New Concept of Engineering Design for Folding Structures

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1. Introduction

Recently, Holnicki *et al.*[1)] designed an active shock-absorber system from which one of the collaborators suggested the concept of a pantograph truss as the concept of *the Multi-Folding Microstructure*(MFM). We have successfully carried out control experiments on a fundamental framework. To develop this new structure, we must estimate the allowance vanish energy on the multi-folding method or examine the defense of an important structure against impact. There are several different folding patterns on system as a means of controlling the stress of a member and using the folding characteristics, to actively regulate it. In this paper, based on the fundamental concept of MFM, we describe the correspondence of the numeric verification and theoretical method according to the difference with the gaps of asymmetric folds that are folded in fact. Our main objective is to understand the adequate behavior characteristics using the theory of elastic stability and to discover the elasticity of various folding patterns, establishing how to fold, and how to create theoretical interpretations through control experiments. To observe a large-scale deformation of the dynamic behavior, we analyze the equilibrium equation with only geometric nonlinearity for a basic truss model. This paper is presented some interesting mechanism and some results through the multi-folding simulation to develop new structures.

2. Theory of Elastic Folding

In this section, we describe the basic mechanism for the multi-folding structure with geometric nonlinearlity as an absorption system for impact energy.

We assume that the structure is joined by the elastic stiffness EA of two bars with the ratio $\gamma = h/L$ of the height divided by L. However, there is no stress on the members at the initial position. For the theoretic approach of the folding mechanism, we assume that the bar is not buckled and that it is perfectly elastic. The elastic buckling model is well known as a snap-through behavior for 2bar truss.

The energy principle is applied to solve a force, taking into account geometrical nonlinearity based on an elastic stability. In this paper, we think that there is only primary path. While the length of an initial member is shown as ℓ_0, and the length after the deformation is defined as $\hat{\ell}$.

Consider the total potential energy for 2bar truss model in the following:

$$\mathcal{V} = \sum_{i=1}^{2} \frac{EA\ell_0}{2}(\varepsilon_i)^2 - fQ_1L \tag{1}$$

Rewriting **Eq.**1, let us show

$$\mathcal{V} = A_{11}Q_1^2 + A_{111}Q_1^3 + A_{1111}Q_1^4 - fLQ_1 \tag{2}$$

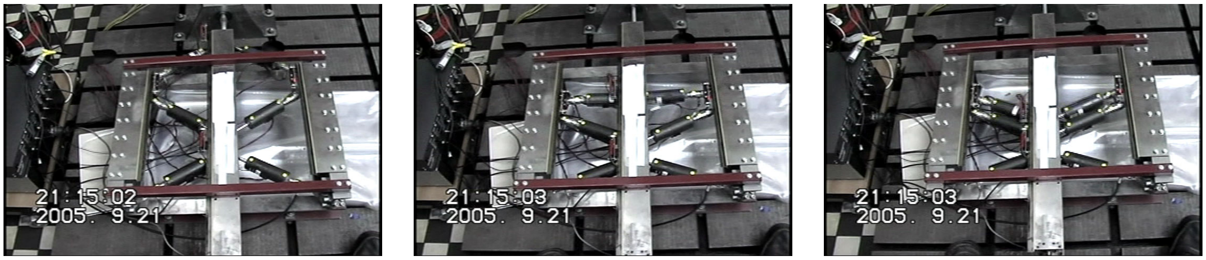
here,

$$A_{11} = \beta L\gamma^2, \quad A_{111} = -\beta L\gamma, \quad A_{1111} = \frac{\beta L}{4}$$

$\beta = EA/(1+\gamma^2)^{3/2}$. Therefore, the non-linear equilibrium equations based on the principle of the minimum potential energy are expressed in the following:

$$\left(\frac{d\mathcal{V}}{dQ_1}\right) = 2A_{11}Q_1 + 3A_{111}Q_1^2 + 4A_{1111}Q_1^3 - fL \tag{3}$$

From Eq.(3), the main equilibrium path is obtained as global folding of the system in the following:



(A) (B) (C)

Fig. 1 Folding process by Holnicki *et al.* experiment in Polish Academy of Sciences

$$f(Q_1) = \frac{2A_{11}Q_1 + 3A_{111}Q_1^2 + 4A_{1111}Q_1^3}{L} \\ = \beta\, Q_1(Q_1 - \gamma)(Q_1 - 2\gamma). \quad \cdots\cdots \quad (4)$$

This equation is primary path for 2bar truss without bifurcation path.

3. Folding process by the experiment

To develop the active control concept for the multi-folding system under impact loads, it has been carried out the real experiment described by Holnicki *et al.* in details. The photoghraphs of the experimental process show in **Fig.**1. Picture (A) is the initial location of structural system. It is possible to move smoothly along the vertical direction for all joints and the top point of the system which there are six same absolvers(stiffness), subjects to the dynamic load. In this paper, to confirm the process of the foldings comparing with numerical results, the process is the picture (A) → (B) → (C) of **Fig.**1.

4. Local and Global Structural Instability

In this model, we have not considered the effects of gravity for all elements. In this idealized model, the rolling hinges supported on the walls don't create any friction problems.

Therefore, it is easy to gain a physical meaning in which there are several equilibrium curves for different deformations from the maximum limit point. Then, this point is called *bifurcation point of the Hill-top type*, the eigenvalue also at this singular point is zero. The

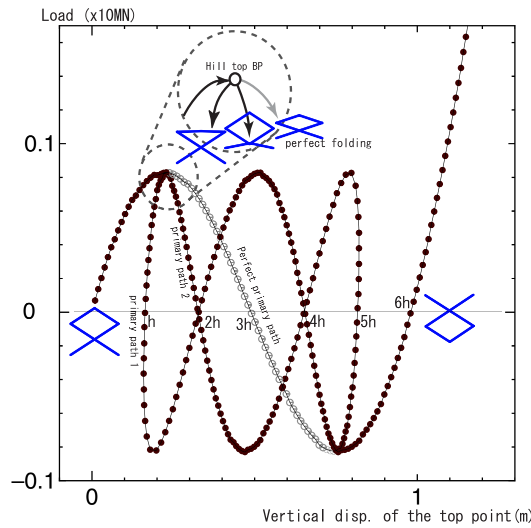


Fig. 2 Static equilibrium curves

primary path goes through zero level of the height $3h$, and the system along this path can also fold perfectly as well. Other static paths of this system are shown as bifurcation paths, such as the deformations at BP in **Fig.**2. At first, the line of less strength after BP is one of bifurcation paths as local buckling, which means local snap-through behavior has occurred at the top couple of members.

Acknowledgment

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Reference

1) J. Holnicki-Szulc, P. Pawlowski and M. Wiklo, High-performance impact absorbing materials - the concept, design tools and applications, *Smart Materials and Structures*, **12** (2003), 461-467.