DEFORMATION OF THIN-WALLED CIRCULAR TUBE SUBJECTED TO IMPACT THEREE-POINT BENDING BY USING NUMERICAL SIMULATION

NGHIÊN CỨU BIẾN DẠNG CỦA ỐNG TRÒN THÀNH MỎNG CHỊU TẢI VA ĐẬP UỐN BA ĐIỂM BẰNG MÔ PHỎNG SỐ

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Abstract: *Crashworthiness is one of the most important criteria in the design of piping systems, suspension pipes in particular or energy absorbers in general. The objective of this paper is to study the deformation of thin-walled tube subjected to impact three-point bending using numerical simulation. Results are agreed very well with theoretical and experimental results. Based on the finite element modeling, deformation of thin-walled tube is presented when the diameter and spacing of two supporters change. Limited ratio of diameter and thickness is clarified to prevent overall bending in designing circular tube.*

Keywords: *Crashworthiness, circular tube, impact, three-point bending, simulation.*

Classification number: *2.4*

Tóm tắt: *An toàn khi va chạm luôn được xem là một trong những tiêu chí quan trọng của thiết kế các hệ thống ống dẫn, ống treo nói riêng hay những thiết bị hấp thụ năng lượng nói chung. Nội dung chính của bài báo này là nghiên cứu ứng xử biến dạng của ống tròn thành mỏng chịu tải va đập uốn ba điểm bằng phương pháp mô phỏng số. Kết quả mô phỏng bằng phương pháp phần tử hữu hạn đúng so với tính toán bằng lý thuyết và cả thực nghiệm. Biến dạng của ống tròn thành mỏng được trình bày với các giá trị khác nhau của đường kính và khoảng cách của hai gối đỡ. Tỷ số giới hạn giữa đường kính ống và bề dày được tìm thấy để tránh hiện tượng uốn toàn cục khi ống tròn chịu tải va đập ngang.*

Từ khóa: *Va chạm, ống tròn, uốn ba điểm, mô phỏng.*

Chỉ số phân loại: *2.4*

1. Introduction

Crashworthiness is always one of the most important criteria in design. Crashworthiness is defined a deformation in controlled manners without failure of structure. In this point of view, behaviour of thin - walled circular tube subjected to bending impact load by numerical method using LS - DYNA is presented in this paper. Crushing force and displacement at impact position are considered.

In this paper, behaviour of circular tube is analyzed based on three-point bending theory that is developed by Wierzbicky [1]. The energy from impactor is absorbed entirely by the formation of hinge lines that cause deformation on the tube. The deformation of the tube is divided into distinct zones of compression and tension.

Energy equilibrium equation is applied to obtain solutions for specific parameters such as mean crushing force, instantaneous crushing force as well as bending moment.

$$E_{ext} = E_{\text{int}} \text{ and } \dot{E}_{ext} = \dot{E}_{\text{int}} \qquad (1)$$

$$\dot{E}_{ext} = P \times \dot{\delta} \text{ and } \dot{E}_{\text{int}} = \sum \dot{E}_l \qquad (2)$$

With:

E_{ext}: Energy of impactor;

E_{int}: Energy absorbed of tube;

E_l : Energy absorbed by folds;

P: Instantaneous force;

$\dot{\delta}$: Displacement.

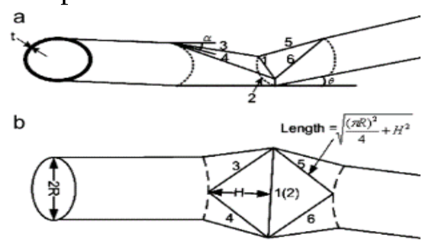

***Fig.1**. Theoretical deformation of circular tube [2],[3].*

During impact, the total energy from the impactor is absorbed by the displacement of the hinge lines as shown in figure 1 and displacement of hinge lines are listed in table 1. Energy absorbed of tube, E_{int}, is calculated by sum of the energy generated by the movement of hinge lines.

