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SCISSORING ORIGAMI INSPIRED DEPLOYABLE BRIDGE FOR A DISASTER

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Many natural disasters cause not only critical situations for facilities and resident's life, but also significant damage to economy. It is obvious that quick rescue action must be undertaken and that there are many problems due to the occurrence of secondary disasters at rescue work-site. For example, many bridges were damaged by a huge earthquake in 2011 in Japan's Tohoku areas, called the Great East Japan Earthquake. We need to develop a new rescue structure to survive these disasters. We have to consider how to rebuild damaged infrastructures and how to build a new type of rescue system. Therefore, we suggest a new type of emergency bridge, Mobile bridge(MB). In this paper, we discuss the scissors type of bridge in order to evaluate its numerical approach including a reinforced strut and characteristics. Moreover, we analyze the design method of calculation model based on theoretical equilibrium theory based on origami-folding engineering.

Keywords: Origami, Mobile bridge, Emergency bridge, Scissors structure, Rescue system, Strut reinforce.

1 INTRODUCTION

In recent years, natural disasters such as earthquakes, floods and tsunamis have caused widespread social damages. For example, many bridges were damaged by a huge earthquake in 2011 in Japan's Tohoku areas, called The Great East Japan Earthquake. We need to develop a new rescue structure to survive these disasters. We have to consider how to rebuild damaged infrastructures and how to build a new type of rescue system (Ario *et al*. 2011). Therefore, we suggest a new type of emergency bridge, Mobile Bridge(MB), with a scissors structure as shown in Figure 1 (Ario *et al*. 2011). This experimental MB can expand and fold main structural frame, and its characteristic provides rapid construction on site (Ario 2006). However, the MB is a flexible structure because of consisting many number of hinge connection. That is, the MB has an engineering issue such as wind vibration, earthquake shaking. Therefore we consider the strut reinforcement to raise more performance of the MB. In this paper, we suggest strut reinforcement for the MB after the expanding, and try to build a calculation technique. From the result of numerical simulation, we inspect mechanical property of MB by the reinforcement.

Figure 1. Mobilebridge ver 2.0 at CMI.

2 MECHANICS OF SCISSORS STRUCTURE

In this section, it is reviewed mechanics of scissors structure**.** FBD of a unit scissors structure is shown in Figure 2 (Chikahiro *et al*. 2011). When the length of the members is L_0 and the expanding angle of inclination is θ, the sectional length λ and height 2*h* are $L_0\sin\theta=\lambda$ and $L_0\cos\theta=2h$**.** So, the construction and storage of such a structure can be shown by the angle θ.

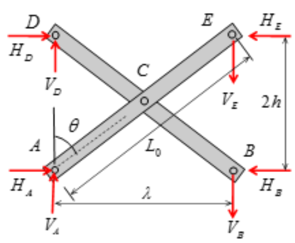


Figure 2. FBD of scissors structure.

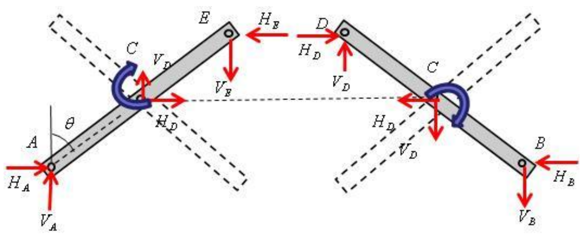


Figure 3**.** Continuity conditions of each member for AE and BD.

This unit scissors structure can be designed by using the equilibrium equations. The equilibrium equations concerning each external force V_A, H_A and V_E, H_E are given as two expressions, and the equilibrium equation of the moment concerning each nodal point from A to D is set up with four expressions, as shown in the following:

$$\sum H = H_A - H_B + H_D - H_E = 0 \tag{1}$$

$$\sum V = V_A - V_B + V_D - V_E = 0 \tag{2}$$

$$\sum M_{at\,A} = (H_D - H_E)2h + (V_B + V_E)\lambda = 0 \tag{3}$$

$$\sum M_{atB} = (H_D - H_E)2h + (V_A + V_D)\lambda = 0 \tag{4}$$

$$\sum M_{atD} = (-H_A + H_B)2h + (V_B + V_E)\lambda = 0 \tag{5}$$

$$\sum M_{atE} = (-H_A + H_B)2h + (V_A + V_D)\lambda = 0 \tag{6}$$

Looking at the members AE and BD that intersect as shown in Figure.3, it is apparent that the equilibrium equations of a couple of moments occur at Point C.

$$\textit{Member}\text{ of }AE:\ M_C = -H_A h + V_A(\lambda/2) = H_E h - V_E(\lambda/2) \tag{7}$$

$$\therefore\ (-H_A - H_E)h + (V_A + V_E)(\lambda/2) = 0$$

$$\textit{Member}\text{ of }DB:\ M_C = H_D h + V_D(\lambda/2) = -H_B h - V_B(\lambda/2) \tag{8}$$

$$\therefore\ (H_B + H_D)h + (V_B + V_D)(\lambda/2) = 0$$

It can be present following matrix by arranging the eight calculated equilibrium equations.

