Determination of tube material hardening law using bulging tests

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ABSTRACT: The paper is focused on the determination of mechanical characteristics for metallic materials shaped like tubes as used in tube hydroforming process. First, a procedure is described to carry out experimental tube bulging tests. It permits to identify a law linking the internal pressure to the bulge height. Second, based on this law and an original geometric modelling, strain and stress can be evaluated all over the free bulge zone of the tube. Third, numerical results obtained by finite element simulation are treated to validate the experimental behaviour law of the tube. It is shown that: measuring experimentally internal pressure and bulge height during tube bulging allows to determine tube hardening law and thickness distribution along the bulging area; a deviation of 2% is noticed between numerical and experimental results.

KEYWORDS: experimental test, analytical modelling, numerical simulation, finite element

1 INTRODUCTION

Hydrogen may become the future energy carrier and will have to be stored in vehicles in the next years ([1],[2]). Tube hydroforming could become an interesting solution for forming metallic liners as used in pressurized hydrogen storage. It has been demonstrated that material data obtained from tube bulging are more suitable to simulate hydroforming process than the classical tensile test ([3], [4]).
In [5], an analytical approach of tube bulging tests has been developped, based on geometric observations. Analytical results have been compared to finite element simulations. A good agreement between the two methods has been noticed.
This paper recalls the key points of these analytical and numerical modelling, and explain a methodology to determine a tube hardening law using experimental tests.

2 FRAMEWORK DESCRIPTION

2.1 *Experimental tests*

An experimental device has been manufactured to lead tube bulging tests (Figure 1).

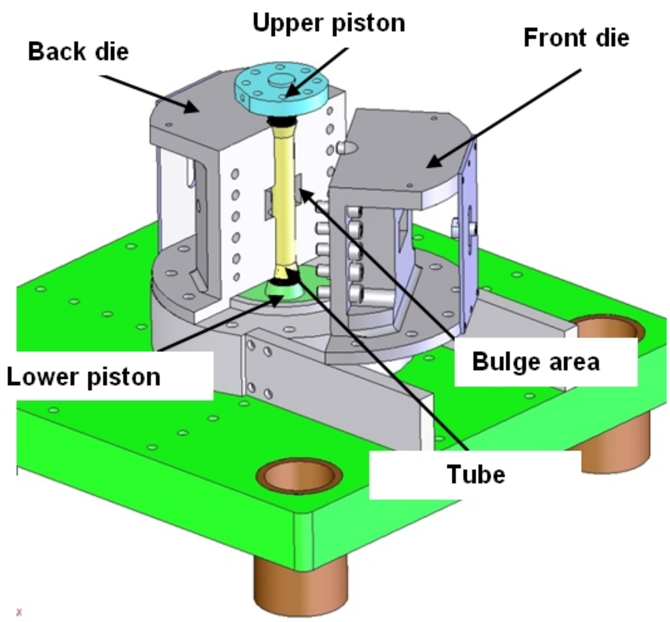

Figure 1: Experimental device for tube bulging tests

Geometric dimensions adapted to this tool are summerized in table 1. A pressure sensor is plugded in the upper piston to measure internal pressure during bulging. Three displacement transducers (Figure 2) are used to determine precisely maximal bulge height. Experimental bulging tests allow to define the law linking internal pressure to maximal bulge height, needed in the analytical modelling to calculate tube hardening law.

Table 1: Dimensions for bulging tests

Tube length	250mm
Tube diameter	35mm
Tube thickness	1 to 3mm
Bulging area length	50mm

