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Shape Determination of Steel Truss Structures Subjected to Thermal Loading

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Abstract*— Truss structures experience thermal loading due to heating from source. For long span truss structure, effect of such thermal loading might to be especially critical in the sense that excessive deformation or failure due to over-stressing of member might occur. This paper is about shape analysis of truss structures subjected to thermal loading, with constrains in member strain. Strain is chosen as the constraint because it can be easily and directly measured. By constraining the member strains to certain prescribed values, stress caused by thermal loading can also be controlled. The governing equations for shape analysis are formulated by combining stiffness equation for truss structure and constrains. The existence condition of solution formulated by combining stiffness equation for truss structure and constrains. The existence condition of solution formulated with the use of generalized inverse matrix is adopted as the basis of analysis. Newton-Raphson method is used in the shape analysis process to obtain the shape satisfying the constraints

***Index Terms*—generalized inverse, existence condition for solution, shape analysis, constrains, strains, thermal loading.**

I. INTRODUCTION

Thermal loading due to change in the temperature can be considered as a kind of external loading in structural analysis. Stresses will be induced in the structure if free expansion of structural members is restrained. Effect of stress as well as deformation due to thermal loading might be especially critical in large-span lightweight truss structures. Fig. 1 show an example where members in large-span lightweight truss structures might experience different changes is temperatures. That is, in the side A, members of truss experience higher changes in temperature due to direct exposure to sunlight. However, in the side B, members of truss experience higher changes in temperature due to direct exposure to sunlight.
Shape analysis constitutes an important step in the design process of truss structures. If x=a vector represtessing the shape of structures and g_i=i^{th} constraint function, then the process of shape analysis with constraints could be expressed as follows: Obtain x under the condition.

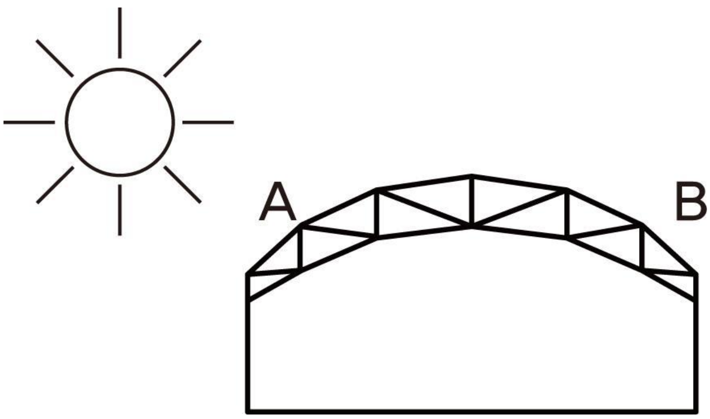

Fig. 1. Change in temperature in a large-span roof structure due to uneven exposure to sunlight.

$$g(x) \le 0, \quad i = 1,2... \qquad (1)$$

During shape analysis, topology of structure is kept unchanged with the shape of structure being the only design variable. In this research study, member strain has been chosen as the constraint due to the reason that strain could

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be easily measured. Overstressing or excessive deformation of truss structure under the effect of thermal loading could be avoided by limiting the strain to suitable level.

Results of literature review have shown that shape analysis with constraint has been carried out by various researchers [1-5]. However, shape analysis of truss structures under thermal loading with member strains as constraints has not yet been carried out with the objective of studying the applicability of a solution algorithm for shape analysis of truss structures under thermal loading with members strains as constrains by the use of generalized inverse.

This paper consists of four sections. Background to the research study is explained in section 1. Section 2 describes the basic governing equations as well as the solution algorithm. Results of three numerical examples are presented in section 3. Section 4 summarizes the work and outlines topics for future research.

II. BASIC FORMULATION

Shape analysis considered in this study involves deformation analysis of truss structures under thermal loading with constraints in member strains. Hence, two sets of equations which must be solved simultaneously are necessary: i. force-displacement and ii. Strain-displacement relations. A brief description of the basic equations are given below. More detail explanation could be found in Ref.[6,7,8]

A. Governing Equations

Finite element method is used in the formulation of force-displacement relation. Effect of temperature changes is treated as equivalent external force during analysis. Let us assume that the number of members and degrees of freedom of a truss structure are m and n respectively. Using a two-node truss element, force (F)-displacement (U) relation could be expressed as follows:

$$F = KU \tag{2}$$

Where $F=\sum\theta$, $K=\sum k$, θ : equivalent member nodal force due to temperature change, K : structure stiffness matrix, and $\sum$ represents assembly process symbolically, k and θ are given by the following two equation respectively:

$$k = \frac{E_e A_e}{l_e}\begin{bmatrix} l^2 & l_m & -l^2 & -l_m \\ l_m & m^2 & -l_m & -m^2 \\ -l^2 & -l_m & l^2 & l_m \\ -l_m & -m^2 & l_m & m^2 \end{bmatrix} \tag{3}$$

$$\theta = E, A, \alpha\Delta\gamma \begin{Bmatrix} -l \\ -m \\ l \\ m \end{Bmatrix} E \tag{4}$$

where E, A, l_e : Young's modulus, cross- sectional area and length of member e respectively, l, m : directional cosine of member axis with respect to global x and y axes respectively, a : coefficient to thermal expansion and ΔT : change in temperature.