$$\begin{bmatrix} 1 & 0 & -1 & 0 & 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 & 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & \lambda & \lambda & 0 & -2h & \lambda \\ 0 & \lambda & 0 & 0 & 2h & \lambda & -2h & 0 \\ -2h & 0 & 2h & \lambda & 0 & 0 & 0 & \lambda \\ -2h & \lambda & 2h & 0 & 0 & \lambda & 0 & 0 \\ -2h & \lambda & 0 & 0 & 0 & 0 & -2h & \lambda \\ 0 & 0 & 2h & \lambda & 2h & \lambda & 0 & 0 \end{bmatrix} \begin{Bmatrix} H_A \\ V_A \\ H_B \\ V_B \\ H_D \\ V_D \\ H_E \\ V_E \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{9}$$

However, the pivot is set up from the condition of continuity of the member. $2h = L_0\cos\theta$, and $\lambda = L_0\sin\theta$. An unknown reaction force can be solved by thinking about the loading condition and the boundary condition for the equations of equilibrium.

3 MECHANICS OF A TWO-UNIT SCISSORS STRUCTURE

A two-unit scissor structure under the cantilever condition, which includes pinned support at points B^L_1 and A^L_1 and a load P at point A^R_2, as shown in Figure 4 is considered as an example.

In this problem, it is possible to treat the external forces as the left and rights sides of internal forces operating on the hinges at points $B_{1,2}$ and $A_{1,2}$, Hence, these relationships are expressed as,

$$\begin{Bmatrix} (B_{1.2})_x \\ (B_{1.2})_y \\ (A_{1.2})_x \\ (A_{1.2})_y \end{Bmatrix} = \begin{Bmatrix} (B_1^R)_x \\ (B_1^R)_y \\ (A_1^R)_x \\ (A_1^R)_y \end{Bmatrix} + \begin{Bmatrix} (B_2^L)_x \\ (B_2^L)_y \\ (A_2^L)_x \\ (A_2^L)_y \end{Bmatrix} \tag{10}$$

$$\{(B_{1.2}), (A_{1.2})\}^T = \{(B_1^R), (A_1^R)\}^T + \{(B_2^L), (A_2^L)\}^T \tag{11}$$

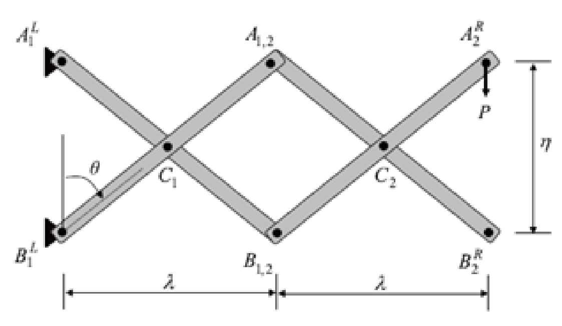


Figure 4. Two-unit cantilever model.

The matrix form for each scissor unit in the two-unit scissor problem can be also obtained by following a procedure similar to the one described for the unit scissor model. The equilibrium equation for the first unit can be expressed as

$$\mathrm{L}\{(B_1^L),(A_1^L)\}^T = -\mathrm{R}\{(B_1^R),(A_1^R)\}^T - \{(C_1,0)\}^T \tag{12}$$

Similarly, the equilibrium equation for the second unit can be expressed as

$$\mathrm{L}\{(A_2^L),(A_2^L)\}^T = -\mathrm{R}\{(A_2^R),(A_2^R)\}^T - \{(C_2,0)\}^T \tag{13}$$

Substituting Eq. (12) and Eq. (13) into Eq. (11) and rearranging them, the matrix form for the two-unit scissor problem under the cantilever condition is obtained:

$$\{(B_1),(A_1)\}^T = -(L^{-1}\mathrm{R})^2\{(B_2),(A_2)\}^T - L^{-1}\mathrm{R}\{(B_{1,2}),(A_{1,2})\}^T - L^{-1}\mathrm{R}L^{-1}\{(C_2,0)\}^T - L^{-1}\{(C_2,0)\}^T \tag{14}$$

By substituting the initial condition of $(A^R{}_2)_y = P$ and the other nodal forces = 0 into Eq. (14), the unknown reaction forces for the two-unit scissor structure can be expressed as $(A^L{}_1)_x = -(B^L{}_1)_x = -2P\tan\theta$ and $(A^L{}_1)_y = P$, $(B^L{}_1)_y = 0$. When the theoretical results for the one-unit and two-unit scissor structures are compared, we can see that the vertical reaction forces are the same, but the horizontal reaction forces are doubled. It is clear that the horizontal reaction forces may become very large if the number of scissor units is increase.

