International Journal of Mechanical Sciences 90 (2015) 213–227

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Plastic response and failure of rectangular cross-section tubes subjected to transverse quasi-static and low-velocity impact loads

Bin Liu, C. Guedes Soares*

Centre for Marine Technology and Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisboa 1049-001, Portugal

ARTICLE INFO

Article history:
Received 8 September 2014
Received in revised form
8 November 2014
Accepted 12 November 2014
Available online 20 November 2014

Keywords:
Rectangular cross-section tube
Quasi-static test
Impact test
Numerical simulation
Force–displacement response
Failure mode

ABSTRACT

Quasi-static punching tests and dynamic drop weight impact tests have been performed to examine the plastic response and failure of clamped rectangular cross-section tubes struck transversely by a hemispherical indenter. The laboratory results are compared with numerical simulations. The span lengths of the tube specimens are 125 and 250 mm, and they are impacted at different locations along the span. The results show that the impact location strongly influences the impact response of the tubes. Since the tubes are fabricated with strain-rate-insensitive high strength steel, the experimental plastic response and failure are similar when the tubes are loaded statically or under low impact velocity. The experimental results are presented in terms of the force–displacement responses and the failure modes, showing a good agreement with the simulations performed by the LS-DYNA finite element solver. The numerical results manage to describe the process of initiation and propagation of the material fracture and provide detailed information to analyse the large inelastic deformation and failure of ship structural components subjected to impact loading. The deformation and failure characteristics of the tube specimens are well described on the basis of the failure modes of the beam and plate models. Moreover, the crack initiation in both upper and lower walls is well described by the matrix of the infinitesimal strain tensors and the deformed shape of the first failing element.

1. Introduction

Rectangular cross-section tubes can be found in different structures and can be subjected to impact loads. The rectangular tubes struck transversely by a hemispherical indenter could provide some insight about the basic deformation and failure mechanisms of ship collision and grounding scenarios, where the hemispherical indenter represents the idealised bulbous bow or the ground obstruction.

Unfortunately, there is not much relevant investigation reported in the literature in this respect. Only some investigations have been carried out on the energy absorbed in the bending behaviour of circular tubes under transverse load [1–8].

Initially, the behaviour of simply supported circular tubes under a wedge-shaped indenter was examined [1–3]. Three modes of deformation were identified during the indentation process: pure crumpling, combined crumpling and bending, and structural collapse. Afterwards, rigid-plastic analytical formulations were proposed to evaluate the permanent deflection and the energy absorption capability of laterally loaded circular tubes [4,5]. In order to better describe the local damage of circular tubes, a theoretical analysis was presented to evaluate the large shape distortion and the sectional collapse of tubes subjected to combined loading in the form of lateral indentation, bending moment and axial force [6]. Moreover, quasi-static and dynamic perforations of steel circular tubes under a small spherical indenter were investigated to determine their maximum energy absorbing capabilities [7]. Recently, Jones and Birch [8] proposed a simplified method to estimate the maximum permanent transverse ductile displacement of circular tubes struck by a large wedge-shaped mass, giving clearer insight into the deformation behaviour of circular tubes. The failure mode of laterally loaded circular tubes starts with local denting and is followed by global bending collapse.

Laterally impacted tubes combine the structural characteristics of beam and plate elements, thus some aspects of particular relevance to the behaviour of beams and plates subjected to dynamic loads are presented to describe the basic mechanisms of rectangular cross-section tubes subjected to lateral impact. For laterally impacted beam and plate elements, some initial studies compared rigid plastic theory with experiments [9–14] while more recently comparisons have been made with finite element results, which allow obtaining detailed information of the structural response of the specimens [15–21].

An energy dissipation method based on rigid-plastic theory was developed to estimate the permanent deflection of beams and

* Corresponding author. Tel.: +351 21 841 7957; fax: +351 21 847 4015.
E-mail address: c.guedes.soares@centec.tecnico.ulisboa.pt (C. Guedes Soares).

http://dx.doi.org/10.1016/j.ijmecsci.2014.11.012
0020-7403/

plates subjected to large dynamic loads [9–11]. Nevertheless, this method does not consider the initiation of material fracture that is an important aspect in the analysis of laterally impacted beams and plates. Afterwards, simplified theoretical methods based on the rigid-plastic theory were proposed to predict the onset of failure of beams [12] and plates [13,14] subjected to impact loads. However, true stress–strain material relationships should be more accurate than these rigid-plastic material models when it is necessary to represent the response of specimens subjected to large plastic deformation. Therefore, theoretical formulae that included a material power law relation are developed for estimating the deformation and failure of thin clamped circular and square plates punched by a spherical indenter [22–24].

