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Implementing ALD in Product Development: The Effect of Geometrical Dimensions on Tubular Member Deformation

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Abstract**—**The product development process has undergone many changes concomitant with world progress in order to produce products that meet customer needs quickly and inexpensively. Analysis-Led Design (ALD) is one of the latest methods in the product development process. It focuses more on up-front engineering, a product quality optimization process that starts early in the conceptual design stage. Product development and manufacturing through ALD utilizes digital tools extensively for design, analysis and product optimization. This study uses computer-aided design (CAD) and finite element method (FEM) simulation to examine the modes of deformation of tubular members under axial loading. A multiple-combination impact absorption tubular member, referred to as a compress–expand member, is proposed as a substitute for the conventional thin-walled cylindrical tube to be used as a vehicle's crash box. The study of deformation modes is crucial for evaluating the geometrical dimension limits by which a member can absorb energy efficiently.

Keywords**—**Analysis-led design, axial collapse, tubular member, finite element method, thin-walled cylindrical tube, compress-expand member, deformation modes.

I. Introduction

A. Analysis-Led Design (ALD)

PRODUCT development is a thorough process that requires a huge amount of resources to be channeled throughout in order to obtain a fully functional, well-developed product. It consists of brainstorming the general concept of the product and deciding its function, design and methods of manufacture, as well as its marketing method. A good product must fulfill several characteristics such as being able to function efficiently, being of very high quality, and most importantly being able to satisfy the customers' needs.

However, in reality, complaints about a product do occur frequently. Several factors trigger the complaints. For example, the functions of a product may not match the needs expected by the market, or the functions provided by a product may not be fully utilized as a result of the changing market environment. Thus a technology's aims are sometimes not translated well into consumer demands, and the product produced may lack the robustness it needs in the market.

To probe the roots of these problems and find a solution, it is necessary to retrace each step in the process taken to develop the product. Most manufacturing methods used nowadays are of the problem-solving and recurrence prevention or improvement type. Fig. 1 depicts this product manufacturing process. In this method, before the product is mass manufactured, a prototype is subjected to a series of trial production and testing to detect any glitches or malfunction. This trial-and-error process is conducted continuously until the product's design is altered to achieve best performance. After the product is mass produced and enters the market, the same problem-solving cycle is adopted to solve any troubles that emerge. Some information from the market is fed back to the development and manufacturing stage to improve product performance and prevent the recurrence of common problems in the future.

However, upon entering the 21st century, the inadequacies of this conventional method became clear due to the enormous cost and time required to finally meet the customers' satisfaction. A new production method called Analysis-Led Design (ALD) has been proposed to cut the cost and time needed to respond to customers' demands. In the problem solving and recurrence prevention type of production, a product depends on the results of trial-and-error cycles and feedback in order to detect problems and supply any solutions or improvements. ALD adopts an active and advanced approach to respond to customers' demands. Rather than acting only when the problems occur, it considers every possible problem and solves them in advance, early in the product development stage.

As shown in Fig. 2, ALD utilizes up-front engineering, concentrating most of the resources (almost 70%) at the initial conceptual design stage of product development. At this stage, the physical and concrete models of the product are yet to be developed. Using ALD, the concept, technological features, theory and mechanism of how the product would eventually perform are extensively studied and clarified. Without the product's physical constraints, there is a higher degree of freedom to determine the possibilities of the product, and a wider dimension to detect any unprecedented problems that could happen to it. Through ALD, any possible problems are addressed and solved before the product has its physical design.

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Therefore, it reduces the probability of design alteration after a detailed design process. This not only cuts development costs and time, but also improves the product quality.

