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Unified ring-compression model for determining tensile properties of tubular materials

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ABSTRACT

The stress-strain relation is the key mechanical properties in safety design and evaluation for tubular structures. However, conventional uniaxial tension and compression tests have some drawbacks and limitations for these structures. In the current investigation, a unified ring-compression model to acquire the stress–strain relation of tubular material is introduced based on the equivalent energy principle. In the model, a unified relation among strain energy, load, deflection, geometric parameters and material property parameters is proposed to depict the elastoplastic response during ring compression test. The model has only four undetermined parameters which can be calibrated by a few FEA (finite element analysis) calculations. The accuracy of the model has been verified within a wide range of imaginary materials by using FEA. Results show that both the forward-predicted load-deflection relation and the reverse-predicted stress-strain relations from the model are in excellent accord with the results from FEA. In addition, the model is verified with three homogeneous ductile materials by conducting ring compression and standard tensile tests. And it is applied in obtaining the hoop stress-strain relation of tubular zirconium alloy in the nuclear power engineering.

1. Introduction

Various tubular structures are widely applied in engineering due to their excellent load-carrying capacity and energy-absorbing feature, such as the fuel-cladding tubes in nuclear reactor [1,2] and the sealing ring in pressure vessel, pipeline in oil and gas transmission and energy absorbers in transportation sector and air-drop cargo etc. The mechanical property like hoop stress-strain relation of these structures is very important due to a variable pressure and temperature upon their inner and outer surfaces. However, the tube longitudinal tensile tests show some inconvenience in acquiring tensile properties of tubular structures, such as the centered clamping of tubular specimen. Additionally, it is hard to know the material properties in the hoop direction while the material is anisotropic between longitudinal and hoop orientation [1–6]. In fact, a ring hoop tension test was developed by Wang [3] to acquire the hoop properties. But the ring tensile test has two major drawbacks, non-negligible friction between test specimen and D-blocks and limited for thin tubes. A simple theory for obtaining yield stress and average hardening modulus via ring compression between rigid plates was proposed by Reddy and Reid [4,5]. While the material in their theory was only assumed to be rigid linearly strain hardening. To avoiding drawbacks in the above tests, an inverse method based on finite element analysis (FEA) is introduced by Nemat-Alla [6]. But just a rough result can be obtained after complex and multiple parametric simulations in FEA. The ring compression test in longitudinal direction is also widely used to determine the friction coefficient [7–9]. Additionally, the buckling mechanism of lateral ring compression [10,11] and energy absorption capacity [12–17] of ring structures are widely concerned during recent decades. To optimize the tubular absorbers, the behavior of such absorbers under various loading conditions was investigated experimentally and numerically by Baroutaji and Morris [14–16]. However, the potentialities of the ring compression test method in these researches are highlighted without enough theoretical description. For a long time, there is only elastic solution of ring lateral compression from Timoshenko [18], De-Lin M [19] and Kourkoulis [20]. Due to a lack of elastic-plastic analytical solution, the materials properties of tubular structures are mostly obtained only depend on empirical formula [4,5] and iteration algorithm based on FEA [6], respectively. An explicit relation between energy absorption capacity and materials properties is very important.

In fact, the work done by the punch during ring compression contains abundant information about elastic-plastic material properties. Herein, a unified model among strain energy, compression load, deflection, geometric parameters and tensile properties under plane stress

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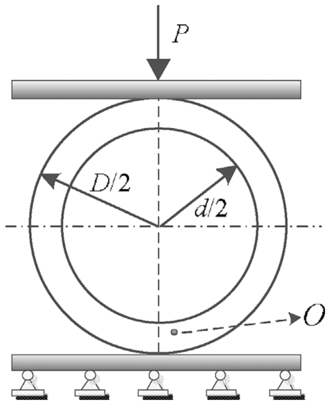

Fig. 1. The schematic diagram of ring compression.

condition is established. By solving this model, the stress–strain relation of tubular material is acquired combining the experimental data from ring compression test. Finally, verifications and applications for the model are carried out by both FEA and practical materials.

2. Theoretical model

2.1. The equivalent energy method

For most metal and alloy with high strength, the uniaxial stress-strain relations materials are nearly meet the stress–strain relation as a piecewise power-law model [21]

$$\sigma = \begin{cases} E\varepsilon & \varepsilon \le \varepsilon_y \\ K\varepsilon^n = E^n\sigma_y^{1-n}\varepsilon^n & \varepsilon \ge \varepsilon_y \end{cases} \tag{1}$$

where σ is the true stress, ε the true strain, E the Young's modulus, σ_y the yield stress, K the strength coefficient and n the strain hardening exponent.

