International Journal of Solids and Structures 49 (2012) 3211–3223

Contents lists available at SciVerse ScienceDirect

International Journal of Solids and Structures

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

Structural behaviour of aluminium self-piercing riveted joints: An experimental and numerical investigation

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ARTICLE INFO

Article history:
Received 21 September 2011
Received in revised form 29 March 2012
Available online 6 July 2012

Keywords:
Aluminium self-piercing rivet
Structural behaviour
Testing
Modelling
Point-connector model
Large-scale analysis
AA6063
AA7278

ABSTRACT

The present paper deals with the structural behaviour of self-piercing riveted joints based on aluminium and steel rivets. Two T-components made of two open aluminium profiles in alloy AA6063 temper T4 joined by 6 and 12 rivets, respectively, were designed and tested under quasi-static loading conditions. A new test device was designed to perform the tests of the T-components under two different load cases. Experimental results of the T-components joined by using aluminium self-piercing rivets were then compared with the corresponding components joined by using steel rivets in terms of force-displacement curves, deformation modes of the components as well as rivet failure modes. Further, the experimental results of the T-components based on aluminium rivets were used to validate a resultant-based point-connector model for self-piercing rivets proposed by Hanssen et al. (2010) using shell elements.

1. Introduction

The self-piercing riveting (SPR) technique is an alternative to the welding technology and is nowadays widely used in the automotive industry. Significant knowledge about the behaviour of a SPR connection under static and dynamic loading conditions (including fatigue) can be found in the open literature (Fu and Mallick, 2003; Han et al., 2007, 2010; Hoang et al., 2011,2010; Lee et al., 2006; Li and Fatemi, 2006; Mori et al., 2006; Porcaro et al., 2004, 2006, 2008; Sun and Khaleel, 2007; Sun et al., 2007; Wood et al., 2011). Recently, self-piercing riveted connections based on a single aluminium rivet have been studied by Hoang et al. (2010) and Abe et al. (2009) in order to facilitate recycling of an aluminium car body in the future by reducing the unfavourable iron content. Be aware that unfavourable alloy content could also be the case if we do not adjust the alloy of the aluminium rivet to the aluminium alloy to be joined. Moreover, the possibility of using aluminium rivets as an alternative to steel rivets can contribute to the reduction of the car weight. A quick calculation reveals that the substitution of steel rivets with aluminium ones in the body of a Jaguar XJ, in which more than three thousands rivets are presents, can save approximately 1 kg of weight. Finally, the use of aluminium rivets to join aluminium plates solve also problems related to galvanic corrosion which is imminent when using steel rivets to join aluminium sheets as stated by He et al. (2008).

The work of Hoang et al. (2010) have shown that the behaviour of a connection using an aluminium rivet to connect two aluminium sheets was similar to that of using steel rivets in terms of initial stiffness, maximum strength, and softening behaviour after the onset of failure. Their findings showed a great potential of aluminium self-piercing rivets for replacing the steel ones. However, in order to push forward the application of aluminium rivets in the automotive industry, research has to be carried out in order to better understand the structural behaviour of aluminium riveted joints. In addition, a reliable point-connector model is needed to describe the local behaviour of the riveted connection in a reasonable way for full car crash simulations with shell-element based models. Traditional approaches (e.g., node-to-node constraints, node-to-surface and surface-to-surface constraining by contact formulations, using beam elements, brick elements for the connector, etc.) were basically developed for spot welded connections, and may be used for modelling self-piercing riveted connections. However, the physical mechanisms during the failure of a rivet connection are complex, and completely different from that of a

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http://dx.doi.org/10.1016/j.ijsolstr.2012.05.039

Nomenclature

Δx	mechanical interlock
Δt	thinning of the bottom plate
F_{max}	maximum force
$d_{F_{max}}$	displacement at maximum force
d_f	ductility of the T-components
$\boldsymbol{\sigma}$	Cauchy stress tensor
$\bar{\sigma}, \bar{\varepsilon}$	flow stress, and effective plastic strain
$a_i\ (i = 1,8)$	parameters of the anisotropic yield function YLD2000
σ_0, Q_i, C_i	Voce parameters defining strain hardening of material
D_u	diameter for model's domain of influence
h_m, h_s, h	master plate thickness, slave plate thickness, and total plate thickness
f_n, f_t	normal resultant force and tangential resultant force
M_m, M_s	moment acting on the master plate and slave plate
η, η_{max}	normalised stretch measure and damage measure
f_n^{max}, f_t^{max}	SPR model parameters defining the maximum normal and shear capacity
ξ_n, ξ_t	dimensionless model parameters defining the softening region for normal and shear loading
$\delta_n^{fail}, \delta_t^{fail}$	model parameters defining the normal and tangential deformation at failure
$\alpha_1, \alpha_2, \alpha_3$	dimensionless model parameters defining dependency of the current stretch measure on the damage measure