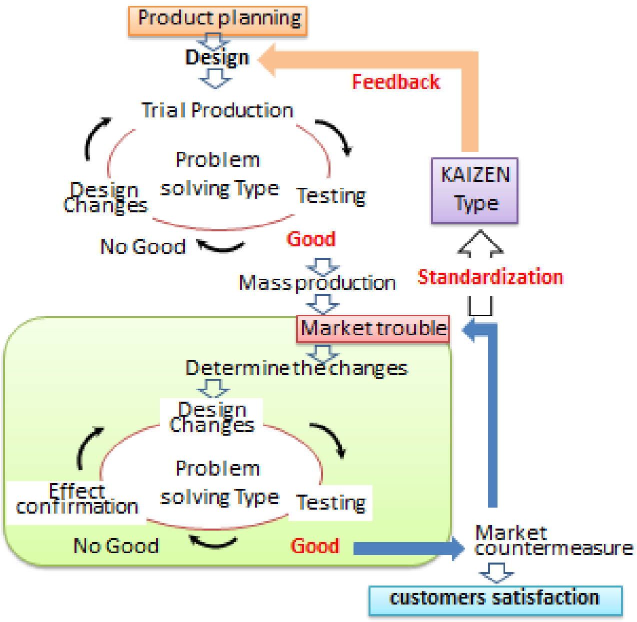

Fig. 1 Manufacturing Process Flow

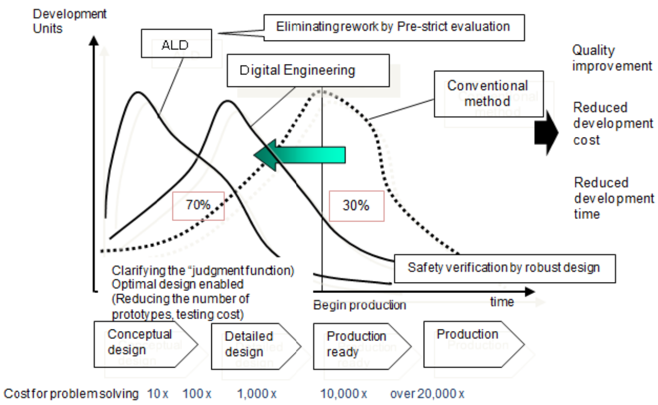

Fig. 2 Up-front Engineering through ALD

Generally, to conduct an extensive analysis on a product, the product needs to be modeled and tested continuously. In the conventional method, a physical prototype of the product is built and subjected to several physical experiments. This requires a great deal of resources. Through the ALD method, modeling through computer-aided design (CAD) and analysis through numerical simulation such as the finite element method (FEM) are used extensively. The use CAD software to create an imaginary model of a product and numerical simulation software to conduct product analysis eliminates the need to create physical prototypes or to set up difficult experiments.

The ALD framework shown in Fig. 3 illustrates several aspects that are essential to fully adopt the ALD method in the product development and manufacturing process. The ALD method requires both business management and technology management to embrace the most current digital technology available. In terms of engineering, digital design tools such as 3D-CAD and FEM simulation software play a major role in product development through ALD. This paper attempts to utilize these tools to develop a vehicle crash box from the proposed tubular member components. A three-dimensional digital model of the components is created and their behavior is simulated using simulation tools. The results obtained are intended to serve as a guideline for further development of the components.

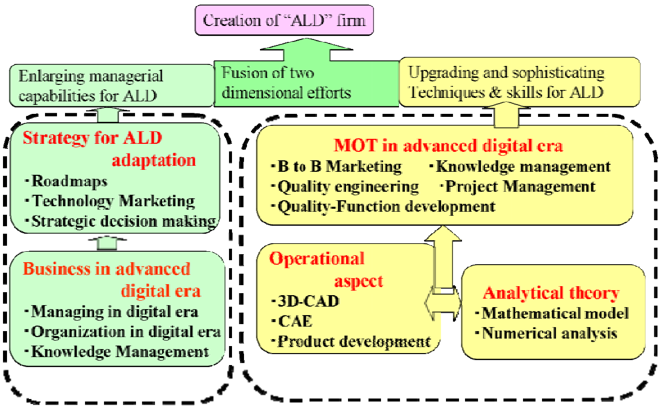

Fig. 3 ALD Framework

B. The Crash Box

Vehicle safety features are becoming increasingly important part in modern vehicle design. Recent trends show that apart from financial factors, consumers also consider the safety features when choosing a vehicle. In view of these trends, car makers have also invested many resources to improve and install safety features on their cars, such as hindrance detectors, automatic braking systems and other electronic safety control systems.

