EFFECT OF TREATED ZONE GEOMETRY ON THE DYNAMIC PLASTIC BUCKLING OF STEEL COMPOSITE THIN TUBULAR STRUCTURES

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ABSTRACT

Thin tubes made from steel composite are experimentally investigated showing their energy absorption capacity during dynamic plastic buckling. In fact, steel-steel composite cylindrical tubes are characterized by a specific outer surface heat treatment. Only 15% of tubes outer surface are heat treated for a certain depth along the tube thickness with different geometrical shapes. The patented idea• *aims to enhance the impact resistance of tubular structures not only through the treated area but especially through its geometry.*

A key point emerging from this study is that the structure impact response (i.e., the plastic flow mechanism and the absorbed energy) is influenced by the loading rate coupled with the heat treated configuration. To study the geometry effect of carburizing treated zone, several shapes are tested :three different ring-shape configurations (2, 4 and 6 rings), a configuration with three uniformly distributed vertical strips parallel to the axis of the tube and finally one treated helically case with tilt angle of 45°. All the experimental tests are carried out using a dynamic drop mass bench of a maximum impact velocity of 10 m/s.

The obtained results show the enhancement in the energy absorption, notably in the case of 4-ring (and then helically case with a tilt angle of 45°) is higher than 78% in comparison with the non-treated tube.

Keywords: *plastic buckling; surface heat-treatment, dynamic loading; energy absorption*

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• Patent submitted in France: INPI No. 1400843, Inventor : Akrum ABDUL-LATIF

1 INTRODUCTION

Adopted since several decades by different transport vehicles, the thin-walled tubular structures are widely used as a fundamental tool in developing a passive safety concept, i.e., energy dissipating devices based on large plastic deformations (e.g., Abramowicz and Jones, 1986; Johnson and Reid, 1986, Jones, 1998; Al-Ghamdi, 2001; Abdul-Latif, 2000; Baleh and Abdul-Latif, 2007, Abdul-Latif and Baleh, 2008, Abdul-Latif, 2011; Menouer et al., 2014).
Understanding the behavior of collapsed structures and the materials behavior is essential to asses the energy absorption. Different studies reveal that the crushing process remains sensitive to several key parameters like magnitude, type and method of application of loads, strain rates, deformation or displacement patterns and material properties (Baleh and Abdul-Latif, 2007; Karagiozova and Jones, 2000; 2001).
Under dynamic loading, the axial crushing of cylindrical tube is an effective shock absorber device and is highly dependent on inertial effects of strain rate (Karagiozova, 2000, 2001; Jones, 2003). As a main subject of this work, the plastic buckled tubes can dissipate a large amount of energy due to the available long stroke per unit mass and stable average load in the entire collapse process (Yasui, 2000). The bending and stretching strains combination and its progress along the buckled tube guarantees the participation of material in the absorption of energy by plastic work. Three collapse modes of tubular structures have been shown in the literature survey: axisymmetric mode, diamond mode, and mixed one. The main geometrical parameters controlling these modes during plastic buckling are: the η (=R/t) ratio of diameter (R) to thickness (t) and the λ (=R/L) ratio of diameter to length (L) (Karagiozova, and Jones, 2002; Bouchet et al., 2002; Al Galib and Limam, 2004; Baleh, 2004; Abdul-Latif et al., 2005). Note that the mean collapse load is the most important parameter in evaluating the absorbed energy.
From the energy point of view, the limit of the performance of axially crushed tubes can be enhanced using an innovated idea. This is based on the generation of complex loading conditions through the combination of local heterogeneities dictated by the steel-steel composite and the external load. Hence, 15% of tubes outer surface is heat treated proposing different shapes. A key point that emerges from this study is that the response of the structure (i.e., plastic flow mechanism and the energy absorbed) is largely influenced by the treated shape and the loading rate. To study the geometry effect of carburizing treated zone, seven different distinct shapes are tested: three different ring-shape configurations (2, 4 and 6 rings), a configuration with three uniformly distributed vertical strips parallel to the axis of the tube and finally a helically treated case with tilt angle of 45°. The behavior of the crushed materials demonstrates the dependence of the plastic buckling on the composite type and loading rate.

