Thin-Walled Structures 127 (2018) 169–179

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

In-plane and out-of-plane bending responses of aluminum mortise-tenon joints in lightweight electric vehicle inspired by timber structures

Qiang Liu[a], Jinsha Wang[a], Xinshen Huang[a], Tianming Wu[a], Zhijian Zong[a,*], Qing Li[b]

[a] School of Engineering, Sun Yat-Sen University, Guangzhou City 510006, China
[b] School of Aerospace, Mechanical and Mechatronic Engineering, Sydney University, Sydney, NSW 2006, Australia

ARTICLE INFO

Keywords:
Aluminum
Mortise-tenon joint
Electric vehicle
Lightweight
Crashworthiness

ABSTRACT

This study aims to identify the bending characteristics of the mortise-tenon joint and reinforced mortise-tenon joint inspired by the traditional timber structures. Experimental investigation was carried out into the mortise-tenon joints through the in-plane and out-of-plane bending tests in comparison with the conventionally extruded aluminum beam. Failure processes of the mortise-tenon joint and reinforced joint were similar, the vicinity of the mortise-tenon joint provided the main loading resistance. While the designed mortise-tenon joint showed relatively lower load bearing capabilities compared with the aluminum beam under in-plane bending, the reinforced stiffeners could help improve the peak load. The reinforced joint showed the highest load bearing and energy absorption capability under both the in-plane and out-of-plane bending. The energy absorption (EA) and specific energy absorption (SEA) of mortise-tenon joint and reinforced joint under the in-plane bending were lower than those of the aluminum beam, whilst the EA and SEA of mortise-tenon joints under the out-of-plane bending were higher than those of the aluminum beam. By comparison, for both the mortise-tenon joint and reinforced joint, load bearing and energy absorption capabilities under out-of-plane bending were higher than those under the in-plane bending. This study provided a novel joined structure for mechanical loading.

1. Introduction

In recent years, environmental pollution, increasing fuel costs, depletion in fossil energy reserves and growing consumer expectations lead to sparking of strong interests in Electric Vehicles (EV) [1]. However, the range that an electric vehicle can travel without recharging presents a significant challenge mainly due to the restriction of energy storage and the weight of vehicle body structures. For this reason, automotive manufacturers have been taking an intensified action to develop lightweight electric vehicles [2]. Lightweight design can be addressed from three aspects on novel materials, structural optimization and advanced processing technology, of which novel materials have been counted to be the most effective approach; thus the lightweight materials such as aluminum alloys with only one-third of steel density have been increasingly used in the vehicles particularly in the body frame of electric passenger car.

The body frame of electric passenger car comprises a number of aluminum beams (extruded profiles); and in the assembly process the most important issue is to connect the aluminum components. The extensive studies have concerned with the behaviours of different aluminum joints (e.g. welding joint, screw connections, press joining, etc). In this respect, Barnes and Pashby [3] considered the solid welding, liquid-state welding, adhesive bonding and mechanical fasteners for the joining space frame components in a form of volume production; and they found a combination of these techniques could integrate the benefits of each technique and minimize their shortcomings. Asle Zaeem et al. [4] investigated the local and global welding buckling distortion of a thin wall aluminum T joint, the thermal model, the stresses and deformations of the mechanical model, and the global buckling of weldment were studied. Marta et al. [5] used friction stir welding (FSW) to join pure aluminum (AL 1050) plates with ultrafine grained structure (UFG); and they found that FSW was one of the most attractive methods for joining UFG aluminum, especially in comparison with other techniques such as tungsten inert gas (TIG) or metal inert-gas (MIG). Zhao et al. [6] used friction stir welding to fabricate 6013-T4 T-joints, the distribution features and formation mechanisms of defects in T-joints were observed, and the effect of defects and welding parameters on tensile properties of T-joints was also investigated. Bonazzi et al. [7] studied the metal inert-gas welding operation on aluminum T-joint thin plate by the integration of both simulation and experiments, and demonstrated the results of the mechanical simulations could well predict the welding-induced distortion. Bi et al. [8] studied the

* Corresponding author.
E-mail address: zhjzong@vip.163.com (Z. Zong).

https://doi.org/10.1016/j.tws.2018.01.033
Received 14 November 2017; Received in revised form 27 December 2017; Accepted 24 January 2018
0263-8231/

shunting characteristics of dissimilar aluminum alloys 2219/5A06 of unequal-thickness for the resistance spot welding (RSW) process; and suggested that increasing the welding current could be a preferred method to overcome the shunting effect. Hong and Shin [9] described the microstructural changes and defects encountered during laser welding of aluminum; and they analyzed the mechanical properties of welds such as hardness, shear and tensile strengths. Oliveira et al. [10] used one-sided laser beam to fabricate 6013-T4 T-joints, the influence of the shielding gas, seam angle, beam focal position, and beam positioning relative to weld centerline were investigated. Zheng et al. [11] investigated the effect of adhesive characteristics on the strength of adhesive-bonded lap shear aluminum; and they divulged that the joint strength depended on not only the adhesive properties but the bond adhesion between the adhesive and adherend. Gültekin et al. [12] studied the mechanical properties of different single lap joint (SLJ) configurations with different adherent width values subjected to tension experiments; and they found that increasing the adherent width could increase the load-carrying capacity of the joints more than increasing overlap length could do. Ghosh et al. [13] investigated the effects of bond line thickness of the adhesive in the lap joints of the dissimilar metals subject to shear loading; and they found that the joints of 10 wt% TiO_2 nano-filler content epoxy adhesive exhibited the maximum lap shear strength of the joints. Zhao et al. [14] explored the influence of sheet thickness on the fatigue behaviour of single-lap self-piercing riveted joints in aluminum alloy 5052; and they showed that the fatigue life of the joints increased with increasing sheet thickness. Fiore et al. [15] studied a mixed method for joining aluminum alloys with glass reinforced polymer's substrates (GFRP); and showed that the time at which the rivet was inserted greatly influenced the performances of the joints. Johan et al. [16] investigated the force-displacement responses and failure behaviours of aluminum sheets joined by flow-drill screws; and they revealed that the connection strength increased whereas ductility decreased with the shear loading. Fragapane et al. [17] investigated the static and the fatigue characteristics of aluminum-aluminum (AW 6082-T6) single-lap bolted joints. Mostafa and Mukesh [18] studied the shear strength of clinched joints using two layers of AA7075 aluminum sheets in different temper states; and they quantified the effects of clinched geometric and processing parameters on shear strength.

