures very good tightness for the transport of gases and fluids due to a better control of the tolerances between the overlapping surfaces of the mating tubes.

Under these circumstances the aim of the present paper is threefold: (i) to introduce a new environmentally friendly joining process for connecting two tubes by their ends at room