2 EXPERIMENATLE PROCEDURE

2.1 Originality and experimental methodology

This actual investigation is based on a patented concept (Abdul-Latif, 2014), where the first results show the importance of this new methodology. Enhancement of the energy absorption capacity through the coupling of the steel-steel composite configuration and the loading rate is considered.
In fact, the basic idea is to make a steel-steel composite (i.e., increase the tube wall strength in certain zones) via the heat treatment of a given area. The definition of the targeted area is based on its form within the treated structure which requires special attention.

The originality of this technique consists of partially coating the outer surface of the tube with a thin layer of a specific paint before the heat-treatment. Therefore, the coated area should resist against any change in phase during treatment. This allows keeping its initial mechanical behavior.
This study is addressed to study the mechanical behavior of tubular steel-steel composite structures under quasi-static and dynamic regime. The material of the structure is subjected to an important stress conditions enhancing the energy dissipation capacity. Thus, the influence of the loading rate and the shape and layout of the heat treated area is investigated.

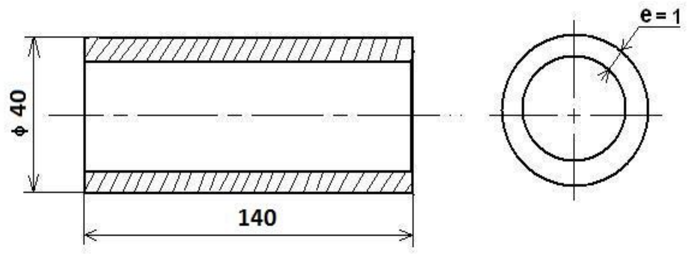


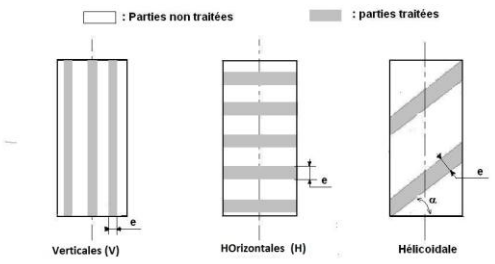
Figure 1. Initial geometry of the used samples

2-2. Material, geometry and heat treatment

The investigation focuses on several cases using tubes of 40mm diameter and 1mm thickness and an initial length of 140 mm (Fig. 1).
The choice of this mild steel is evidently based on the ability of the metal to receive a particular heat treatment. Indeed, after a few trials subcontracted by a specialized company (Bodycoat) nitriding, carburizing and carbonitriding, it turned out that it provided better leverage to control appropriately the depth of treatment.
The opportunity is therefore to give a judicious choice in controlling the geometrical parameters (the shape and the depth of the treated zone). The carburizing heat treatment can suitably control the depth of treatment by 0.4 mm to set this important geometrical factor. To study the geometry effect of carburized zone with only 15% of tubes outer surface, different shapes are tested which are three different ring-shape configurations (2, 4 and 6 rings), a configuration with three uniformly distributed vertical strips parallel to the axis of the tube and finally a helically treated case with a tilt angle of 45°.

2-3. Samples Preparation

After machining, several operations are performed before the heat-treatment which are cleaned and degreased. Tubes are then painted by immersion in a paint solution (LUISO W36 for gas carburizing) that can provide protection for non-hardened parts up to 6mm in depth, at temperatures around 970°C. Furthermore, the different types of area (or shapes) that are tested can be classified into three categories (fig. 2) noted by (nH nV and nHe) where n indicates the number of bands, H horizontal positioning, vertical V and helical He. The first three configurations are: 2H, 4H and 6H having a ring form arranged equidistantly over the entire length of the tube. The second category deals with longitudinal strips over the entire length of the tube and arranged regularly and parallel to the tube axis. The third category is based on helical strips with a helicoidal angle He45°.



(a)

(b)

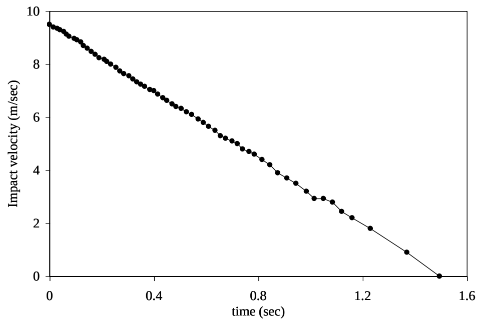
Figure 2. (a) Scheme of proposed configurations, (b) view of the geometry of the patterns of 2V configurations, 4H and 2He before heat treatment

All tests were performed under the same experimental conditions using a free-ends mode. In the case of quasi-static regime, tests are conducted using a universal testing Instron machine type 5582. It has a maximum load capacity of 100 kN with a range of cross-head speeds varying from 0.001 to 500 mm/min. Furthermore, the obtained quasi-static strain rate is a parameter that has no significant influence on the material behavior. Therefore only a speed of 5 mm/min is employed for this study.

