A design method for the coupling scissors-type bridge

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1. INTRODUCTION

Natural disasters appeared many centuries ago. It seems the natural disaster impacts are getting worse year by year and becomes one of the challenging issues for our global development. Previously, the flooding in Hiroshima in 2018 and the Higashi-Nihon-typhoon in 2019, their results brought massive flooding and overflow of the river, which demolished bridge structures and disconnects people between two regions.

There are many kinds of temporary bridges in Japan in the company, public and military sectors. However, they still needed a lot of laborers and a high capacity of cranes for their assembly procedure.

Therefore, we would like to propose a new kind of Smart Bridge as one of the smartest constructions, which is using the scissors structure (hereinafter SCI) to expand and fold itself by a few people within an hour to finish (see **Fig.1**). In the history, there were many kinds of Mobile Bridges invention (hereinafter MB) such as structure with the expanding and folding equipment as a patent by Ario et al. (2010), and another topic by Ario et al. (2013), by Chikahiro et al. (2016) and by Hama et al. (2017).

Fig. 1 The mobile bridge version 4.0

2. THE EQUILIBRIUM THEORY

(1) The mechanism of scissors structure by the simple support model

A two-units SCI model with the reaction of the nodal force by hinge, pivot, and pin supports (see **Fig.2**). All members have the same length and the same angle of inclination θ, measured from the vertical direction. The length and height of a scissors unit are defined as λ and η. The left-hand side scissors-unit consists of nodes A, C_L, D, F, and G_L, and the second scissor unit consists of nodes C_R, B, E, G_R, and H. All nodal points are considered as hinges. All loads are applied at a nodal location only. Hence, no bending moments are transmitted or applied at these nodal points by Chikahiro et al. (2016), and by Ario et al. (2016).

The horizontal (hereinafter H) and vertical (hereinafter V) equilibrium equations for the left-hand side unit are given as the following.

From the left-hand side SCI, we obtain the equation as below.

$$\left\{\begin{array}{c} H_{CL} \\ V_{CL} \\ H_{GL} \\ V_{GL} \end{array}\right\} = -\left\{\begin{array}{c} H_A \\ V_A \\ H_B \\ V_B \end{array}\right\} - \left\{\begin{array}{c} H_D + H_F \\ V_D + V_F \\ 0 \\ \eta\, H_F + \lambda\, V_F \end{array}\right\}$$

$$\Leftrightarrow \{CG_L\} = -[R_1]^{-1} Y_1 \{AB\} - [R_1]^{-1}\{Z_{DF}\} \qquad (1)$$

From the right-hand side SCI, we obtain the equation as below.

$$\left\{\begin{array}{c} H_{CR} \\ V_{CR} \\ H_{GR} \\ V_{GR} \end{array}\right\} = -\left\{\begin{array}{c} H_A \\ V_A \\ H_B \\ V_B \end{array}\right\} - \left\{\begin{array}{c} H_E + H_H \\ V_E + V_H \\ \eta\, H_H + \lambda\, V_H \\ 0 \end{array}\right\}$$

$$\Leftrightarrow \{CG_R\} = -[L_2]^{-1} Y_2 \{AB\} - [L_2]^{-1}\{Z_{EH}\} \qquad (2)$$

At the nodes C and G, the external forces V_C, H_C, V_G, H_G are in the equilibrium with internal forces H_{GL} and $V_{CR}, H_{CR}, V_{GR}, H_{GR}$ (see **Fig.2**).

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The sum of forces for each other has separated by individual unit expressed as below:

$$\begin{Bmatrix} H_{CL} \\ V_{CL} \\ H_{GL} \\ V_{GL} \end{Bmatrix} + \begin{Bmatrix} H_{CR} \\ V_{CR} \\ H_{GR} \\ V_{GR} \end{Bmatrix} = \begin{Bmatrix} H_{C} \\ V_{C} \\ H_{G} \\ V_{G} \end{Bmatrix}$$

$$\Leftrightarrow \{CG_L\} + \{CG_R\} = \{CG\} \quad (3)$$

Substitution equation (1) and (2) into equation (3) and rearranging will be as below:

$$S\{AB\} = \{CG\} + [R_1]^{-1}\{Z_{DF}\} + [L_2]^{-1}\{Z_{EH}\} \quad (4)$$

$$S = \{-[R_1]^{-1}[Y_1] - [L_2]^{-1}[Y_2]\} \quad (5)$$

Here,

$$R_1 = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & \eta & -\lambda \\ -\eta & -\lambda & 0 & 0 \end{bmatrix}, Y_1 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -\eta & \lambda & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$L_2 = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ -\eta & \lambda & 0 & 0 \\ 0 & 0 & \eta & \lambda \end{bmatrix}, Y_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -\eta & -\lambda \end{bmatrix}$$

If the determinant of S, which is a coefficient matrix for the vector $\{AB\}$ is not **0**, the reaction forces at the supports have a unique solution. Moreover, if the external forces are known, then equation (4) can be solved respectively by Chikahiro et al. (2016).

