Thin-Walled Structures 132 (2018) 642–657

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Experimental and numerical investigations of the plastic response and fracturing of an aluminium-plated structure with transition circular arcs subjected to impact loading

Weiyuan Guan[a,b,c], Guangjun Gao[a,b,c,*], Yao Yu[a,b,c], Jian Li[a,b,c]

[a] Key Laboratory of Traffic Safety on Track of Ministry of Education, Central South University, Changsha, Hunan 410075, China
[b] Joint International Research Laboratory of Key Technology for Rail Traffic Safety, Central South University, Changsha 410075, China
[c] National & Local Joint Engineering Research Center of Safety Technology for Rail Traffic Vehicle, Central South University, Changsha 410075, China

ARTICLE INFO

Keywords:
Aluminium-plated structure
Dynamic response
Fracture
Energy absorption
Load-bearing capacity

ABSTRACT

A new aluminium-plated structure with transition circular arcs used for railway vehicles is presented. Two impact experiments were performed using a test trolley to examine the plastic response and fracturing of the aluminium-plated structure. The results show that the deformation mode of the aluminium-plated structure switches from global plastic bending deformation to local fracturing at the transition circular arc region, which is consistent with the design. Numerical results are presented in terms of deformation modes, force responses and levels of absorbed energy, demonstrating good agreement with the experimental results. From the results of the numerical simulation, fracturing processes and variations in element stress triaxiality are presented. It is found that the stress state of elements affecting the initiation of cracking is of a tension state, while the stress state of elements affecting the end of cracking is of a shear state. A validated finite element analysis of an aluminium-plated structure with right-angled, circular arcs and chamfering transition sections is presented. Plastic and fracture energy levels of the aluminium-plated structure with three transition sections are measured as 2.56, 27.62, and 30.13 kJ and 0.98, 2.41, and 2.16 kJ, respectively, as the second fracturing point. Finally, the finite element analysis illustrates the impact energy effects involving different combinations of trolley mass and velocity, and experimental boundary conditions for varying bolt yield stress and pre-stress levels are defined in the finite element model to investigate the effects of bolted joints on the dynamic responses of an aluminium-plated structure with transition circular arcs.

1. Introduction

Structural impact problems (e.g., dropped objects, vehicle impacts, and ship collisions) have an increasingly influential effect on modern society. The design of crashworthy structures has attracted growing attention from numerous fields such as naval architecture and ocean engineering, aircraft manufacturing engineering, automotive manufacturing engineering, bridge manufacturing engineering and train manufacturing engineering. The vast majority of related studies have aimed to find or enhance structural-load-carrying capacities. Although high strength structures exhibit higher load-bearing capacities and more stiffness at higher impact velocities, the controllable trigger mechanism can address contradictory requirements for structural strength and collision performance. Therefore, the structural design of a controllable trigger mechanism plays an important role in the collision performance of vehicles. Aluminium plates are widely used as key parts of crashworthy car-bodies, and thus, studying the plastic responses and fracturing of aluminium-plated structures with controllable trigger mechanisms is of central significance.

A considerable amount of literature has been published on the performance and failure modes of plates subjected to impact loading through experimental and numerical investigations. Yu and Jones [1] examined the deformation and failure modes of aluminium alloy and mild steel beams subjected to local impact. They found that the strain rate is correlated with the dynamic inelastic failure of a structure. Alves and Jones [2,3] developed an analytical model to predict the plastic response and failure of beams made from a ductile strain rate-sensitive material subjected to static and dynamic loading. Static and dynamic tests of beams were conducted to examine displacements on failure. Furthermore, a reasonable correlation was found between theoretical predictions and experimental results on displacements on failure. Mannan et al. [4] conducted a series of experiments on plastic

* Corresponding author.
E-mail address: gjgao@csu.edu.cn (G. Gao).

https://doi.org/10.1016/j.tws.2018.09.031
Received 11 February 2018; Received in revised form 11 July 2018; Accepted 13 September 2018

deformations and on the failure of aluminium beams subjected to impact loading at velocities of 11–114 m/s and performed comparative studies using an analytical method. Grytten et al. [5] studied the low velocity perforation of square plates with an experimental investigation and analysed the perforation process to investigate effects of anisotropy, dynamic strain ageing and thermal softening under low velocity impact using numerical simulations. Zhou et al. [6] investigated the energy absorption characteristics and deformation behaviours of empty polyurethane foam-filled magnesium alloy thin-walled beams with quasi-static and dynamic three-point bending tests. Their results show that the strain rate and the beam material's strength, ductility, foam density and wall thickness influence the deformation modes and energy absorption capacities of thin-walled beams. Qi et al. [7] numerically investigated bending behaviours of double-hat beams composed of aluminium alloy, high strength steel and aluminium-steel hybrid materials subjected to lateral impact. They found that geometric parameters of the double-hat beams largely affected collision performance. Liu and Soares [8] conducted a comprehensive experiment of clamped rectangular cross-section tubes subjected to quasi-static punching and dynamic drop weight impact tests. The tube specimens were impacted at different locations, and deformation and failure modes of the high strength steel material were analysed. They also found that the impact location strongly influenced the crush behaviours of the tubes. Li et al. [9] examined the load-deformation characteristics, failure modes and energy absorption capacities of different structures subjected to dynamic loading. They found that foam-filled double circular tube structures exhibit high levels of dynamic bending resistance and energy-absorbing effectiveness. Zeinoddini et al. [10,11] conducted an experimental and numerical investigation of the cyclic responses of axially pre-loaded tubes subjected to lateral impacts and discussed effects of pre-loading on the dynamic failure and behaviours of tubes. Bambach et al. [12] studied crucial effects of strain hardening on the mechanical responses of high-manganese steel and introduced a new energy absorption metric based on plastic deformation energy. Kim et al. [13] studied force, indentation and energy absorption capabilities of steel-plated structures subjected to low temperatures through the use of an experimental and numerical technique. Al-Thairy and Wang [14] described a numerical simulation through which an axially compressed steel column was subjected to transverse impact. They analysed the plastic responses and failure modes of transversely impacted beams and columns with and without axial compressive forces and investigated the effects of impact energy levels, plastic hinge locations and damping on behaviours and failure modes. Villavicencio and Soares [15] examined the dynamic responses of stiffened plates through drop weight impact tests and numerical simulations. The impact responses of stiffened plates were found to be highly sensitive to levels restraint provided at supports. Moreover, stiffeners had little influence on the plastic responses of the plates.