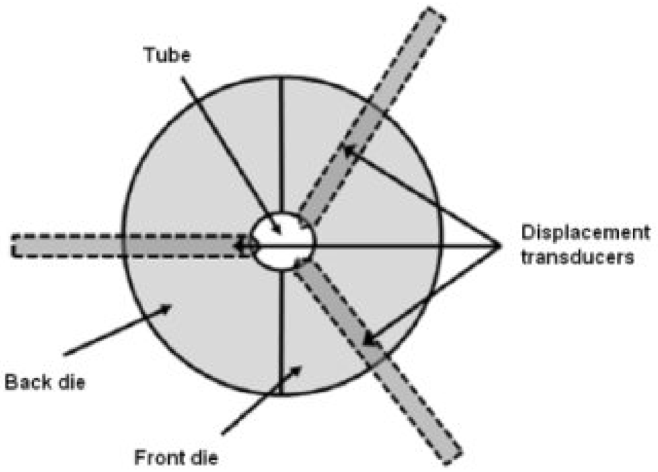

Figure 2: Displacment transducers positionning

2.2 Analytical modelling

The proposed geometric configuration (figure 3 ; table 2) is based on observations done on deformed tube. “q” index in table 2 stands for internal and external curvature.

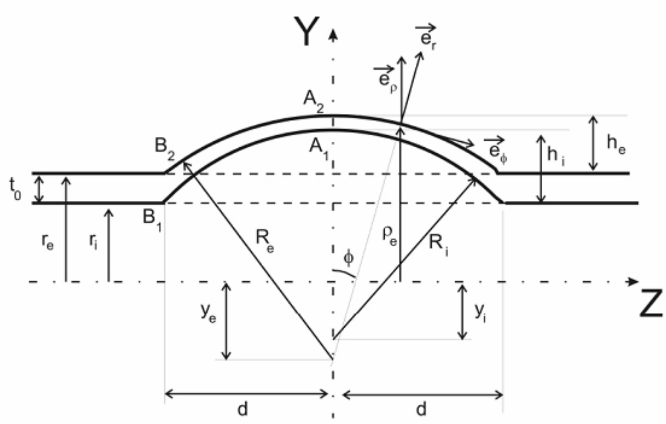

Figure 3: Geometric configuration for tube bulging

Table 2: Geometric configuration for tube bulging

Parameter	Description
r_q	Initial radius of the tube
t_0	Initial thickness of the tube
$2.d$	Length of the free bulge area
R_q	Curvature radius of the strained tube in (Y,Z) plan
ρ	Curvature radius of the strained tube on (X,Y) plan
y_q	Distance between the curvature centre and tube axis
h_q	Maximal bulge height of the tube
t(z)	Tube thickness at z coordinate

Few assumptions have to be made :

- the tube is supposed to deforme in two arcs of circuferemce in bulge area
- the bulged zone presents a circular symmetry around tube axis Y and a mirror symmetry through Z axis
- no sliding takes place in the blocked area during experiment

A geometric analysis based on volume calculation and material incompressibility permits to caculate thickness distribution all along the free bulge region [5]. Strain and stress are then express by the tensors (1) and (2).

$$\underline{\varepsilon}(z) = \begin{pmatrix} \varepsilon_r(z) & 0 & 0 \\ 0 & \varepsilon_\theta(z) & 0 \\ 0 & 0 & \varepsilon_\phi(z) \end{pmatrix} \quad (1)$$

$$\underline{\sigma}(z) = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \sigma_\theta(z) & 0 \\ 0 & 0 & \sigma_\phi(z) \end{pmatrix} \quad (2)$$

where :

- $\varepsilon_r(z)$ is the strain in the thickness direction

$$\varepsilon_r(z) = \ln\left(\frac{t(z)}{t_0}\right) \quad (3)$$

- $\varepsilon_\theta(z)$ is the strain in the meridian direction

$$\varepsilon_\theta(z) = \ln\left(\frac{\rho_e(z)}{r_e}\right) \quad (4)$$

- $\varepsilon_\theta(z)$ is the strain in the longitudinal direction

$$\varepsilon_\phi = -\varepsilon_r - \varepsilon_\theta \quad (5)$$

and :

- $\sigma_\theta(z)$ is the stress in the meridian direction

$$\sigma_\theta(z) = \frac{p.\rho}{t.\cos(\phi)}.\left[1 - \frac{\rho}{2.R.\cos(\phi)}\right] \quad (6)$$

- $\sigma_\phi(z)$ is the stress in the longitudinal direction

$$\sigma_\phi = \frac{p.\rho}{2.t.\cos(\phi)} \quad (7)$$

2.3 *Finite element simulations*

Experimental tube bulging test is simulated using the Ls-Dyna FE program and figure 4 illustrates modelling and strain distribution in the bulge area. Table 3 summerizes the key parameters used in this numerical model. This FE simulation gives the numerical pressure variation with maximal bulge height. To evaluate experimental hardening law accuracy, a comparison is done between numerical and experimental pressure versus maximal bulge height law.