3. The influence line of scissors structure, results and discussions

(1) The influence line of a scissors structure

The coupling of scissors structure (hereinafter CSCI) is a combination of many scissors in one set and generate their energy by homogeneous behavior. However, the initial of this paper, the author will consider the influence line (hereafter IL) of a deck. Then its load will subject to the main scissors structure by consideration in orderly.

The IL analysis of SCI will obtain by the calculation of its section forces members, and the equilibrium equations of all nodal forces will combine by the equations (6) and (7) by Hama et al. (2017).

$$L_2 b_i^L + R_1 b_i^R + b_i^C = 0 \quad (6)$$

$$b_i^R + b_{i+1}^L = P_i \quad (7)$$

Here, $b_i^* = \{(B_i^*)_x, (B_i^*)_y, (A_i^*)_x, (A_i^*)_y\}^T$, $* = \{L, R\}$
$b_i^C = \{(C_i)_x, (C_i)_y, 0, 0\}^T$
$P_i = \{(P_i^B)_x, (P_i^B)_y, (P_i^A)_x, (P_i^A)_y\}^T$

The equations obtained from the equilibrium condition of each nodal force by considering in a horizontal and vertical axis. The bending moment of the central point by reviewing every single member of the scissors unit (see **Fig.3**). Therefore, the axial forces, shear forces and bending moment will be calculated by their coordinate reverse to member direction, and following equations.

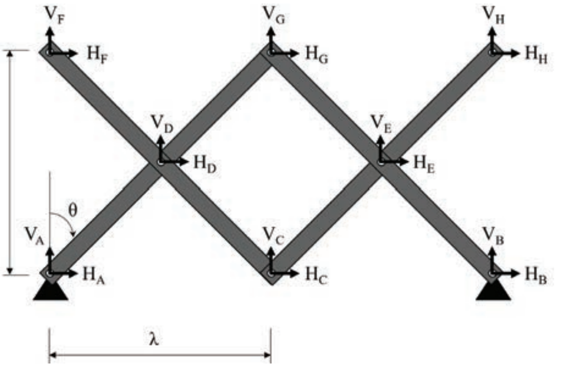

Fig. 2 Two-units scissors structure by simple support model

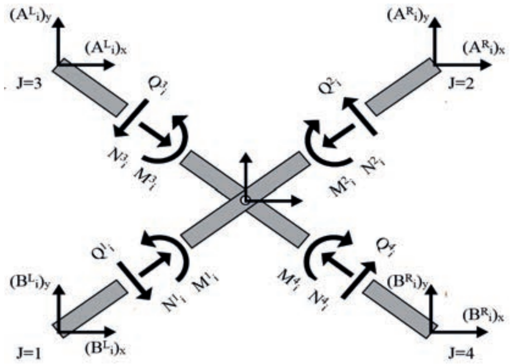

Fig. 3 The sectional forces in a scissors unit structure

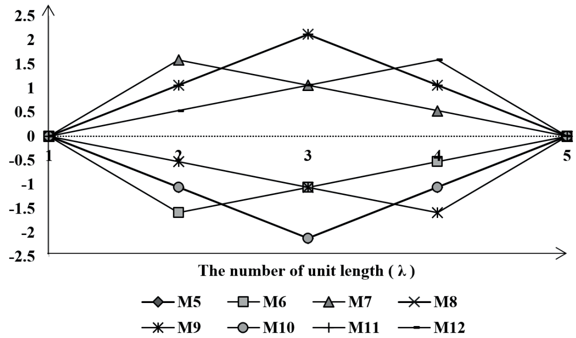

Fig. 4 IL of M, $P = 1$ subject to the normal SCI structure

$$N_i^j = \pm(O_i^*)_x \sin\theta \pm (O_i^*)_y \cos\theta \quad (8)$$

$$Q_i^j = \pm(O_i^*)_x \cos\theta \pm (O_i^*)_y \sin\theta \quad (9)$$

$$M_i^j = \{\pm(O_i^*)_x \cos\theta \pm (O_i^*)_y \sin\theta\}\chi \quad (10)$$

In condition, $0 \le \chi \le L_e/2$.

After this, the letters will represent the following meanings: N, axial force; Q, shear force; M, bending moment; O, represents A or B points.

In the case of 4-units SCI, the load $P = 1$ will subject to every single nodal point substitution from point $B_{1,2} \sim$

$B_{3,4}$. From a simple SCI, we obtain the IL of axial forces, bending moments, and shear forces (see **Fig.4**).