Rate of energy dissipation for each hinge line:

$$\dot{E}_1 = M_0 \pi R \dot{\alpha} \tag{3}$$

$$\dot{E}_2 = M_0 \pi R \dot{\theta} \tag{4}$$

$$\dot{E}_3 = M_0 \sqrt{\frac{\left(\pi^2 R^2\right)}{4} + H^2}\,\dot{\gamma} \tag{5}$$

$$\dot{E}_{\text{int}} = \dot{E}_1 + \dot{E}_2 + 4\dot{E}_3 \tag{6}$$

Table 1. *Displacement of hinge lines.*

Hinge Line	Rotational rates	Lengths
Line 1	$\dot{\alpha}$	πR
Line 2	$\dot{\theta}$	πR
Line 3	$\dot{\gamma}$	$\sqrt{\frac{(\pi R)^2}{4} + H^2}$

Instantaneous crushing force $P(\alpha)$, mean crushing force P_m and bending moment $M(\theta)$ are obtained by substituting the above equations into equation (1) and (2).

$$P(\alpha) = M_0 \left(\frac{\pi R}{2H\alpha} + \frac{\pi}{1.63} + \sqrt{\left(\frac{\pi^2 H^2}{4} + H^2\right)} \left(\frac{1}{1.63R\alpha}\right) \right) \tag{7}$$

With:

$M_0 = \sigma_0 t^2 / 4$: Yield moment per unit length,

$\sigma_0 = 0.92\sigma_u$: Flow stress of tube's material,

H: Half length,

α: Folding angle.

Integrate equation (7) over α to find the value of mean force P_m

$$P_m = M_0 \left(0.5\pi R + 476H + 0.61\frac{H}{R}\sqrt{H^2 + 2.47R^2}\right) \tag{8}$$

And then the bending moment $M(\theta)$

$$M(\theta) = M_0 \left(1.76 \left(\frac{R^{\frac{5}{4}}}{t^{\frac{1}{4}}} \right) \left(\frac{1}{\sqrt{\theta}} \right) + 3.15 + \sqrt{2R + 1.36t}\,(Rt)^{\frac{1}{4}} \left(\frac{1}{\theta} \right) \right) \tag{9}$$

2. Finite element model

The finite element model shown in figure 2 is developed based on the three-point bending model. The dimension of the circular tube is the same as the sample in Mamalis [4] to provide a comparison with empirical result. In which:

- Outer diameter D = 30 mm;
- Thickness t = 1.4 mmp;
- Length L = 200 mm;
- Impactor and supporter radius are 5 mm;
- Distance between 2 supporters L_{sup} = 160 mm.

Numerical simulation is performed with constraint on 6 degrees of freedom for the 2 stoppers and 5 degrees of freedom for the impactor, which is only allowed to move vertically. Belytschko-Tsay four-node shell element are used with size of element to be 2.5 x 2.5 mm for whole specimen. Material properties (stainless steel 316CW) of the tubes are chosen to match with experiment in Mamalis [4] are presented in table 2. With:

σ_y: Yield stress;

σ_u: Ultimate stress;

E: Young's modulus;

ν: Poison ration.

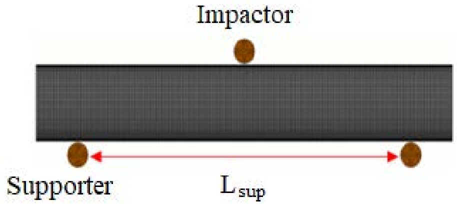

Fig.2. *Model of three-point bending.*

Table 2. *Material properties of stainless steel* 316CW [4], [5].

σ_y (MPa)	σ_u (MPa)	E (GPa)	ν
420	950	207	0.3

3. Simulation results

In bending problem, crushing force and displacement at impact loaded position on the tube need to be understand well. Results of numerical simulation are compared with experimental results in Mamalis [4] and analytical results in Yucheng Liu [2].