4 MECHANICS OF A N-UNIT SCISSORS STRUCTURE

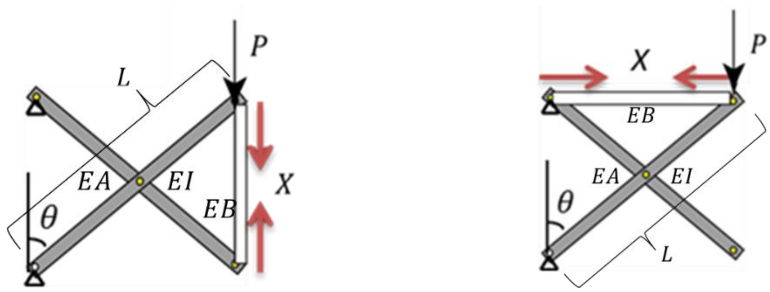
The reaction and section forces for a scissor structure with *n* units can be calculated in a manner similar to that for the two-unit scissor problem. If the relationship between the sectional stresses and the angle θ that acts on each member are considered, we can see that the bending stress that depends on the length of each member is also the predominant sectional stress. From these concepts, it is possible to design a scissor structure simply by considering only the predominant sectional stress, that is, the bending stress.

5 MECHANICS OF A REINFORCED SCISSORS STRUCTURE

5.1 Effect of a Vertical Reinforcement

In this section, the effect of scissors structure with the reinforcement is examined. Although the reinforced scissors structure is statically indeterminate problem, the section forces of scissors structure with the reinforcement also can be solved once statically indeterminate force is solved. Figure 5 (a) shows the scissors structure with vertical member. A unit scissor structure under the cantilever condition, which includes pinned support at left side hinges and a load *P* at upper-right hinge is considered. The section forces of the vertical member have statically indeterminate force *X*. Statically indeterminate force *X* is introduced by the unit load method.

$$\mathrm{X} = -\frac{\sum\int\frac{M_0 M_1}{EI}dx+\sum\frac{N_0 N_1}{EA}\frac{L}{2}}{\sum\int\frac{M_1 M_1}{EI}dx+\sum\frac{N_1 N_1}{EA}\frac{L}{2}+\sum\frac{N_1 N_1}{EA}\frac{L}{2}} \tag{15}$$



(a) Scissors structure with a vertical member (b) Scissors structure with a upper member

Figure 5. A unit scissors structure with a reinforcing member.

Here, P = load, E = Young's modulus, A = cross-sectional area of scissors structure, I = second moment of area of scissors structure, L = length, θ = expanding angle, B = cross-sectional area of reinforcement structure, N_0 = axis force of statically indeterminate, M_0 = bending moment of statically indeterminate, N_1 = axis force of first system, M_1 = bending stress of first system. Statically indeterminate force X of vertical member is

$$X = -\frac{P}{2} + \frac{6Cos\theta}{12Cos\theta+\alpha(12+\beta L^2+(2-\beta L^2)Cos\theta)} \tag{16}$$

where $\beta=A/I$, and we define α parameter of stiffness. $\alpha=EB/EA$. From Eq. (16), a statically indeterminate force X depends on not only the cross-sectional area of scissors structure but also the area of reinforcement structure. Final section forces are obtained by statically indeterminate force X and found by using principle of superposition (17) and (18).

$$N = N_0+N_1X \tag{17}$$

$$\mathrm{M} = M_1+M_1X \tag{18}$$

And, there is a change in comparison with the no reinforced pattern. Bending stress has large change. All bending moment has one member which works load before reinforcement. However, two members have same value of bending moment separately after reinforcement.

5.2 Effect of Upper Reinforcement

An upper reinforced structure is shown in Figure 6(b). Boundary condition and load condition are the same in the previous one. Statically indeterminate force X is introduced by the unit load method.

$$\mathrm{X} = -\frac{\alpha P(-12\gamma+L^2+24\gamma csc^2\frac{\theta}{2})sin\frac{\theta}{2}}{24\gamma cos\theta+\alpha L^2\left(1+cos\frac{\theta}{2}\right)+3\alpha\gamma(7+cos\frac{\theta}{4})csc^2\frac{\theta}{2}} \tag{19}$$

where $\gamma = I/A$. Using two equations (17) and (18), and final section forces are solved. By adding the upper reinforcement, the section forces are decreased. The decrease ratio of the section forces by adding the upper reinforcement is larger than vertical one. Bending moment of work one member is almost disappear and the other member has no bending moment. It leads to support point through a reinforcing structure. First one member is worked all bending moment, parameter α is increased, and suddenly bending stress is decreased and becomes horizontally asymptotic.

6 CONCLUSION

The points which became clear from this research are followed as:

- We introduce the equation from equilibrium of force and moment.
- We can expand equilibrium equations as statically indeterminate problem, and lead statically indeterminate force and sectional forces based on two analytical examples.
- The section forces in a scissor structure can be decreased by the strut reinforcement. Especially, the upper reinforcement is more effective than the vertical reinforcement.
- Reinforcing effect does not so increase even if the stiffness ratio between scissor and strut member is change.

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