Furthermore, the truck model H-25 (see **Fig.5**) will pass in two ways at the highest loading point of this structure, the front wheel load of H-25 P =22.236KN and rear-wheel load P =88.946KN. Therefore, we will obtain the diagrams of the axial forces, bending moments, and shear forces (see **Fig.8**). Then, the small SCI will be analyzed by simple equations and obtain their reaction forces, which subjected to every single nodal point of the main structure.

In **Fig.6**, the small SCI (black scissors structure) will be a deck of the bridge, and it will calculate by 2-units simple SCI model, which subject to a one-unit SCI (light gray SCI). In the structural analysis, we will obtain the reaction forces from the 2-units SCI, and its reaction forces will subject to the main SCI from points $B_1^L \sim B_4^R$. The CSCI will be analyzed by assuming load $\overline{P} = 1$ subject to the main SCI from points $B_{1,2} \sim B_{3,4}$ (see **Fig.7**).

(2) The results and discussions

These structural models are designed by using high strength steel with low alloy, a cross-section of the main member is 400mm × 70mm (height × width), and thickness is 15mm, member length is 6000mm, the one-unit length is 4000mm and total length of structure around 16,000mm. The young's modulus is 200GPa, the shear modulus is 128.7GPa, and its density is 7.85g/cm^3. The yield strength is 275.8MPa, while the tensile strength is 448MPa.

The boundary condition is simple supports by both pinned support. The simulation of Autodesk Inventor will apply the truck model H-25 (see **Fig.9**), which give the rear wheel (18,140kg × 0.4=9,070kg or 88.946KN) subject to the highest bending moment point of a single structure (at nodal point $B_{2,3}$) and the front wheel will subject at nodal point $B_{1,2}$. Furthermore, the truck also reverses the front wheel at nodal point $B_{3,4}$ during the rear wheel is the same position.

The simulation results show that a Von Mises Stress (hereinafter VMS) of CSCI model A is higher than DWT, about 10%. At the same time, it is displacement (hereinafter Disp.), and structural weight is higher. The VMS of CCI model C is lower than DWT, about 2%, while it is structural weight is higher, but the Disp. is lower. The VMS of CSCI model D is lower than DWT, about 20%, while it is structural weight is higher, but the Disp. is lower. Moreover, the 1st Principle Stress (hereinafter 1st PS) and 3rd Principle Stress (hereinafter 3rd PS) have described in **Table 1**.

Table 1 The simulation results of DWT & CSCI models.

Model names	Weight Kg	Disp. mm	VMS MPa	1st PS MPa	3rd PS MPa	VMS ratio
DWT	999.15	7.52	104.96	103.13	12.61	1.00
CSCI (A)	1027.46	9.15	114.98	114.01	25.67	1.10
CSCI (B)	1111.48	8.22	102.49	104.81	32.47	0.98
CSCI (C)	1195.5	6.53	102.49	105.45	28.80	0.98
CSCI (D)	1277.83	5.75	83.79	85.63	25.72	0.80

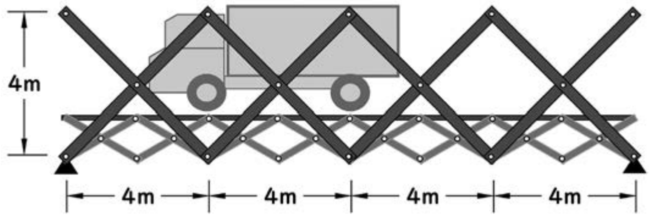

Fig. 5 The truck loading on the scissors structure

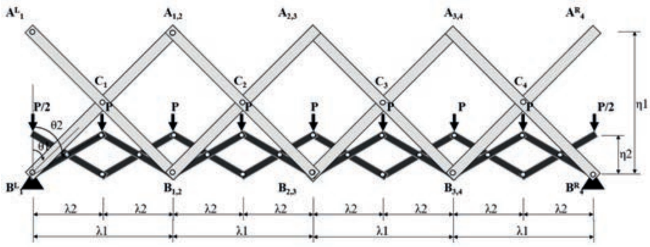

Fig. 6 The loading distribution of the CSCI

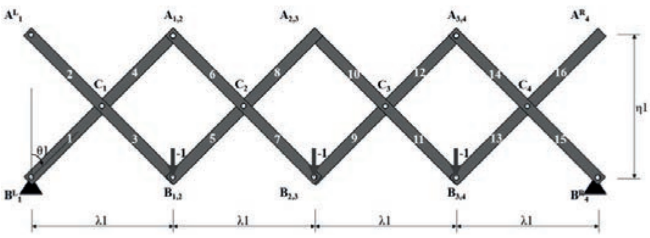

Fig. 7 The loading distribution of the CSCI (P=1)

4. CONCLUSIONS

This paper invented the IL of axial forces, bending moments, shear forces, and Von Mises Stress on the structure of DWT and CSCI four models. The concept is moving of live load along with the structure by truck model H-25 (22,675kg), we obtained the maximum of axial forces, shear forces, and bending moments. To sum up, it is able to be described in the following;

1. Using the equilibrium mechanics theory of a SCI, we obtained the sectional forces of the frame elements with pin-connections. Furthermore, the IL diagram has been using to design the maximum loading point of a structure by equilibrium equation and simply of supposing loading from small SCI to the main SCI.

