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Performance of hollow steel tube bollards under quasi-static and lateral impact load

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ABSTRACT

In order to prevent vehicle access to a protected area, vehicle barriers can be installed around the perimeter of the area. Bollards are commonly used as vehicle barriers. This is due to the fact that they can be readily blended with other architectural features and present fewer disturbances to a building's functionality when compared to other barrier systems. Hollow steel tubes are used in a variety of barrier system applications where they are required to absorb deformation energy. Varying methods, such as finite element analysis or experimental observation, can be used to determine the collapse behaviour and energy absorption of these steel structures under lateral impact load. These methods have high accuracy but demand a significant amount of time and computational resources. Apart from experimental and numerical analyses, Yield Line Mechanism (YLM) is an approach that can provide the collapse response of sections. This is when a section fails and the YLM of failure forms at its localised plastic hinge point. The YLM analysis approach is commonly used to investigate the performance of thin-wall structures that have local failure mechanisms. This paper investigates the collapse behaviour and energy absorption capability of hollow steel tubes under large deformation due to lateral impact load. The YLM technique is applied using the energy method, and is based upon measured spatial plastic collapse mechanisms from experiments. Analytical solutions for the collapse curve and in-plane rotation capacity are developed, and are used to model the large deformation behaviour and energy absorption. The analytical results are shown to compare well with the experimental values. The YLM model is then used to verify the finite element model (FEM), and then the failure behaviour and energy absorption of hollow steel tubes under lateral impact load is investigated in more detail.

1. Introduction

Steel hollow sections have been used as structural elements in building systems and highway barriers, and may be required to dissipate energy when subjected to dynamic loads. They are primarily made from thin-walled sections due to these sections being efficient and versatile (Nagel [19]). Steel sections are economical and provide valuable mechanical properties for use in industry; however, they are prone to local failure due to their thin-walled elements. Thus, the deformation of these sections needs to be investigated in order to assess the performance of steel sections against impact loading.

The performance of hollow sections subjected to axial impact load have been thoroughly investigated (Boutros [6]; Boutros et al. [7]; Daneshi and Hosseinipour [8]; Hosseinipour [12]; Jang et al. [13]; Adachi et al. [3]; Zhang et al. [24,25]; and Alavinia et al. [2]). However, the behaviour of hollow sections subjected to lateral impact loading has not been clearly established, whilst the performance of bollard systems is determined based on field testing standardised in PAS 68 [21]. In this study, the behaviour of steel tube sections subjected to a combination of local deformation due to lateral impact load and bending failure is studied.

When thin-walled sections fail due to lateral impact load, they undergo plastic folding of the cross-section walls. Yield line mechanism (YLM) analysis of the collapse mechanism provides a bending moment–rotation relationship, from which the member strength and energy absorption capacity can be estimated. In the elastic range, where the deformations of the elements are small, the theory of elasticity can be used to determine the load-deformation behaviour of the structure. When increasing the load, local yielding occurs and hinges may develop. The collapse behaviour of the element depends on the behaviour of the plastic hinges. Failure mechanism (yield line mechanism) theory can be used to determine the load deformation behaviour of the structure in the post-failure range.

There are different theories to analyse the collapse behaviour of a complete structure. However, for achieving correct results from a theory, an accurate model should be prepared. The YLM models are based on experimental observations.

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Based on laboratory test observations, Murray and Khoo [18] developed eight basic mechanisms for plates and five combinations of simple mechanisms for channel columns.

Kecman [15] studied the bending collapse behaviour of rectangular and square hollow sections and subsequently developed a YLM model, including travelling yield lines. Koteko [16] investigated the YLM of rectangular and trapezoidal box section beams with a high width to depth ratio compared to Kecman's sections. In Elchalakani et al. [10], the collapse mechanism model for tube members was discussed and included the effect of ovalisation along the length of the tube. According to this study, the mechanism starts when the major axis of the oval reaches 2.2R and the minor axis reaches 1.8R, where R is the radius of the section (Fig. 1).

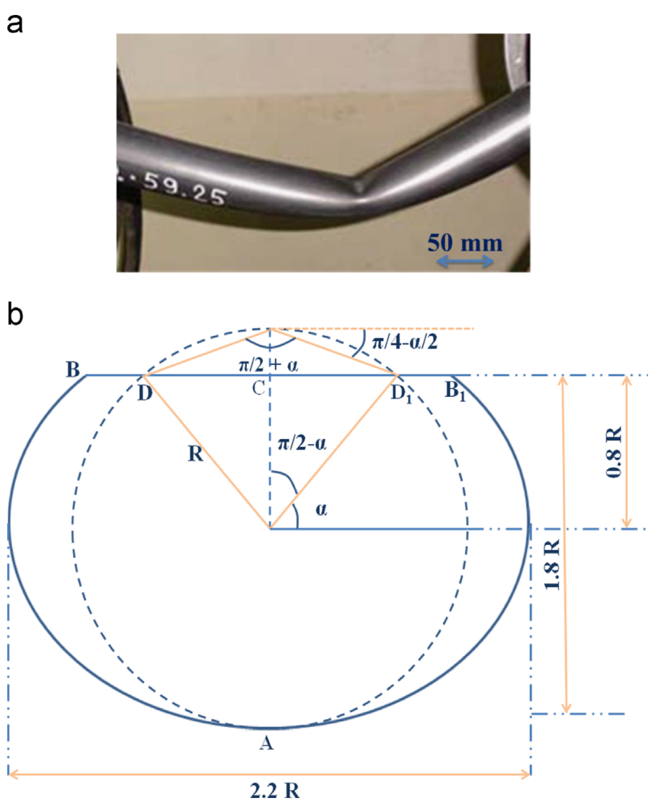

Fig. 1. (a) Front view of deformed section (Poonaya et al. [20]), (b) ovalisation of hollow steel tube.

The mechanisms presented in this paper are based on the experimental observations for hollow sections from studies conducted by Elchalakani et al. [10] and Poonaya et al. [20]. The plastic collapse curves developed from the analysis are shown to compare well with the experimental curves. To fully describe the large deformation of the sections, collapse curve solutions are used in conjunction with elastic and in-plane plastic theory. By using the bending moment–rotation curve, the total absorbed energy can be calculated analytically. The energy absorption results are shown to compare well with the experimental values, and provide analysis with a robust tool for estimating the energy absorption capacity of steel hollow sections under lateral impact load.

2. Development of the YLM model for hollow sections

Experimental observations are used to define a basic YLM model. Fig. 2 shows the common failure mode of steel hollow sections under lateral impact load. It is noted that the collapse deformation shape of the bollards under lateral impact load are similar to the observed deformation shape described in the research work by Poonaya et al. [20] (Fig. 3). In their study, the collapse curve and ultimate capacity of the thin-walled tube under bending was investigated experimentally.

Since the deformation shapes of steel hollow sections under lateral impact load and bending are the same, this study uses the experimental results based on Elchalakani et al. [10] and Poonaya et al. [20] to validate the YLM.

By establishing the YLM model for the sections and calculating the energy absorption of each hinge line, the total absorbed energy can be estimated and therefore, a failure curve can be plotted. The following section explains the calculation of total energy absorption of a defined model for different rotation angles in order to plot the failure curve.

2.1. Failure curve

The energy method is used to estimate the failure curve of the hollow section. The total energy absorption for the YLM model is

Fig. 2. Failure mode of steel hollow section.