Recently, with the increasing commercial requirements for higher performance, higher productivity and lower cost, some novel joining strategies are becoming more demanding for different extruded aluminum components [19]. As a prevalent connection element, mortise-tenon joints have been commonly used in various timber structures and attracted extensive attention [20]. For example, Feio et al. [21] physically tested the full-scale specimens to characterize the behaviours of a traditional mortise-tenon timber joint, and they found the interfacial normal stiffness was of considerable influence in the yield strength and deformation of timber joints. Li et al. [22] investigated the particular features of the ancient wood joint subjected to fully reversed cyclic loading, and studied the stiffness and flexibility of joints, hysteretic model and the relationship between the moment and rotation. Derikvand and Ebrahimi [23] determined the effects of adhesive type and loose tenon dimensions on bending strength of T-shaped mortise and loose-tenon joints. Chen et al. [24] studied the flexural behaviour of dovetail mortise-tenon joints in timber structures; and showed that the main failure mode of the dovetail joints was pull-out. Koch et al. [25] conducted the experimental and numerical investigations into the tapered tenon.

Furthermore, there have been some similar-mortise-tenon structures used in other fields. For instance, Bragança et al. [26] presented a mortise-tenon joint based on sheet-bulk metal forming to connect two metal sheets perpendicularly to each other, and they showed such a mortise-tenon joint was an alternative to existing joining solutions based on welding, adhesive bonding, mechanical fastening or riveting and mechanical folding. Berto et al. [27] proposed a new connection structure (somewhat similar to mortise-tenon joint) to improve the fatigue behaviour of the welded joints.

Note that most of the abovementioned studies has concerned on the welded joint of aluminum profiles. While the mortise-tenon joint is a reliable and simple connection element, these have been very limited studies available to address its feasibility and characteristics in the application of lightweight EV body frame. For the practical application of connecting the aluminum components, some novel designs of mortise-tenon joints were inspired from the timber structures; and their mechanical characteristics were quantified in this study. The bending responses under the in-plane and out-of-plane loading cases were both considered herein. The typical load-displacement curve, damage process and energy absorption were quantified; the difference between the in-plane and out-of-plane bending was compared to systematically investigate the mechanical characteristics of the mortise-tenon joints for EV applications.

2. Materials and methods

2.1. Specimen design

Nature has provided us with extraordinary resources to tackle design challenges facing in modern society [28,29]. As shown in Fig. 1a, an aluminum body frame was developed in the lightweight electric vehicle, which consisted of large number of lateral and vertical aluminum components. The mortise-tenon joints inspired by traditional interlocking joints in ancient timber structures were considered here to connect the aluminum beams. A wooden mortise-tenon joint comprised the two parts, namely protruding tenon and concave mortise, which were engaged by means of an interferential fit, acting as a connector (as in Fig. 1a), which was of good ductility and loading bearing capacity attributable to the internal embedment and frictional interference [30]. The aluminum beams of different directions intersected with each other, forming lots of mortise-tenon joints, which are the basic representative connection elements used in the electric minibus.

In this study, three types of specimens were considered (please see sub-right figures in Fig. 1b). The first was the basic mortise-tenon joint, the lengths of mortise part and tenon part were taken as the constants of 400 and 155 mm, respectively, in which the tenon was inserted into the mortise hole and welded along the intersection lines (Fig. 1b). The second specimen was the reinforced mortise-tenon joint, differing from the first type, where the four isosceles right-angled triangular stiffeners with the length of 50 mm and the thickness of 3 mm were inserted in the corners and welded in the intersection line to reinforce the joint. The third specimen used the basic aluminum beam with the length of 400 mm without hole for comparison.

2.2. Sample preparation

The aluminum beam (with the length of 400 mm), mortise (with the length of 400) and tenon (with the length of 155 mm) (Fig. 1b) were sectioned from the commercial aluminum alloy extrusion profile (6063-T6). The mortise-tenon joint was fabricated through the following process. First, a hole with the same shape of tenon section with a negative tolerance of 0.02 mm was cut in the middle of aluminum beam (mortise); second, the tenon was over-fitted into the middle hole of the mortise, then, the intersection lines of tenon and mortise parts were welded by metal inert-gas welding (MIG) technique. After the basic mortise-tenon joint was finished, the reinforced joint was further fabricated using four isosceles right-angled triangular aluminum stiffeners welded to the crossed corners. As there were some slots on each edge of the extruded profile, the stiffeners can be stuck in the slots before being welded.,