The above references describe well the main deformation and failure characteristics of beams and plates, which provide the basis of the deformation of rectangular tubes. The fully clamped laterally impacted beams can suffer four basic failure modes: large inelastic deformation, tensile tearing failure at the supports, transverse shear failure at the supports and shear failure at the impact point [9,25]. On the other hand, the plate subjected to a spherical indenter suffers both global deflection and local indentation [13,20,24]. The local indentation has the shape of the striker head. The plate elongates below the indenter forming a necking circle and the crack is initiated at this circle. In this paper, the deformation and failure characteristics of beams and plates are combined to reveal the deformation process of rectangular cross-section tubes.

Standard boundary conditions for simply supported or fully clamped specimens are easy to implement in both analytical and numerical models, while it is sometimes difficult to reproduce them exactly in the experiments. This has been demonstrated in former investigations on the boundary conditions of laterally loaded beams and plates [26–30]. In general, the experimental tests cannot satisfy precisely the zero displacement condition at the supports. The load capacity of a structure is strongly dependent on the axial restraint provided at the supports. Therefore, careful design of the experimental supports is required to satisfy the clamped boundaries.

Finite Element analysis is a useful tool for predicting the controlled failure, the maximum deformation, or the largest loading which can be sustained by a structure. However, the nonlinear dynamic analysis should be compared with experimental tests before being used for a structural design. Numerical simulations of laterally impacted beams and plates have been presented, obtaining good prediction of the experimental plastic response and failure [15–21]. In the numerical modelling, an important definition that must agree with the characteristics of each particular impact test and specimen is the material

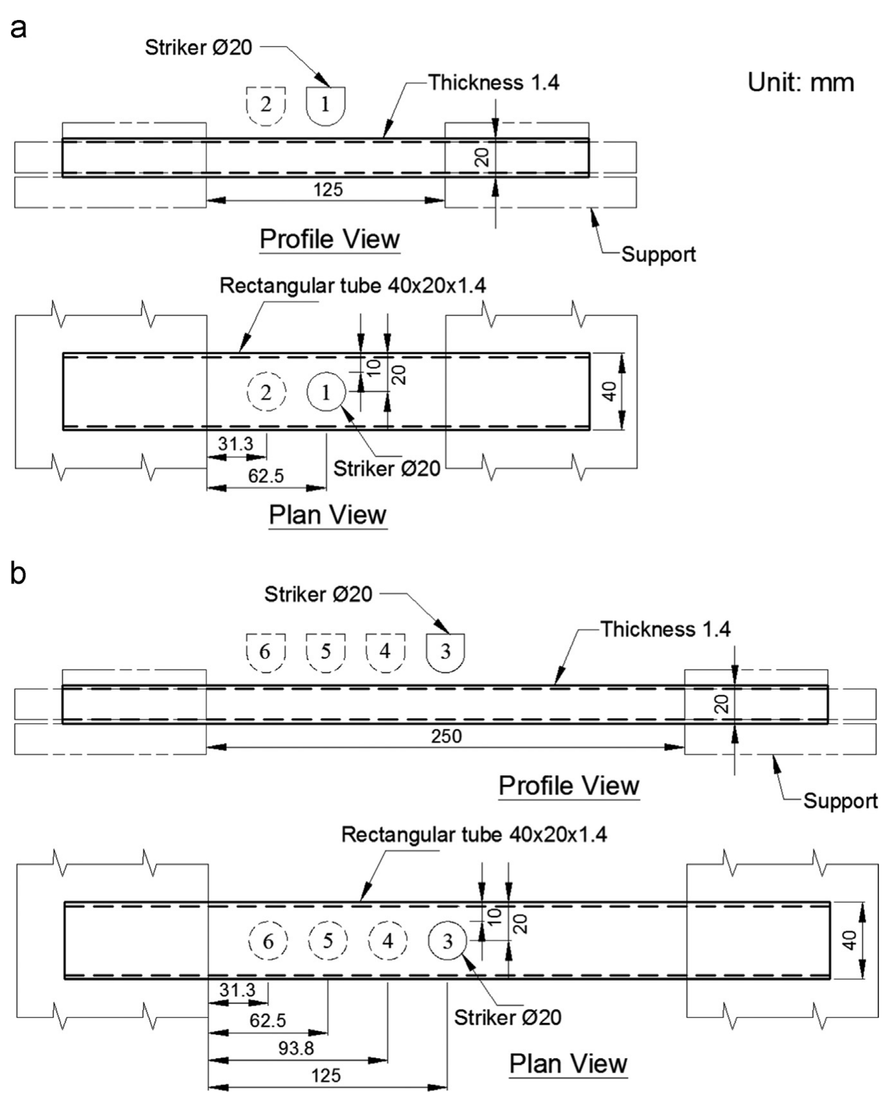

Fig. 1. Geometry of the tube specimens and the impact locations. (a) Span length of 125 mm; (b) span length of 250 mm.