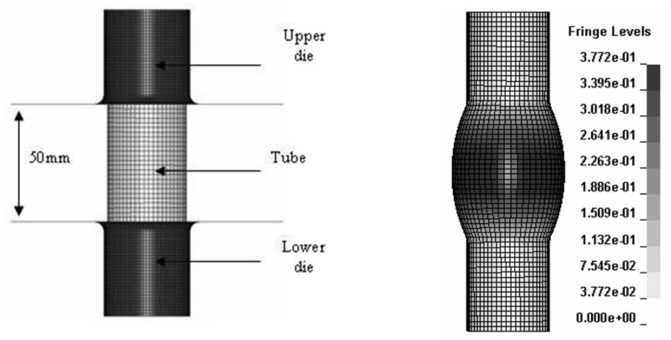

Figure 4: Finite element modelling and strain distribution on the tube

Table 3: Numerical model key parameters

Parameter	Value
Algorithm	Implicit
Number of increments	500
Number of elements	15000
Type of elements	Square thin shell (2x2mm)
Thickness integration points	3
Element formulation	Belytschko-Tsay
Calculation time	6 hours
Material law	Provided by experimental test
Pressure law	Linear from 0 to 345bars
Boundary condition	Upper and lower tube nodes blocked

3 DETERMINATION OF A TUBE HARDENING LAW

3.1 *Methodology*

Figure 5 sum up how the three types of analysis described in first section are used to calculate a tube hardening law and to evaluate its accuracy

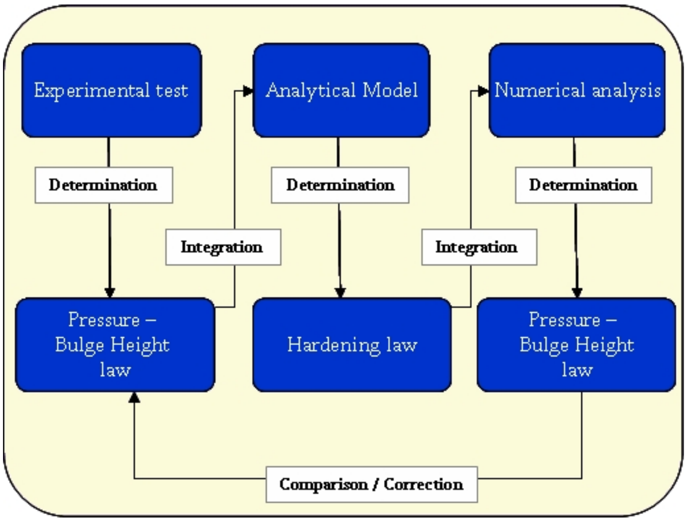

Figure 5: Methodology to determine and evaluate a tube hardening law

3.2 *Application*

This method has been applicated to one type of tube (L=250mm ; d=35mm ; t=1mm) in austenitic stainless steel 316L. Experimental test is leaded until bursting occurs on the tube. Figure 6 shows resultant tube. One can noticed that fracture occurs at a bulge height of 9mm, corresponding to a thickness reduction of 38% and a plastic strain of 50%.

Figure 6: Bulged tube with bursting

Figure 7 gives the corresponding hardening law, calculated using analytical modelling. The material is supposed to be isotropic in this case. This major assumption is discussed in conclusion.

