



Testing, simulation and evaluation of a novel hybrid energy absorber



C. Moreno ^{b,*}, T. Williams ^b, R. Beaumont ^a, D.J. Hughes ^a, R. Dashwood ^a

^a WMG, University of Warwick, Coventry, CV4 7AL, UK

^b OLEO International, Grovelands, Longford Road, Exhall, Coventry, CV7 9EN, UK

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ABSTRACT

Railway vehicles require energy absorbers which dissipate energy at a constant load, resist transverse loading and which are compact. In addition, accurate numerical models of the crumple zones are also required. A novel expansion-splitting (hybrid) energy absorber is proposed by the authors to provide improved energy absorption properties over existing devices.

Dimensionally scaled tubes, incorporating expansion, splitting and expansion-splitting dies, were tested under quasi-static and dynamic conditions. Six different dies, with expansion ratio $R = 1.10$ and $R = 1.25$, die conical semi-angle $A = 15^\circ$ and $A = 30^\circ$ and flaring radii $D = 8$ mm and $D = 12$ mm, were used in the experiments to crush the tubes. Calibrated numerical models and parameters found in previous investigations (fracture strain and friction) were included in the numerical models of the expansion-splitting tubes.

For the quasi-static testing, the expansion tubes exhibited the greatest force efficiency. The splitting tubes exhibited the greatest stroke efficiency. However, the expansion-splitting tubes exhibited the greatest combined overall efficiency.

The numerical simulation accurately predicted the performance of the expansion-splitting tubes under quasi-static conditions. The energy absorption of these tubes was predicted within 2% of the observed test results.

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1. Introduction

Energy absorbers for railway vehicles need to comply with the relevant crashworthiness requirements. BS EN 12663 [1] specifies the maximum load which the energy absorbers may transmit to the different railway vehicle structures. BS EN 15227 [2] specifies the required amount of energy which the energy absorber must dissipate for each type of railway vehicle. Under these restrictive conditions, the railway industry tends to favour type I [3] over type II energy absorbers. Type I energy absorbers exhibit a 'flat topped' constant load-displacement curve which maximise the dissipated energy for any given load. On the contrary, type II energy absorbers reach a pronounced peak force, after which the force decreases sharply.

Splitting and expansion tubes are amongst the most popular energy absorbers used by the railway industry. The splitting tubes achieve the energy dissipation by means of plastic deformation, material tearing and friction. A number of investigators [4–12] have studied the axial splitting of tubes, using flat platens, flaring dies and cutting devices to induce the splitting. Splitting tubes deviate

significantly from ideal type I energy absorbers in that they exhibit two noticeable peak loads, the first one corresponding to the moment when the tube starts splitting and the second one corresponding to the moment when the formed individual strips come into contact with the un-deformed section of the tube. In addition, the energy absorption of the splitting tubes is limited by the flaring radius of the splitting die. Al-Hassani et al. and Reid [13,14] noted that, while decreasing the flaring radius has the effect of increasing the reaction load, there is a limiting radius at which the tube does not split and tube inversion takes place instead. However, splitting tubes have been identified [15] as one of the energy absorber mechanisms with largest stroke efficiency, described as the ratio of stroke to total length of the device.

The expansion tubes achieve the energy dissipation by means of plastic deformation and friction. Studies have investigated the radial expansion of tubes as energy absorbers [16–22]. Expansion tubes conform very closely to the ideal type I energy absorber. However, they exhibit poor stroke efficiency. The length of the expansion die, required to be as long as the expansion tube, limits the expansion tubes to a maximum of 50% stroke efficiency. Almeida et al. and Ahn et al. [17,20] noted that, for expansion tubes with large expansion ratios, the tubes fail under a critical buckling load by plastic instability.

Ko et al. [23] investigated a tearing tube based on the combination of the expansion and splitting energy absorption mechanisms.

* Corresponding author. OLEO International, Grovelands, Longford Road, Exhall, Coventry, CV7 9NE, UK. Tel.: +44 (0) 2476 645555; Fax: +44 (0)24 7664 5900.

E-mail address: carlos.moreno@oleo.co.uk (C. Moreno).

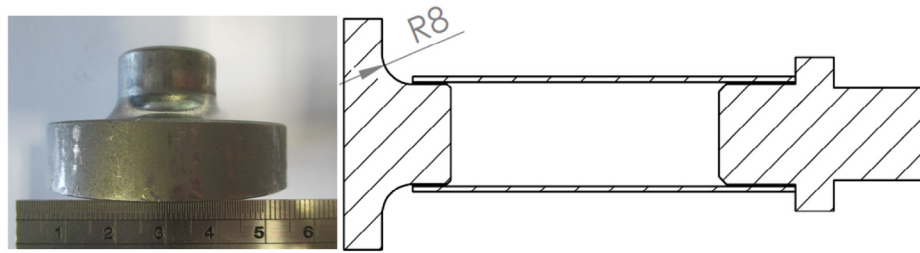


Fig. 1. Dimension of the splitting die.