However, in the history of car production, improving the ability of car structures to withstand impacts and crashes has always been the main safety priority. Numerous studies on the strength of structures against impacts, especially in the field of the static and dynamic response of structures in the plastic range, have been conducted to better understand the failure modes and energy absorption characteristics during impacts. The results of these studies are now available for practical use in a wide variety of situations such as the crashworthiness of vehicles and the safety of offshore and bridge structures. In the automobile industry, one important application of these studies is the crash box. The crash box or energy absorber is a system that converts kinetic energy into another form of energy. It is commonly installed in the front and rear ends of a car's structure to protect passengers as well as the structure during a head-on collision. It absorbs impact energy from the compressive forces needed to deform it; hence, it reduces the deformation of the car's structure, which maintains the passengers' safety space and prevents the impact force from being directly transmitted to the passengers. Until recently, various thin-walled tubular structures have been proposed as the crash box [1], [2], [5]-[14].

Cylindrical tubes are the most common thin-walled tubular structures to be used as the crash box. When applied with axial load, most cylindrical tubes would collapse into two primary modes; the progressive axial collapse and global bending. In the progressive axial collapse, cylindrical tubes developed local buckling that produced a series of folds as the tubes deformed. Energy applied to the tube is converted into strain energy from the continuous bending and expanding deformation of the plastic hinges of local buckles that form during the axial crushing process [1]. During this process, high first-peak loads and load fluctuations with large amplitude were observed in the load-deformation relationship (see Fig. 5 (a)), which corresponds to the bellow-shaped deformation (denoted as 'stable' in Fig. 4) caused by the continuous formation of folds. In the global bending collapse, Euler buckling occurred as the crushing took place. Load decreased rapidly after the tubes bent (see Fig. 5 (b)), which corresponds to the bellow-shaped deformation (denoted as 'unstable' in Fig. 4). Studies before found that the transition between progressive axial collapse and global bending depends on the tube dimensions, material properties, strain hardening and strain rate. Extensive studies of these factors allowed better understanding of tube behavior that would eventually help designers to determine the optimum performance of the tube.

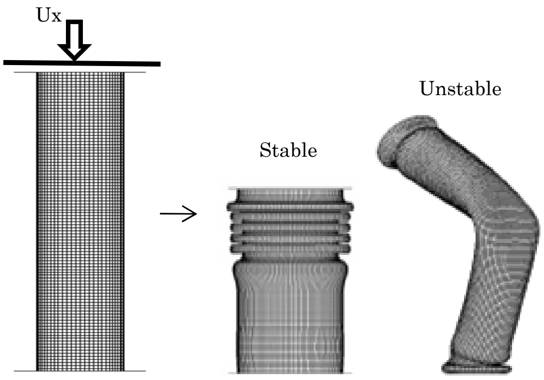

Fig. 4 Cylindrical Tube Deformation Modes

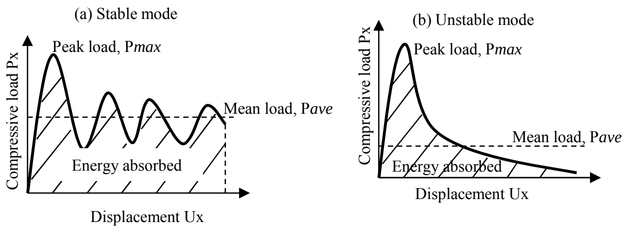

Fig. 5 Load-Displacement Curves for the Deformation Modes of Cylindrical Tubes

C. Compress-Expand Member

Many problems that relate to buckling such as instability, presence of load fluctuation, and poor efficiency in energy absorption have affected the performance of cylindrical tubes. Moreover, most cylindrical tubes have difficulty withstanding large loads in a small diameter because reducing the radius would lead to bending failure (denoted as 'unstable' in Fig. 4); while increasing the thickness would make local buckling more difficult. This limits the dimensions within which cylindrical tubes can deform in 'stable' mode. As shown by the load-displacement curve in Fig. 5, ensuring the tubes deform in 'stable' mode is very important in order to absorb a large amount of impact energy.

This study proposes a multiple-combination impact absorption tubular member, referred to as compress–expand member [3], [4], as shown in Fig. 6. It uses compression and expansion as its energy absorption mechanism. In this study, an axial crushing simulation using FEM was conducted on the proposed compress–expand member. Deformation results obtained from the crushing simulation were then used to plot the distribution of the deformation modes of the proposed member.

