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Optimised design of nested circular tube energy absorbers under lateral impact loading

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Abstract

Arrangements of mild steel (DIN 2393) nested tubes were laterally crushed by dynamic loading. The tests were performed with impact velocities ranging between 3 and 5 m/s, using a fixed mass impinging onto the specimens under the influence of gravity. Two arrangements of nested tube systems were considered; one standard and one optimised design. Their crushing behaviour and energy absorption capabilities were analysed experimentally and simulated numerically using the explicit code LS-DYNA. Results from the numerical analyses were compared to those obtained from experiments. An over-prediction in force–deflection responses was obtained from the numerical code. An attempt was made to explain this inconsistency on the basis of the validity of strain rate parameters used in the Cowper–Symonds relation. It was shown that the optimised energy absorber exhibited a more desirable force–deflection response than the standard arrangement due to a simple design modification that involved mild steel cylindrical dampers.

Keywords: Mild steel; Nested tubes; Energy absorbers; Lateral impact; FEM; Optimisation

1. Introduction

The function of an energy absorber is to absorb kinetic energy upon impact and dissipate it in some other form of energy, ideally in an irreversible manner. Non-recoverable (inelastic) energy can exist in various forms such as plastic deformation, viscous energy and friction or fracture energy in both metallic and composite structures [1–3]. Circular or square sectioned tubes are among the most commonly used structural elements due to their prevalent occurrence and easy manufacturability. Circular tubes, for example, can dissipate elastic and inelastic energy through different modes of deformation, resulting in different energy absorption responses. Such methods of deformation include lateral compression, lateral indentation, axial crushing, tube splitting and tube inversion. It is important to study their energy absorption characteristics and mean crushing loads so as to determine their applicability to practical energy absorption situations. Such practical cases may consist of energy absorbers in the aircraft, automobile and spacecraft industries, nuclear reactors, steel silos and tanks for the safe transportation of solids and liquids.

Energy absorption through material deformation has been extensively studied over the last three decades, particularly in the form of tubular systems. The lateral compression of a single circular tube and its strain-hardening phenomena have been analysed both experimentally and analytically by various authors, such as Burton and Craig [4], DeRuntz and Hodge [5], and Redwood [6]. These authors were among the first to analyse such problems and each one of them proposed a slightly different deformation mechanism for the compression of a tube between rigid flat platens. The effect of strain hardening was further examined by Reid and Reddy [7], who developed a theoretical model based on a rigid linear strain-hardening material model which appears to be the most accurate one to date. The authors improved the strain-hardening prediction by replacing the localised hinges with an arc in which its length changes with deflection. Hence, this theoretical model accounts for both the geometric and material strain-hardening effect.

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An important dimensionless parameter, which they developed, governs the shape of the force–deflection curve. This parameter was defined as 'mR' and is a function of the yield stress in tension, the mean radius R of the tube, the strain hardening modulus E_p and the thickness t. According to Reid and Reddy, it may be possible to maximise the energy absorbing capacity by choosing appropriate tube dimensions such that the mR value is minimised since this is a function of tube geometry. Avalle and Goglio [8] examined the strain field generated during the lateral compression of aluminium tubes and proceeded to verify the known theoretical models. Of the three known theoretical models proposed by the various authors [4–6], it was found that the latter accounted for all the main features observed experimentally, hence this model seems the most realistic in describing the actual behaviour of the tube both qualitatively and quantitatively. Reddy and Reid [9] proposed a method to calculate a more realistic force–deflection curve using a rigid linear work-hardening material model. These tubes were also compressed laterally between rigid platens. It was suggested that an average value of strain-hardening modulus could be used to calculate the parameter mR, therefore these two parameters would be considered constant throughout the deflection range. However, it has been further proposed that if the variation of strain-hardening modulus with strain is known, this could be used to update mR at each load step or load increment and thus obtain a more realistic load–deflection characteristic. It was suggested that the method described above could be used as a basis for obtaining some of the material properties from a ring compression test. Gupta et al. [10] conducted a comprehensive experimental and computational investigation of circular metallic tubes subjected to quasi-static lateral loading. Specimens analysed consisted of both mild steel and aluminium tubes with different diameter to thickness ratios. Their corresponding force–deflection responses were obtained and examined in detail. An in-depth description was provided on the deformation mechanism of a tube compressed between flat rigid platens.

Nested systems in the form of a line of rings subjected to end impact loading were examined by Reid and Reddy [11]. The authors were principally concerned with identifying the main mechanism that controls the deformation of such systems. Upon experimentation, the main parameters were identified and varied, thereby leading to a suggestion for the construction of a mathematical model of the system. It was found that in low-speed impact testing on tube systems, the effect of inertia was secondary; therefore the design of energy absorbing systems could be achieved provided that the material strain rate was taken into account. Reddy et al. [12] described experiments in which a variety of one-dimensional systems with free distal ends, as opposed to fixed ends, were subjected to lateral impact by a rigid projectile. An elastic–plastic structural shock wave theory, which employs a bilinear material model to describe the collapse behaviour of the rings, was used to analyse the deformation of typical ring chain systems.

A nested system in the form of orthogonal layers of aluminium and mild steel tubes under static lateral compression was investigated by Johnson et al. [13]. Such an orthogonal layer consists of a row of tubes stacked upon each other with every second row rotated 90°. The authors concluded that nested ductile tube systems play an important part in producing a monotonic load–deflection response and that the systems which exhibit cracks after loading only induce oscillations into the response and do not produce catastrophic failure in the system as a whole.

A nested system analysed by Shrive et al. [14] consisted of two concentric rings with a layer of smaller tubes between them, the axis of all tubes being parallel. Tack welding was used to attach the rings to the concentric tubes. It was found that increases in system stiffness, maximum load and energy absorption was apparent as the level of tack welding increased. From the impact loading experiment, it was found that full deformation did not occur but maximum opposing forces similar to the quasi-static case were achieved.

Reddy and Reid [15] examined the quasi-static lateral compression of a tube constrained so that its horizontal diameter was prevented from increasing. This was a way of increasing the specific energy absorption capacity of the tube by introducing more plastic hinges into the structure. Also the relationship between a single tube and a system of tubes with different configurations was investigated. It was found that the energy absorbed by a closed system (side constraints) was three times more than that of an open system (no constraints); however, the maximum deflection of the former was less than that of an open system. Overall, it can be concluded that the introduction of side constraints and creating a closed system is a feasible method of increasing its energy absorbing efficiency.

Morris et al. [16] analysed the quasi-static lateral compression of nested tube systems between rigid platens both experimentally and numerically. These energy absorbers consisted of both two and three tube systems that were assembled 'In Plane'. Such a term describes two or more tubes of varying diameter being placed within each other and their axes being parallel. This type of energy absorber was compressed under flat rigid platens at a velocity of 3 mm/min to ensure no dynamic effects were present. It was demonstrated how such a system is well suited to applications where space or volume restrictions are an important design consideration without compromising energy absorbing requirements.

Morris et al. [17] also analysed the post-collapse response of nested tube systems with side constraints. This work showed how the introduction of external constraints allows a greater volume of material within the structure to deform plastically in the post-collapse stage of compression, thereby absorbing more energy. Nested systems consist of 'short tubes' of varying diameter placed within each other with an eccentric configuration. A related work [18] modified the In Plane system by rotating the central tube 90° to define an 'Out of Plane' system. In doing so, the