A stroke to diameter ratio of 1:1 was used. It was asserted that the mean load corresponding to the final stage, that is the combined expansion and splitting stage, increased by 30%, in comparison to the mean load of the expansion-only stage.

This study assessed the stroke efficiency and force efficiency of splitting, expansion and combined expansion-splitting tubes. The stroke efficiency was assessed as the ratio of the stroke to the overall length of the tube assembly. The force efficiency was assessed as the ratio of the mean load to the peak load exhibited by each tube. Finally, an overall efficiency was calculated as a combination of the stroke and force efficiencies of each type of tube.

The experimental results of the present study confirm that expansion-splitting tubes can also fail by plastic buckling instability. This suggests that the maximum mean load displayed by tubes of similar dimensions is not determined by the energy absorption mechanism, whether expansion, splitting or combination of the two. Instead, the tube would fail under the application of a critical buckling load.

The authors of the present study identified that the real potential of this novel expansion splitting tube is two-fold. Expansion-splitting tubes can approximate the excellent stroke efficiency of the splitting tubes, due to the inclusion of the splitting mechanism, while retaining the excellent force efficiency exhibited by expansion tubes. The novel energy absorbers will be subsequently referred to as hybrid tubes, for economy of space.

In order to prove this assertion, tubes with similar dimensions were quasi-statically and dynamically tested by expansion, splitting and hybrid dies. The dimensions of the tubes and the splitting, expansion and hybrid dies, likewise their material properties, are specified in section 2.1. A description of the test equipment and test conditions follows. The finite element methods and numerical models to predict the tubes' behaviour are described next. The test results are given in section 3. The test results for the splitting and expansion tubes are used to calibrate their numerical models. The parameters found in the calibration activity are then included in the hybrid tubes for validation purposes.

2. Materials and methodology

2.1. Sample preparation

Cold drawn tubes, made of mild steel E355 as per BS EN 10305-4:2011 [24], were used as specimens. The splitting and hybrid specimens were cut to a length of 200 mm. The expansion specimens were cut to a length of 150 mm, as it was noted that their mean load did not vary after the steady-state load was reached. The end faces were machined to ensure similar initial conditions for every specimen. For the splitting and hybrid specimens, six equally spaced notches were cut, 0.7 mm wide and 1.5 mm long. The tubes were not heat treated and were tested in their as-received condition. The dimensions of the tubes were 30 mm outer diameter and 2 mm wall thickness. The nominal mass of the 150 mm and 200 mm long tubes was 204 g and 273 g respectively.

The dies were made of steel grade 817M40 (EN24). The dies were hardened by oil quenching. The dies had an average hardness $H_v = 385 \text{ kgf/mm}^2$. According to the formula yield strength $\sigma_y = -90.7 + 2.876 \times H_v$, specified by Reference 25, and the corresponding yield strength was approximately $\sigma_y = 1016 \text{ MPa}$.

The radius of flare of the splitting die was 8 mm (Fig. 1), and its mass was 390 g. Four expansion dies were manufactured (Fig. 2), with expansion ratio $R = 1.10$ and $R = 1.25$ and cone semi-angle $A = 15^\circ$ and $A = 30^\circ$. Fig. 3 shows a schematic representation of the expansion tube assembly. The hybrid tubes comprised the expansion dies with connected flaring dies of radius 8 mm and 12 mm (Fig. 4). Table 1 shows the mass of each die and the average mass of the expansion assembly. The material properties of the E355 steel tubes were determined by tensile test using a contact extensometer. The test pieces were cut from the tube by a waterjet cutting process. The test pieces' dimensions and test procedure were as per BS EN 6892-1:2009 [26]. Fig. 5 shows the stress-strain curve of one of the coupons. The yield strength of the material was 383 MPa.

2.2. Test procedure

2.2.1. Quasi-static test procedure

A screw-driven Instron 5800R 100 kN test machine was used to crush the specimens. Fig. 6 shows the test configuration of a R125A15D08 expansion-splitting specimen, similar to the test assembly of the splitting and expansion tubes. Copper grease was applied on the die radius surface and around the bore of the tubes. The die was fitted onto the tube. The machine crosshead was located under the assembly support. The crosshead compressed the tube against the die and the platen at a constant speed of 16 mm/min. The compressive load was applied until a stroke of 160 mm (115 mm for the expansion specimens) was realised, reaching a stroke to diameter ratio of 5:1 (or 4:1 for the expansion specimens). Three repeat specimens were crushed for each type of specimen. The hybrid specimens with expansion ratio $R = 1.25$ experienced early splitting, before the expansion stage could be fully realised. The strain caused by the

Table 1
Mass of the dies.

Die	Mass (g)
Splitting	390
Expansion R110A15	67
Expansion R110A30	55
Expansion R125A15	104
Expansion R125A30	82
Hybrid R110A15D08	313
Hybrid R110A15D12	444
Hybrid R125A15D08	379
Hybrid R125A15D12	501
Hybrid R125A30D08	357
Hybrid R125A30D12	479
Assembly	Mass (g)
Average expansion assembly	1097

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