welded one. Thus, the application of traditional approaches for riveted connections may not give satisfactory results. In this context the work of Porcaro et al. (2004) can be mentioned. They used a node-to-node constraint approach for modelling single self-piercing riveted connectors, and obtained reasonable results up to maximum load. However, the softening behaviour of the riveted connection beyond maximum load was not correctly described, neither with a force-based failure criterion nor with a strain-based failure criterion. Recently, (Hanssen et al., 2010) have developed a new resultant-based point connector model for large-scale finite element shell analyses. The nature of the model is based on the observed physical failure mechanisms of a self-piercing rivet connecting two aluminium sheets (Hanssen et al., 2010). They showed that the model was able to capture with good accuracy the behaviour of riveted connections with a single rivet up to failure for different loading directions, for different aluminium sheet thicknesses as well as for different rivets and die types. However, the capability of their proposed model for modelling the structural behaviour of self-piercing riveted joints remains an open question.

Thus, in the present study the structural behaviour of aluminium self-piercing riveted joints by using T-component tests was first investigated experimentally. T-components have been commonly used to investigate the joint behaviour in many research works found in the open literature (Clarke et al., 2009; Díaz et al., 2011; Girão Coelho and Bijlaard, 2007; Jones et al., 1983; Seeger et al., 2008; Swanson et al., 2002; Vivio, 2009). However, most of them were designed to investigate structural behaviour of bolted joints, welded joints, and adhesively bonded joints. Within this study, two new T-component specimens were designed, adapting to the SPR process. The geometry was chosen as a function of the joining accessibility, loading complexity, and expected structural behaviour. They consisted of two open profiles in aluminium alloy

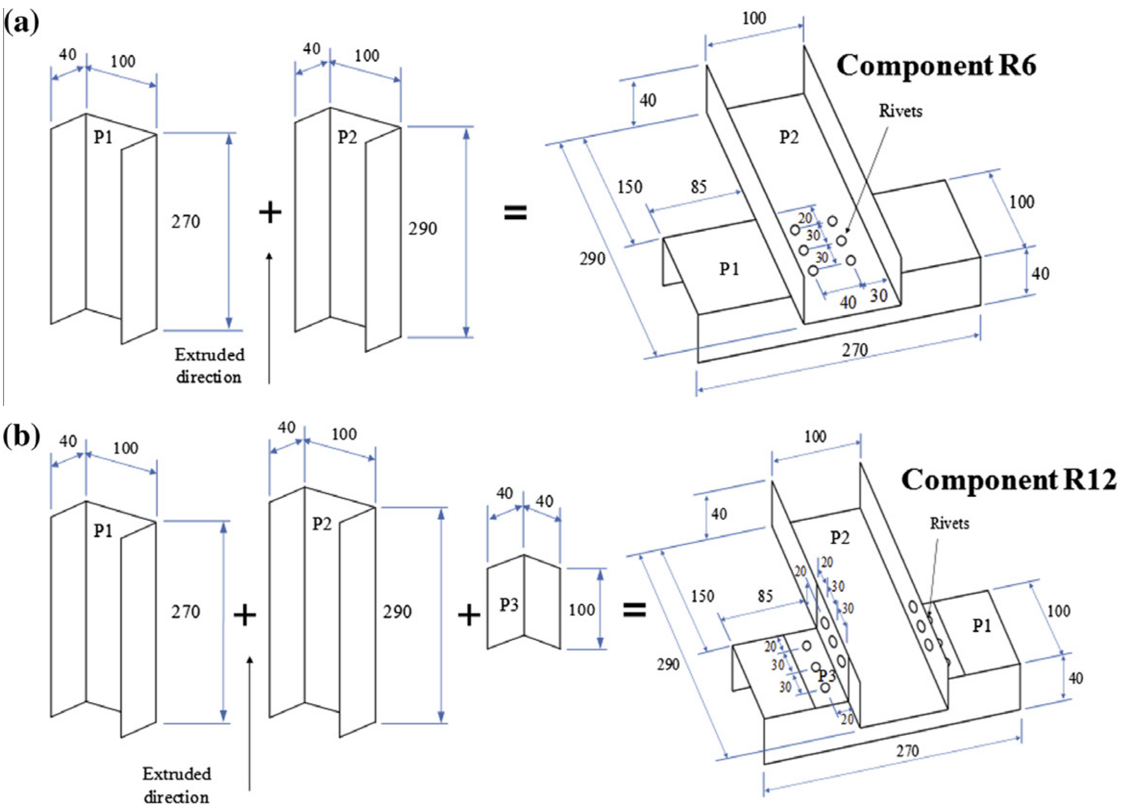

Fig. 1. Geometry of (a) T-component R6 and (b) T-component R12. The nominal thickness of the wall of the profiles is 2 mm. Dimensions are given in mm from the outer wall of the profiles.