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New generation of energy dissipating systems based on biaxial buckling

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ABSTRACT

This work proposes a new generation of energy dissipating system based upon an original patented mechanical assembly: the *Absorption par Compression–Torsion Plastique* (ACTP) presented in Abdul-Latif and Baleh (2005).[1] In fact, the ACTP transforms a uniaxial external loading into biaxial compression–torsion, where several degrees of biaxial loading paths complexity can be created within the loaded tubes. Such a concept which aims to enhance the strength properties of material is now extended to study the biaxial plastic buckling of different materials, and different cross sections under further severe loading conditions.

The intention of this comprehensive experimental study is to further investigate a new severe loading configuration under quasi-static strain regime. Thus, five inclination angles (30°, 37°, 45°, 53° and 60°) are tested using circular and square tubes made from copper and aluminum alloy, respectively. An integrity measure of the mean collapse load and the corresponding energy absorbed shows that the higher the inclination angle (i.e., the higher loading complexity), the greater the rates of change of torsional component, and the greater the mean collapse load, and the corresponding energy absorbed in copper and aluminum tubular structures.

1. Introduction

Reliable and safe design of components and systems especially in transport vehicles (or other systems like nuclear power plants, different structures, etc.) with maximum energy absorption are becoming important engineering subjects. This issue is bolstered by several devices developed with a strong conviction in emerging the response of structures to a large extent. Hence, the goal of these "energy dissipating systems" devices is to mitigate the damage and consequently improve the vehicular crashworthiness. A number of literature surveys represent the state of the art showing different experimental and theoretical concepts in this area (e.g., [1–5]). Understanding the behavior of collapsed structures and materials behavior is essential to assess the energy absorption. For a given structure, this energy depends on several key parameters like magnitude, type and method of application of loads, strain rates, deformation or displacement patterns and material properties [1,6,7].

Plastic buckling of tubular elements is the focus of this work since it gives an excellent specific energy absorption capacity (e.g., [1,8,9]). Hence, tubes of circular and square cross section loaded under axial compression are widely used as energy absorbers. In this case, a large amount of energy can be dissipated due to the available long stroke per unit mass and stable average load in the entire collapse process [10]. The bending and stretching strains combination and its progression along the buckled tube guarantees the participation of material in the absorption of energy by plastic work.

Under axial compressive loading, the literature survey points out three collapse modes for tubular structures: axisymmetric mode, diamond mode, and mixed one. The geometrical key parameters controlling these modes during plastic buckling are: the $\eta(=R/t)$ ratio of radius (R) to thickness (t) [1] and the $\lambda(=R/L)$ ratio of radius to length (L) [8,11,12]. Note that the mean collapse load is the most important parameter in evaluating the absorbed energy. The recorded force–displacement curve has an oscillatory nature with a first maximum peak force. The latter should not be excessive due to design reasons related to the security and ideally be close to the average force. Moreover, it is influenced, for a given

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tube, by the initial imperfections over the tube and to minimize its value, several solutions developed, like make ducts, holes near the tube ends, chamfering, grooving, etc. The concept of a buckling initiator is successfully developed reducing this peak force up to 30% as some more recent studies show [13,14].

The absorbed energy is gaining more recognition in the axisymmetric mode than that in the diamond or mixed one [12]. No analysis yet shows why a particular mode shape is adopted by a given tube for a given material.

For thin-walled square tubes, they deform differently compared to circular tubes. However, the force–displacement relationship features are generally similar due to the fact that both tubes undergo progressive collapse under axial crushing [13,15–21]. For a fully crushed square tube, the geometrical ratio c/t (c is the side length and t is the thickness) has an important role in defining the tube wall deformation mode. With possible stretching, it can undergo severe inner and outer plastic bendings. In the case of thin tube with $c/t=100$ for example [22], a non-compact collapse mode could occur where the folds are not continuous and they are separated by slightly curved panels. Globally, the obtained mode is considered to be relatively unstable with the tendency to Euler-type buckling, which is an undesirable energy-dissipating mechanism.

Contrary to these standard passive systems, the concept used in this work, is based upon an idea recently developed via a patented rig presented in [23,24]. The solution consists of creating a particular complex loading condition provoking an enhancement in strength properties of the loaded structure due to changes in local deformation mechanisms. This specific mechanical assembly (the ACTP) is capable of transforming a uniaxial external loading into biaxial one of combined compression–torsion. Hence, several degrees of loading complexity can be created within the loaded tubes. The biaxial plastic buckling, therefore, becomes more and more complicated since a shear component is added to these sequential phases of compression and bending. This leads to three different strains of compression, bending and shear. For the biaxial buckling of copper circular shells, the reported results illustrate increases in the energy absorption attaining up to 35% under quasi-static loading [23] and 44% under dynamic loading [24] compared to the classical uniaxial case. The intention of the present work is to offer a further improvement in the energy absorption capacity of a tubular structure of square and circular cross section under quasi-static loading conditions. As such, the ACTP is systematically used. A new investigation with further loading path complexity is carried out via other inclination angles. Thus, a comprehensive experimental study is conducted using several structures made from copper (for circular cross section) and aluminum (for square cross section). An assessment of mean collapse load as well as energy absorbed show particularly the efficiency of the developed concept in improving the absorbed energy. Consequently, the higher biaxial loading complexity, the greater the energy absorbed in copper and aluminum cases for a given structure.