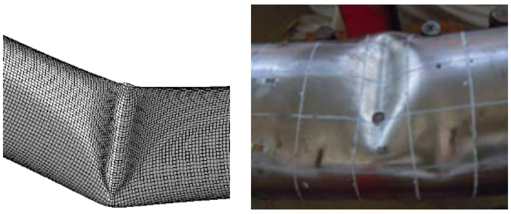

Fig.3. *Deformation in simulation and in experiment.*

Qualitative comparison of deformation in numerical simulation and experiment is presented in figure 3. Numerical simulation of instantaneous crushing force, which is shown in figure 4, is comparable fairy well with experimental results in Mamalis [4]. Several value of friction coefficients between impactor and tube, between tube and two supporters are plotted in figure 4 to clarify the effect of friction to numerical results. It is proved that this effect is not much if the displacement at impact loaded position on the tube rather small. Mean crushing force obtained from numerical simulation shown in figure 5 has good agreement with analytical result. Therefore, it can be convinced that the numerical model in this study is reliable.

According to simulation as well as experiment, deformation process of circular tube consists of three sequential phases. In phase 1, the tube is dented at contacting surface without bending the bottom surface. In consequence, the force rises up. In phase 2, stress increases and approaches to yield stress while denting goes on and the tube starts to bend. At this time, the force is almost saturated at the peak. After that, the tube is totally bent and the force drops rapidly corresponding to phase 3.

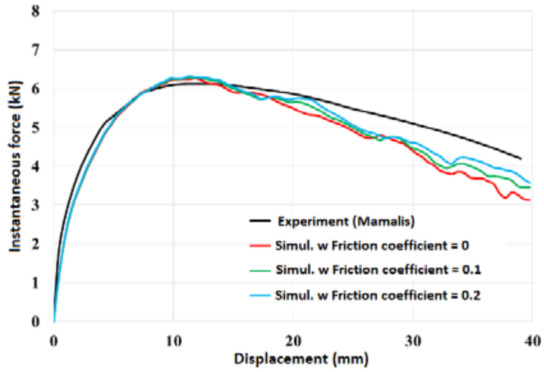

Fig. 4. *Comparison of instantaneous force between simulation and experiment.*

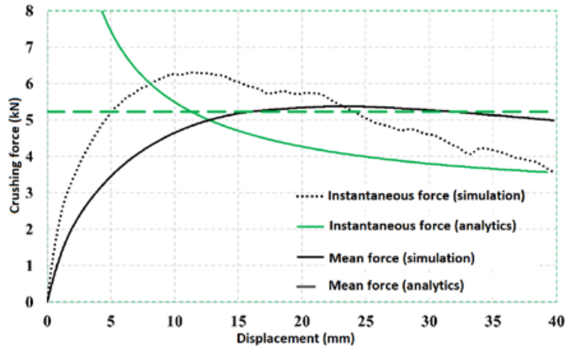

Fig.5. *Comparison of crushing force between simulation and analytics.*

4. Deformation of cross-section at impacted position

In industry, circular tube is widely used in piping systems. Hence, the tube section is an important factor need to be considered during impact. In this section, the pipe cross section is investigated by changing the pipe diameter parameters based on the standard dimensions in application.

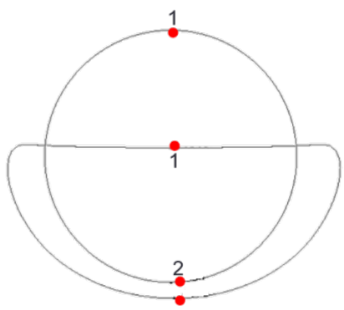

Fig.6. *Location of calculation node.*

Finite element model has the same dimensions as the previous section. The impactor is applied mass of 40 kg and velocity of 10 m/s to get the initial kinetic energy. The thickness of 2 mm is maintained for all of circular tubes which have different diameters. The results are expressed by the displacement of the impactor, Node 1 (the node at impact position) and Node 2 (the node at the bottom of the tube as shown in figure 6. Some typical results of deformation behaviour with different values of D/t and distance between two supporters are shown in figure 7. When the diameter increases and the thickness is kept constant, the tube is less dented. The deformation process is divided into 3 phases as mentioned in part 3. The bending phase does not happen as the diameter increases because the energy of the load has been absorbed entirely by the first denting phase. At that time, the displacement is only due to denting behaviour without bending. When D/t is about 135, displacement starts to increase. That value is considered the limit in designing circular tube to prevent overall bending. Besides, L_{sup} = 2000÷4500 mm are all calculated similarly to the case of L_{sup} = 2000 mm and each of them has its own limited D/t value, which tents to rise following the increase of L_{sup}.