Recently the focus has shifted to using the controllable trigger mechanisms, as they offer significant improvements in structural collision performance. Types of controllable trigger mechanisms including prebuckle, parallel and dished indentations; cut-outs; stiffeners; fillers; and wrapping are discussed in Yuen and Nurick [16]. The introduction of imperfections was found to spur the controllable and predictable collapse of tubular structures at a specific location, improving the energy-absorption properties of structures. Gümrük and Karadeniz [17] presented a conceptual trigger design of an energy absorbing member, investigated axial crushing behaviours of top hat thin-walled sections by numerical simulations and demonstrated the effectiveness of the design. Qureshi and Bertocchi [18] proposed a new box-beam crash absorber with sinusoidal patterns embedded on beam surfaces and demonstrated that these are even more effective than conventional tubular structures subjected to axial loading. Liu et al. [19] studied the plastic responses and failure of clamped pre-notched beams subjected to transverse impact loading through drop weight impact tests. Boundary conditions and material characteristics were found to heavily influence structural engineering outcomes. Song et al. [20] examined thin-walled square tubes using patterned windows subjected to axial compression. The crushing performance of the windowed tubes was in turn greatly enhanced. They also investigated the influence of window sizes on the collision performance of the examined tubes. Torabi and Keshavarzian [21] studied the load-carrying capacity of V-notched plates composed of Al 6061-T6 through experimental tests and theoretical predictions. They found that while the Equivalent Material Concept and V-notch mean stress criterion are always more conservative than the Equivalent Material Concept and V-notch maximum tangential stress criterion, both criteria accurately predict experimental results. Damghani Nouri et al. [35,36] analysed experimental and numerical tests of cylindrical and conical absorbers with longitudinal reinforcements subjected to impact loading. Expanded metal sheets, due to their low weights and effective collapse mechanisms, were found to exhibit a high capacity for energy absorption, and experimental, numerical, and analytical approaches were employed for the analysis [37–39]. It was found that multi-layer tubes can enhance energy absorption capacities.

In the present work, a new aluminium-plated structure with transition circular arcs is proposed to better balance engineering properties of structural strength and collision performance. The plastic responses and fracturing of aluminium-plated structures with transition circular arcs are examined through a trolley impact test and are analysed via numerical simulations. The experimental and numerical results are discussed in terms of deformation modes, force responses, absorbed energy levels and stress states of the failed elements. Comparisons of fracture force and energy responses of circular arcs and of chamfering and righted-angled transition sections of the examined structure are drawn to analyse load capacities in evaluating ductile crack initiation and propagation and the final failure point observed under impact loading. Moreover, the effects of different levels of impact energy involving different combinations of trolley mass or velocity on the plastic responses and fracturing of the aluminium-plated structure are analysed. To investigate the effects of bolted joints on dynamic responses of the aluminium-plated structure, two types of boundary conditions for various yield stresses and the pre-stress of bolts are discussed in reference to the proposed numerical model.

2. Experimental details

2.1. Geometrical description

The geometry of the aluminium-plated structure with transition circular arcs used in the impact test is presented in Fig. 1. Regions at both installation holes with a diameter of 32 mm at specimen ends were

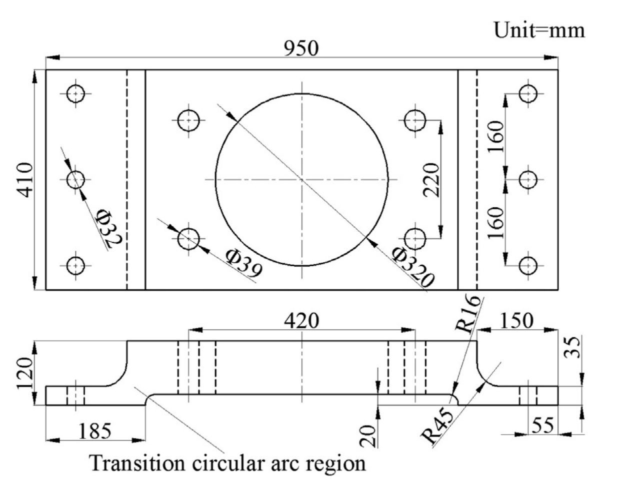

Fig. 1. The geometry of the aluminium-plated structure with transition circular arcs.