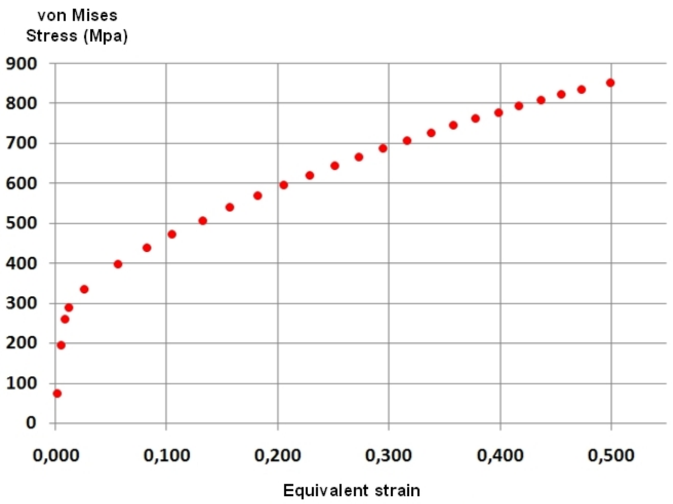

Figure 7: Experimental tube hardening law

This material law is used to simulate tube bulging. A comparison between numerical and experimental pressure variation with bulge height (figure 8) permits to evaluate accuracy of the hardening law.

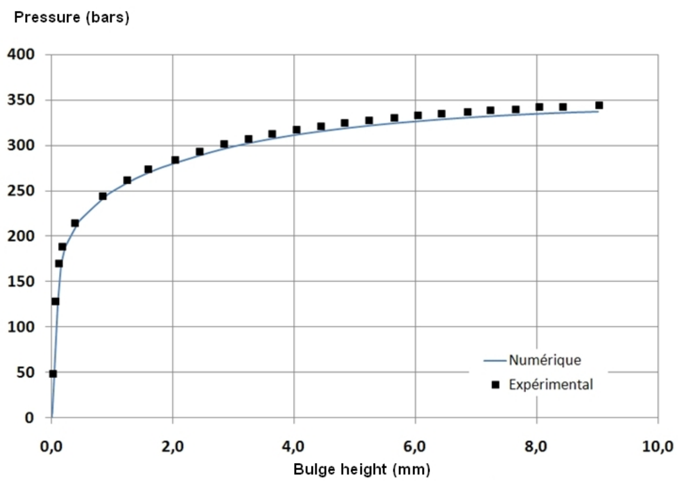

Figure 8: Experimental and numerical pressure variation with bulge height

A deviation of 2% is noticed on the numerical bursting pressure (Experimental bursting pressure : 34.5MPa / Numerical bursting pressure : 33.8MPa) which allows to consider that the experimental hardening law determine with this methodology is accurate to properly describe this material behaviour. Moreover, this method permits to validate the relevance of one major analytical assumption : the tube is supposed to deforme in arcs of circumference in the bulge area. Figure 9 shows the three bulge profiles. Experimental and numerical ones are very close, and a maximal deviation of 2% is noticed between analytical profile and the two others in a relevant area defined by [Z=-15mm ; Z=15mm].

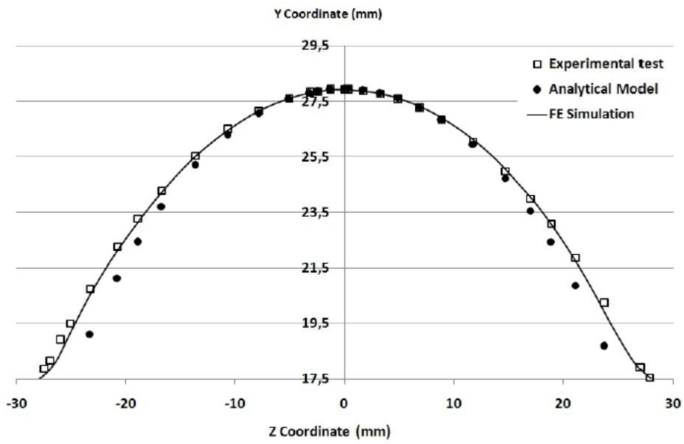

Figure 9: Experimental, analytical and numerical bulge profile

4 CONCLUSIONS

This paper has developped an original method to determine an accurate tube hardening law. Limitations of this analytical model is presently evaluated by running FE simulations with different bulge area length. Moreover, tube anistropic behaviour is investigated to improve material modelling in the analytical model, as drawing processes to manufacture seamless tubes modifies certainly natural behaviour of the material.

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