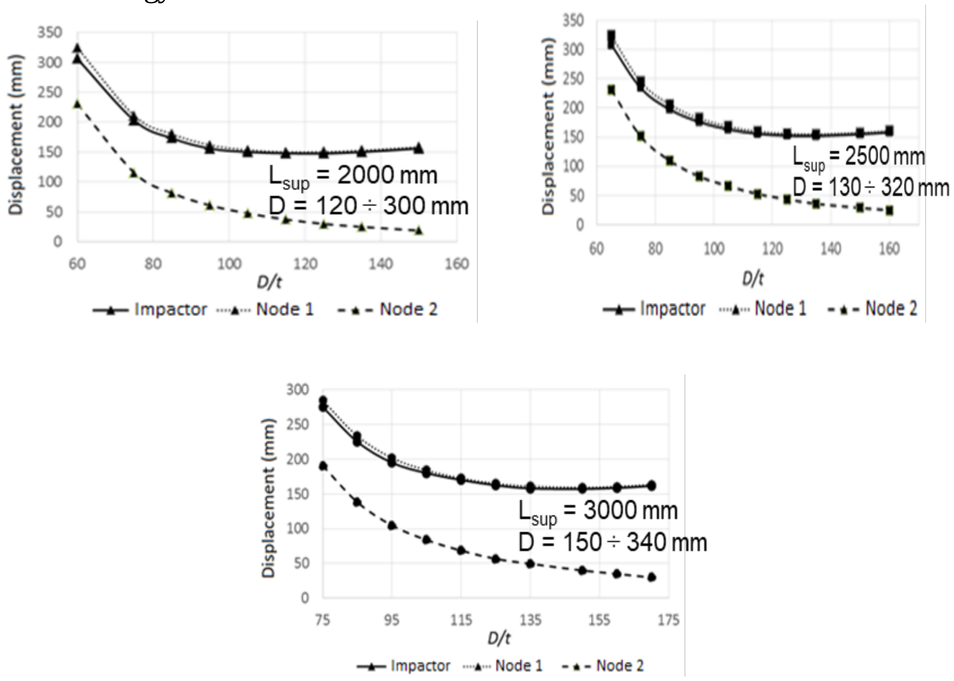

Fig.7. *Displacement study with different D/t ratio and L_{sup}.*

Figure 8 provides a good estimation capability for designing supporters for piping system in industry, which helps reduce time for preliminary design.

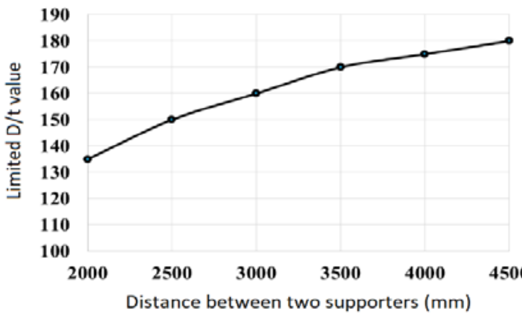

Fig.8. *Limited value of D/t with distance between two supporters.*

5. Conclusion

This paper presents bending behavior of thin-walled circular tube used widely in industry. Simulation results have good agreement with theoretical and empirical results. Tubes with increasing diameter and constant thickness are less dented; however, this is only true for a limited D/t value. Given the distances of the two stoppers, the limited value of the D/t is identified.

These results support more detailed understanding of three-point bending behavior and contribute practically for industry using circular piping system ❑

Acknowledgement

This work was supported in part by Ho Chi Minh City University of Technology – VNU-HCM under Grant T-KTGT-2017-58.

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Ngày nhận bài: 8/10/2018
Ngày chuyển phản biện: 12/10/2018
Ngày hoàn thành sửa bài: 1/11/2018
Ngày chấp nhận đăng: 9/11/2018