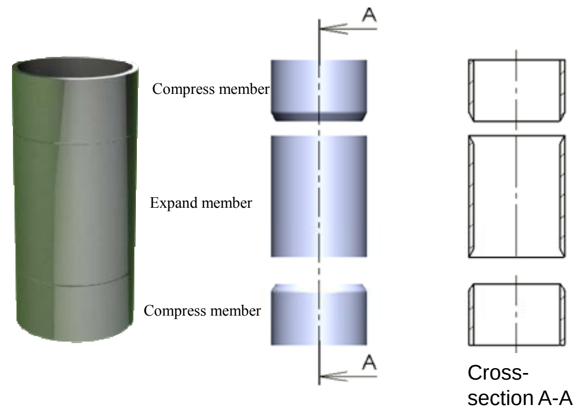

Fig. 6 Compress-Expand Member

II. Analysis and Results

A. Analysis Method

In this study, MSC Marc, a general purpose FEM solver, was used to conduct the axial crushing simulation of the compress–expand member as shown in Fig. 7. The analysis used an 8-node, isoparametric, arbitrary hexahedral solid element to model the compress–expand member. The material was assumed to have the properties of steel and be an isotropic body obeying the Von Mises yield criterion. Next, the relationship between stress, σ, and strain, ε, in the uniaxial stress state of the material during the post-yield (plastic) period was represented using the bilinear hardening law in (1). Here, stress, σ, is the function of yield stress $\sigma y = 205.9$ MPa, strain, ε, work hardening coefficient, Eh (Eh/E=1/20, 1/100, 1/200), and Young's modulus, E=206 GPa, Poisson's ratio of the material is set to ν=0.3.

For the boundary condition, the member's bottom is fixed to a rigid surface while at the top; crush surface defined with displacement control in the axial direction will compress the member. In this case, the coefficient of friction is set to 0.3. In addition, a glue function is used to create the rigid surface and keep the member's top fully restrained during contact. Further, the analysis of large plastic deformation in this study uses the updated Lagrange formulation for the nonlinear deformation behavior, and the Newton-Raphson method for solving nonlinear equations.

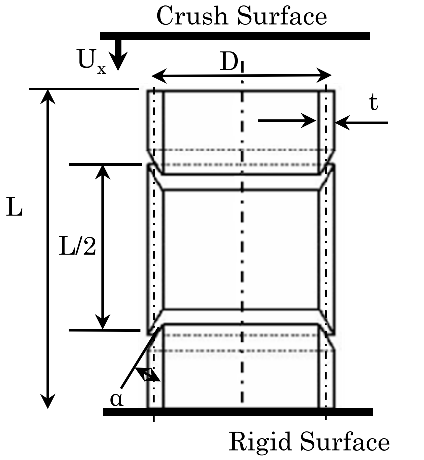

Fig. 7 Model Geometry and Loading Condition
Note. L=length, t=thickness, R=radius, α=contact angle (30°)

$$\sigma = \sigma_y + E_h\left(\varepsilon - \frac{\sigma_y}{E}\right), \quad \varepsilon \geq \sigma_y/E \qquad (1)$$

B. Results

1. Investigation of Deformation Modes

The axial crushing simulation of the compress–expand member was conducted to a number of models with geometrical parameters as follows: thickness, t=1mm; diameter, D=10-50mm; length, L=25-625mm; and work-hardening coefficient ratio, Eh/E=1/20, 1/100 and 1/200. Deformation modes obtained were then plotted on a normalized dimension axis of diameter-thickness ratio, D/t, versus length-diameter ratio, L/D. Members that collapsed perfectly in the axial direction were denoted as ‘stable’, whereas members that developed global bending (Euler buckling) were denoted as ‘unstable’.

Fig. 8 shows the compress-expand member deformation modes and Figs. 9-11 show the distribution map of these modes. As shown in Fig. 9, a larger L/D brings a transition from the stable mode to unstable mode. However, the L/D value needed for a transition to the unstable mode rises gradually with an increase in the D/t value. From one perspective, this means that a larger length with smaller diameter increases the probability of members to develop global bending. However, it can be improved through increasing the diameter or reducing the thickness parameters. Further, as shown in Figs. 10 and 11, reducing work hardening coefficient ratio too can improve compress-expand member deformation to stable mode.

These distribution maps are very useful as they indicate the geometrical dimension limits for a stable deforming mode to takes place, which will in some degree provide some guidelines for the proposed compress–expand member designing process.