3 IMPACT APPARATUS

All the experimental tests are carried out using a dynamic drop mass bench of a maximum impact velocity of 10 m/s and of a maximum kinetic energy of 2.5 kJ. It is equipped with a dynamic load cell of 20 tons, a 5000g accelerometer, and a laser beam displacement transducer (series M5L of international Bullier) for a measurement bracket of 100mm. These instruments are connected to a rapid acquisition chain (2.5MHz), which ensures the simultaneous recording of these experimental data: force, acceleration and displacement.

(a)



(b)

Figure 2: (a) overview of the drop mass bench; (b) changes in the impact speed

Tests are conducted under initial impact velocity of about 9.5 m/s use a maximum masse of 45.5 kg. As a typical example, the rate of change of the impact velocity during crushing process is obviously illustrated in figure (2).

In order to ensure the experimental results accuracy, each test is repeated three times under the same experimental conditions (applied velocity and temperature). If the differences between the three responses exceed 5%, then another test should to be performed.

4 RESULTS AND INTERPRETATION

It is now known that the absorbed energy is controlled by the plastic hinges and localized areas of plasticity which differs from one deformation mode to another. Thus, three issues are mainly considered: local hardness (micro-hardness) before crushing, deformation mode and the crushing load (and the energy dissipated by plastic buckling).

4.1 Behavior of treated specimens

Figure 3 analyzes the effect of heat treatment on the tube wall behavior by comparing the non heat-treated and treated samples. Several Vickers micro-hardness tests are made.
Figure 3 shows micro-hardness evolution of 8 traces of the cross section of the wall starting from the outer radius to the inner one. Unlike the wall of the non treated specimen, which shows a relatively constant Vickers hardness over the whole thickness, the treated specimen demonstrates a remarkable increase in hardness from 180 HV to 780 HV, i.e., 300%. This decreases substantially linearly to 200 HV at trace 5, and in a constant evolution until the inner end of the wall.

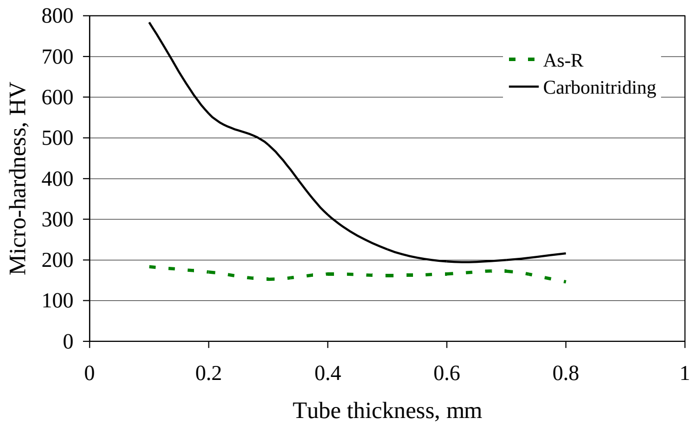


Figure 3: Effect of the carburizing on the hardness of the tube wall.

Initial **AM** **MXA** **DM**

Figure 4. Specimen before and after plastic buckling

Concerning the collapse mode of tubes, it is obvious that whatever the loading configuration (quasi-static or dynamic), three modes of deformation are generated: axisymmetric mode (AM), diamond mode (DM), and mixed mode (XM). However, it is noted that in terms of proportion is the mixed mode axisymmetric dominant (MXA) that appears frequently, particularly in quasi-static due to a better centering of the applied load. An examination of the tested tubes at the end of collapse (figure 4) reveals that their plastic buckling where the three different modes are captured.