2. To aware of the significance of the structure, we try to analyze the CSCI structure in many cases and investigate their numerical results to a normal structure has been using currently.
3. The comparison between the stress of DWT and CSCI shown that the CSCI model A is over-stressing only 10%, while the stress of CSCI model B is lower than DWT 2%, but displacement is over only 10%.

The results showed that if we develop the CSCI model, B is more significant and suitable for an emergency case because it can deploy to reach another side of the river only a few hours. This type of bridge construction is super-quick and safe as one of the smart reconstructions after the damage of a bridge caused by a disaster. However, the connection points, the upper member reinforcement, and the deck should be considered more about their mechanism design.

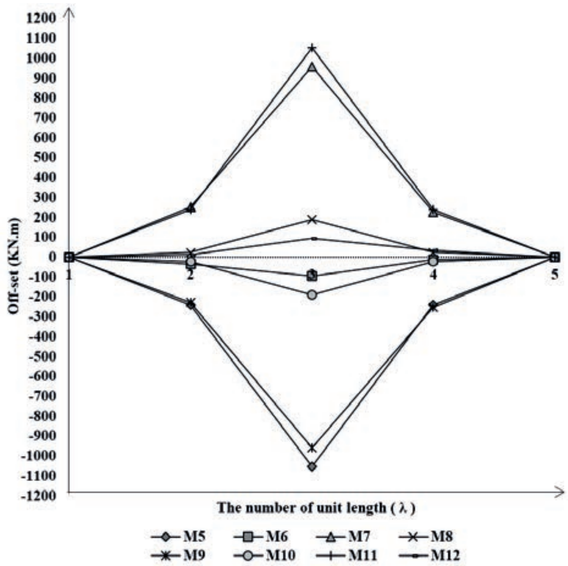

Fig. 8 IL of M by H-25 truck subjection at the middle point

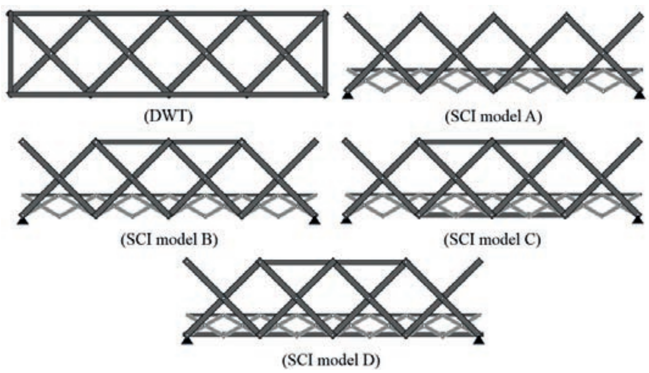

Fig. 9 Five models of the structural simulation

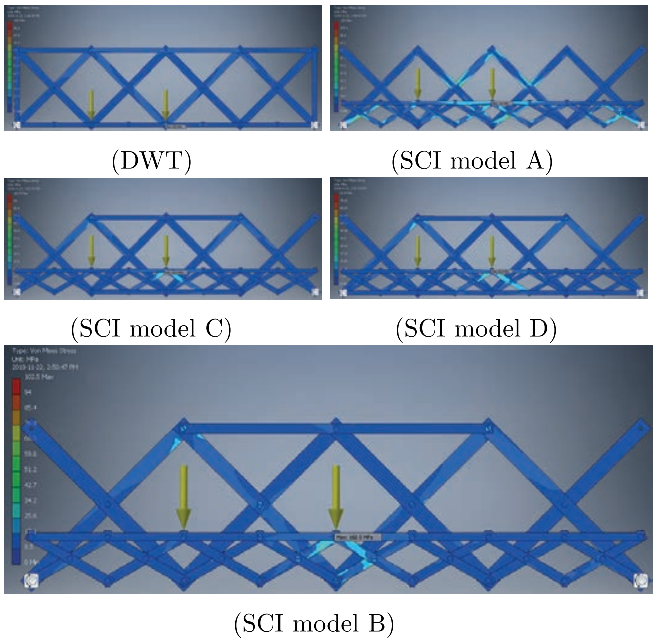

Fig. 10 Five models of the structural simulation results

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