For an arbitrary deformed material point O during compression as shown in Fig. 1, there is an equivalent relation between the actual 3-D stress state and the equivalent uniaxial stress state according to the von-Mises criterion, i.e.

$$u_O = u_{eq}|_{(x_O, y_O, z_O)} \tag{2}$$

where u_O and u_{eq} are respectively strain energy density of 3-D stress state and the equivalent uniaxial stress state.

When the current equivalent strain of the material RVE at arbitrary point O is noted as ε_{eq} and ε_{eq} is not more than ε_y, its equivalent strain energy density u_{eq} is deduced as

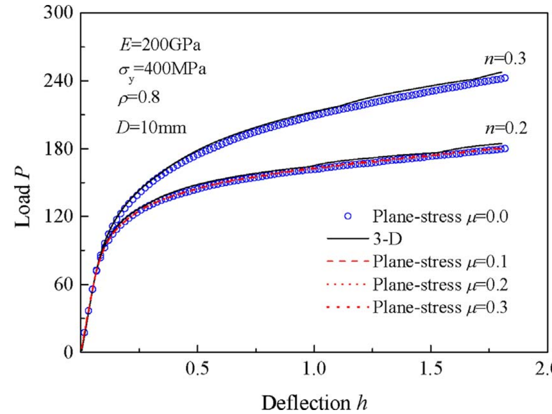

Fig. 3. The influence from model dimensions and coefficient of friction.

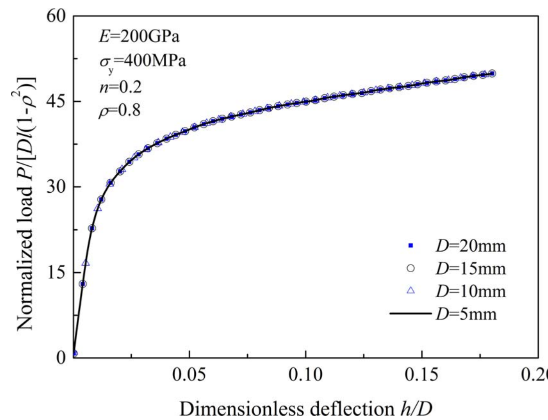

Fig. 4. Normalized load-dimensionless deflection curves from different diameters D with fixed ρ.

$$u_{eq} = \int_0^{\varepsilon_{eq}} \sigma d\varepsilon = \frac{E\varepsilon_{eq}^2}{2} \quad \varepsilon_{eq} \le \varepsilon_y \tag{3}$$

where ε_y is the initial yield strain ($\varepsilon_y = \sigma_y/E$).

Combining with the derivation of u_{eq} for a relatively large plastic deformation ($\varepsilon_{eq} > > \varepsilon_y$) [22], the expression of u_{eq} is

$$u_{eq} = \begin{cases} \frac{E\varepsilon_{eq}^2}{2} & \varepsilon_{eq} \le \varepsilon_y \\ \frac{K}{n+1}\varepsilon_{eq}^{1+n} & \varepsilon_{eq} > > \varepsilon_y \end{cases} \tag{4}$$

Based on the integral mean value equivalence proposed by Chen and Cai [22,23], it has

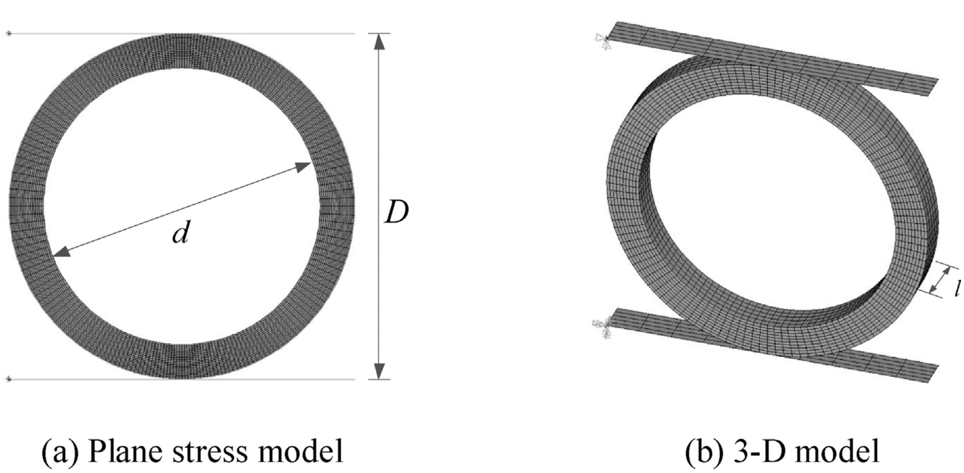

Fig. 2. The FEA model of ring compression.