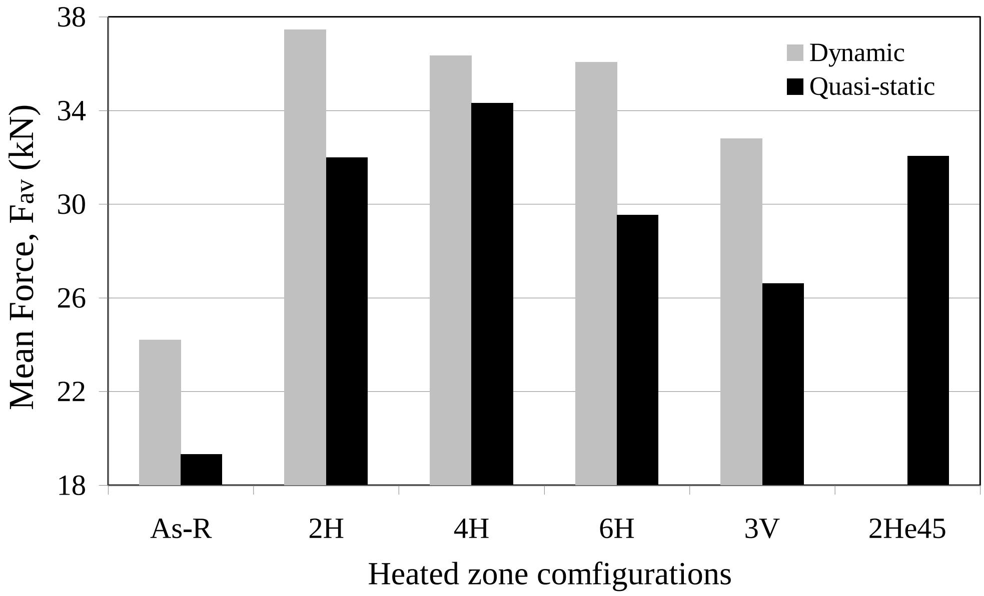


Figure 5. Comparison showing the variation of crushing mean load depending on the heat treated zone configuration and crushing regime

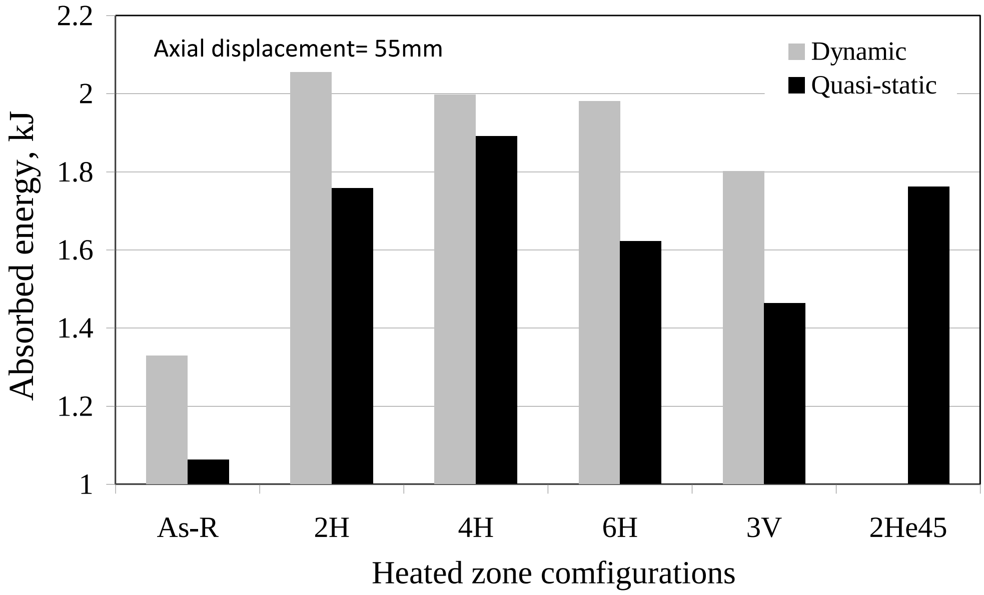


Figure 6. Comparison regarding the variation of energy absorbed controlled by the heat treated zone configuration and the speed of loading for an axial displacement of 55mm