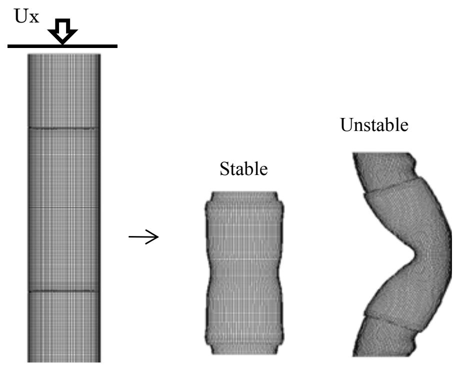

Fig. 8 Compress-Expand Member Deformation Modes

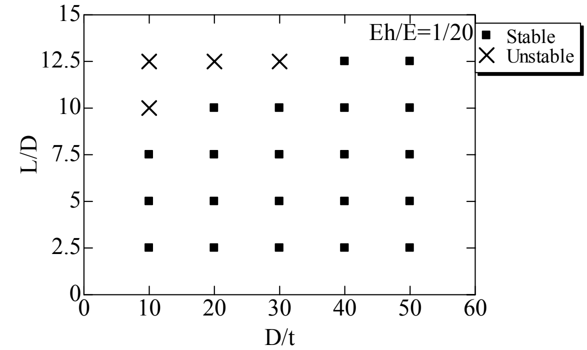

Fig. 9 Distribution Map of Compress–Expand Member Tube Deformation Modes (E_h/E=1/20)

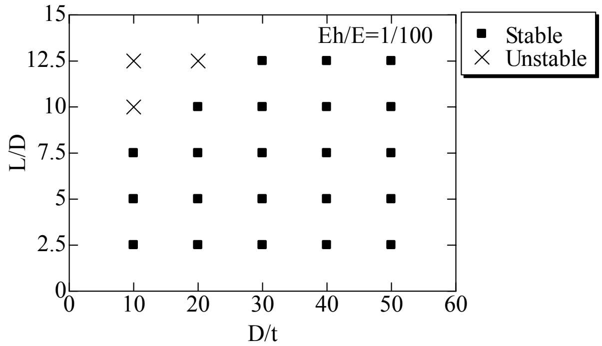

Fig. 10 Distribution Map of Compress–Expand Member Tube Deformation Modes (E_h/E=1/100)

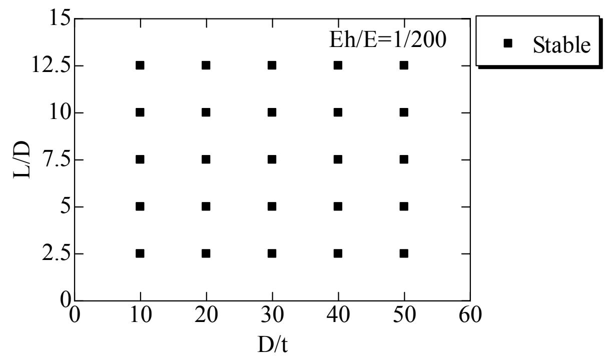

Fig. 11 Distribution Map of Compress–Expand Member Tube Deformation Modes (E_h/E=1/200)

2. Comparison with Cylindrical Tubes

For this analysis, we compared the deformation modes for compress-expand members and cylindrical tubes with work hardening coefficient ratio, Eh/E=1/20. Fig. 12 shows the modes distribution map of cylindrical tube. Tubes that collapsed perfectly in the axial direction were denoted as 'stable', whereas tubes that developed global bending (Euler buckling) were denoted as 'unstable'.

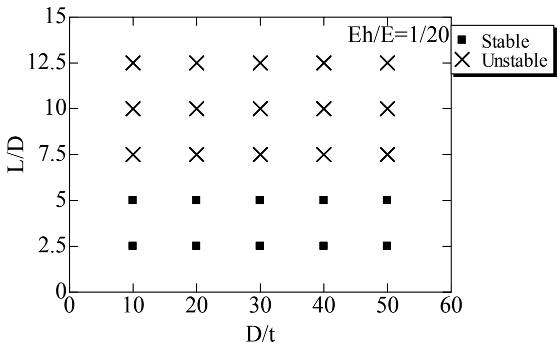

Fig. 12 Distribution Map of Cylindrical Tube Deformation Modes

Comparing this with Fig. 9, it was noted that the proposed compress–expand member covers a wider geometrical dimension, which allows stable mode to take place than the cylindrical tube.