2. The ACTP rig

Fig. 1 illustrates the ACTP device schematically. Made from a tempered steel hollow cylindrical body (1), it consists of four parallel helicoid machined grooves (2). They are characterized by a well defined inclination angle controlling the rate of change of torsional component during collapse process. To investigate the effect of this key parameter, five different interchangeable cylindrical bodies (1) are designed with five distinct propeller inclination angles of 30°, 37°, 45°, 53° and 60°. The last two inclination angles (i.e., 53° and 60°) which lead to the highest loading complexity are realized and tested in the current study. The helicoid grooves are intended to receive a crosspiece (5) provided with four pivots

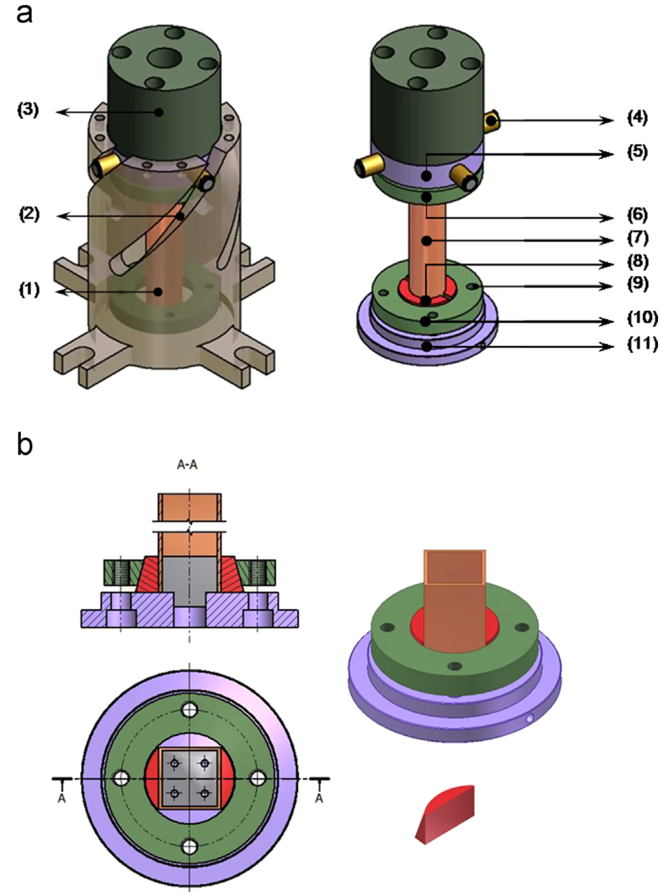

Fig. 1. 3D presentation of the ACTP device showing the assembly of tube ends fixation for (a) circular tubes and (b) square tubes. (1) cylindrical body; (2) helicoid groove; (3) interrnediale cylinder; (4) roller; (5) crosspiece; (6) higher disc; (7) specimen; (8) lower conical half-shells; (9) lower tightening screw; (10) lower conical clip; (11) basic disc.

equipped with bronze rollers (4) and to guide it in its movement of descent by inculcating a rotational movement. The two principal parts of this apparatus form a slide-helicoid connection. This mechanism permits to transform an initial external load of uniaxial nature into a biaxial combined compression–torsion one. The bronze rollers (4) minimize the friction in the contact zone between the grooves (2) and the crosspiece (5).

Obviously, the crushed circular (or square) tube (7) is mutually dependent on the crosspiece and cylindrical body by a mechanical tube extremities fixation system. The system is made principally from a hard steel disc (11). Two half-conical shells (8) and a clip (10) over which these conical surfaces are machined and assembled in opposition attached to the disc maintain the necessary tightening pressure in locking both crushed tube extremities (Fig. 1a). As a new extension, the square tubes extremities fixation system is designed with two square clamps (Fig. 1b) using the same concept as in the circular tubes. Therefore, whatever the tube type, its deformation is totally conditioned by the crosspiece in its movements of descent and rotation.

It is difficult to evaluate the friction effect on the deformation operation during tests. However, an approximate method has been already proposed [23] defining its effect on the total absorbed energy. The following experimental methodology helps to evaluate the friction effect and its influence by the loading complexity. Indeed, as it is imposed by the rig design, a rolling friction type is used. Many crushing tests have been realized using square aluminum tubes under different loading conditions.