The influence of the heat-treated zone configuration on the mean crushing load (F_{av}) is presented in figure (5). This figure obviously shows the effect of this zone and its shape on the absorbed energy. The enhancement of the absorbing capacity is determined with respect the as-received tube (not heat-treated tube, noted As-R), where its mean collapse load (F_{av}) is compared to the other cases. Under quasi-static load, enhancements in the F_{av} are: 77.7% for 4H against 65.3%, 52.8%, 66.3%, and 37.8% for 2H, 6H, He45° and 3V cases, respectively.
As far as the energy absorption is concerned, figure (6) illustrates a clear enhancement in the energy dissipated. In fact, this figure shows the evolution of energy absorbed versus the five treated configurations for a given axial crushed length of 55mm under quasi-static and dynamic loading. As an example, for this axial displacement under quasi static condition, the best enhancement regarding the energy absorbed is captured in the case of 4H with a value of 1.9 kJ. However, another evolution is recorded at dynamic loading, which gives us a best energy absorbed in the case of 2H with a value of 2 kJ. So, the best enhancements are: 78% for 4H and then 67% for 2He45° in quasi static with respect to the As-R case against 55% for 2H and 51% for 4H under dynamic loading. The best variation in the heated configuration which absorbs the highest amount of energy seems to be controlled by the loading speed. However, this conclusion will require further investigation to be confirmed.

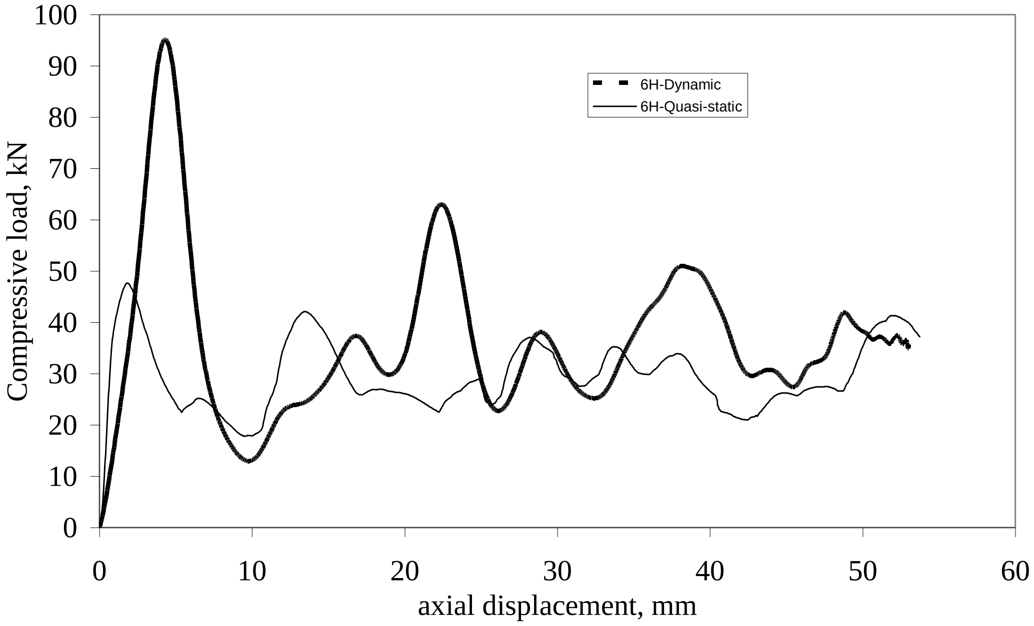


Figure 7. Loading rate effect on the collapse loading evolution versus the axial deflection for a case of 6H

Figure 7 shows a typical example of the crushing load evolution versus axial displacement in the case of 6H, with a compressive speed of 5 mm/min in quasi-static regime and 9.5m/sec as initial impact velocity for the dynamic regime. These two loading conditions point out a remarkable increase in the maximum dynamic load of 104% before the beginning of plastic deformation. It is recognized also that the general trend of their evolution provides: F_{va}= 36.3 kN for dynamic loading against 27 kN for quasi-static one. This result confirms a noticeable sensitivity of the structure to the employed strain rate range.

5 CONCLUDING REMARKS

In this work, the energy absorbing device that includes a thin-walled tube is tested under dynamic and quasi-static compressive loads. On the outer surface of the tube, different heat-treated zones of 15% are proposed. To study the geometry effect of carbonitriding treated zone, several shapes are tested: 3 ring-shape configurations of 2, 4 and 6 rings, a three uniformly distributed vertical strips and a helically with tilt angle of 45°. All the tests are carried out using a dynamic drop mass bench of a maximum impact velocity of 10 m/s and an Instron tension-compression universal testing machine of 5 mm/min for quasi-static loading condition.

The obtained results show the enhancement in the energy absorption, notably in the case of 4-ring (and then helically case with a tilt angle of 45°) is higher than 78% for quasi-static loading and 55% for dynamic loading compared to the non-treated tube. Whatever, the heat-treated zone configuration, the obtained results confirm a noticeable sensitivity of the used structure to the strain rate range.

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