III. Conclusions

In this study, the deformation modes of the proposed compress–expand members were investigated by numerical simulation using FEM. The following conclusions were reached:

1) The transition of compress–expand member deformation modes can be manipulated by changing the member's geometrical parameters and material properties. Increasing the L/D ratio to a certain value can cause a transition from the stable mode to unstable mode. However the limit value of L/D that turns the deformation modes from 'stable' to 'unstable' can be increased by increasing the D/t ratio. Materials with smaller work hardening coefficient improve the deformation of the compress-expand member to stable mode.
2) The compress–expand member has a wider geometrical dimension that allows 'stable' mode deformation to take place in comparison to the cylindrical tube. This allows a greater variety of options in the geometrical dimension when designing the compress-expand member as a crash box.

This study has demonstrated the role of digital tools in product development that is emphasized in the ALD method. The numerical simulations conducted highlighted the advantages of the compress-expand member in terms of shorter time and lower costs, which facilitate an efficient product development process.

Acknowledgment

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References

[1] Alexander J. M. An Approximate Analysis of the Collapse of Thin Cylindrical Shells under Axial Loading, Quarterly Journal of Mechanics and Applied Mathematics, 1960, 13 (1): 10-15.
[2] Wierbicki T. et al. Alexander Revisited: A Two Folding Elements Model of Progressive Crushing of Tubes, International Journal of Solids and Structures, 1992, 29(24): 3289-3295.
[3] Haruyama S., Tanaka H., Chen D., Aidil Khaidir B. M. Study on the Deformation Modes of Axially Crushed Compact Impact Absorption Member, World Academy of Science, Engineering and Technology, 2012, 66(225): 1222–1230.
[4] Haruyama S., Tanaka H., Chen D., Aidil Khaidir B. M. Axially Crushed Characteristics of Compact Impact Absorption Member, Proceedings of the 8th International Conference on Innovation & Management, 2011, 1047–1051.
[5] Abramowicz W., Jones N. Dynamic Axial Crushing of Circular Tubes, International Journal of Impact Engineering, 1984, 2(3): 263–281.
[6] Abramowicz W., Jones N. Dynamic Progressive Buckling of Circular and Square Tubes, International Journal of Impact Engineering, 1986, 4(4): 243–270.
[7] Chen D-H, Masuda K. Deformation Modes for Axial Crushing of Cylindrical Tubes Considered of the Edge Effect, Transactions of the Japan Society of Mechanical Engineers, 2007, 73(773): 1029–1036 (in Japanese).
[8] Chen D-H, Hiratsuka T. Study of Axially Crushed Cylindrical Tubes with Corrugated Surface Based on Numerical Analysis, Transactions of the Japan Society of Mechanical Engineers, 2006, 72(722): 1464–1471 (in Japanese).
[9] Chen D-H. et al. Crushing Behaviour of Hexagonal Thin-Walled Tube with Partition Plates, Transactions of the Japan Society of Mechanical Engineers, 2006, 72(724): 1978–1984 (in Japanese).
[10] Hiratsuka T., Chen D-H., Ushijima K. Axially Compression of Corrugated Cylinder, The Society of Automotive Engineers of Japan, Paper No. 20055304.
[11] Ushijima K., Haruyama S., Hanawa H., Chen D-H. Strain Concentration for Cylindrical Tubes subjected to Axial Compression, Transactions of the Japan Society of Mechanical Engineers, 2005, 71, (707): 1023–1029 (in Japanese).
[12] Ushijima K., Haruyama S. et al. Study on Axially Crushed Cylindrical Tubes with Grooved Surface, Transactions of the Japan Society of Mechanical Engineers, 2005, 71(707): 1015–1022 (in Japanese).
[13] Ushijima K., Haruyama S. et al. Strain Concentration for Cylindrical Tubes Subjected to Axial Compression, Transactions of the Japan Society of Mechanical Engineers, 2005, 71(707): 1023–1029 (in Japanese).
[14] Wierzbicki T., Bhat S. U., Abramowicz W., Brodkin D. Alexander Revisited: A Two Folding Elements Model of Progressive Crushing of Tubes, International Journal of Solids and Structures, 1992, 29(24): 3269–3288.