Relation between member axial strain and nodal displacement could be expressed as follows:

$$\varepsilon = \frac{l}{l_e}\begin{bmatrix} -l & -m & l & m \end{bmatrix}\begin{Bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \end{Bmatrix} \tag{5}$$

when u_j, v_j : global x and y displacement of nodal j (j=1,2) respectively, Eq.(5) could be rewritten using matrix notation as follows:

$$\varepsilon = B_e u_r \tag{6}$$

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Assuming that strain in $p(\leq m)$ members are constrained to the prescribed values, then the p constrains equations could be expressed as follows:

$$\varepsilon = BU \tag{7}$$

where ε : vector of member strains with size pxl, $B=\sum B$ and U : vector of structure nodal displacements.
Basic equation for shape analysis with constraint in member strains are obtained by combining Eq.(2) and (7) into the following augmented form:

$$\left[\frac{F}{\varepsilon}\right] = \left[\frac{K}{B}\right] U \tag{8}$$

Denoting

$$A = \left[\frac{K}{B}\right] \text{ and } b = \left[\frac{F}{\varepsilon}\right] \tag{9}$$

Eq.(8) could then be written in the following more compact form:

$$AU = b \tag{10}$$

Matrix A on the left hand side of Eq.(10) is a rectangular matrix with size $(n+p) \times n$. Hence Eq.(10) could not be solved by using ordinary inverse matrix. As mentioned earlier, shape analysis is carried out using shape of structure x as design variable with all other parameter kept constraint. Thus matrix A is a function of x ,$i, e, A=(x)$. Since the shape of structure satisfying the prescribed member strain is to be determined and remain unknown in the beginning of analysis, Eq.(10) will not be satisfied in general. An initial shape has to be assumed and corrected by means of iterative calculation until the required shape is obtained.

B. Solution Algorithm

Condition for the existing of solution for Eq.(10) is used the basis of shape analysis. This condition could be expressed using generalized inverse as follows:

$$(I_j AA^+) = 0 \tag{11}$$

Where I_j : identity matrix of size $jx\,j$ and A^+: Moore-penrose generalized inverse for A. For size A of $(n+p) \times n$, A^+ will be of size $(n+p) \times n$. Here, generalized inverse[6] is adopted due to the reason that A is not a square matrix, Since A is a function of shape of structure x, then the task here now is to find x such that Eq.(11) is satisfied. Since x is not known beforehand, interactive calculation needs to be carried out. Here, Newton-Raphson interactive scheme is adopted.
The left hand side of Eq.(11) is first denoted as follows:
Using Taylor series expansion and by retaining only the linear term, $g(x)$ could be written in the following form for the purpose of interactive calculation:

$$g(x_{j+1}) = g(x_1) + \nabla g(x_1)(x_{j+1} - x_j) \tag{13}$$

where

$$[\nabla g(x_1)]_{jk} = \frac{\partial g_k(x_1)}{\partial x_j} \tag{14}$$

$\nabla g(x_n)$ is the Jacobian matrix with size $(n+p) \times q$ where q : number of design variable and subscript in vector x represents iterative step. Assuming that the required shape is obtained at $(j+1)^m$ iterative step, then the correction to x vector could be obtained from Eq.(13) as follows:

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$$\Delta x_i = -[\nabla g(x_i)]g(x_i) \qquad (15)$$

$$x_{j+1} = x_i + \Delta x_1 \qquad (16)$$

The evaluation of Jacobian matrix $\nabla g(x_n)$ involve the calculation of differentiation of both A and its generalized inverse A^+. Remembering that $g(x)$ is given by Eq.(12) and carrying out the differentiation with respect to x, it can be shown that the jacobian matrix could be written as follows:

$$\frac{\partial g(x)}{\partial x} = \frac{\partial\{A(x)A^+(x)\}}{\partial x} b(x) + \left[A(x)A^+ - I_j\right]\frac{\partial b(x)}{\partial_x} \qquad (17)$$

Partial differentiation appearing in the first term on the right hand side of Eq.(17) could be evaluated using the following expression:

$$\frac{\partial g(x)}{\partial x} = \frac{\partial\{A(x)A^+(x)\}}{\partial x} b(x) + \left[A(x)A^+ - I_j\right]\frac{\partial b(x)}{\partial_x} \qquad (18)$$

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C. *Summary of the Solution Process*

(a) An initial shape x_0 is assumed.
(b) Compute K and B in Eq.(8)
(c) Constrains on member strains are prescribed (ε in Eq.(8))
(d) From the given change in temperature patterns, Compute F in Eq.(8)
(e) Form matrix A and vector b in Eq.(9)
(f) Evaluate $g(x_i)$ and solve Eq.(15) for Δx_i
(h) Update the shape of structures using Eq.(16)
(i) Repeat the step (a) to (h) until the required shape is obtained. Replace x_0 in step (a) with x_1 for $i \geq 1$.
Criteria for convergence of solution is required in step no (i) above. In this study, the following convergent criteria has been adopted.

$$\left[\frac{\varepsilon_c}{\|\varepsilon_c\|}\square\frac{\varepsilon_s}{\|\varepsilon_s\|} - 1.0\right] \leq \xi \qquad (19)$$

Where, ε_c: vector of member strains at the end of each iteration, ε_s : vector of prescribed member strains and ξ: specified convergent tolerance. A value of $1\text{x}10^{-5}$ has been chosen for ξ.

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III. NUMERICAL EXAMLES

Three plane truss structures, with Young's modulus $E=200x10^9 N/m^2$, member area $A=0.05\ m^2$ and coefficient of thermal expansion $a=12x10^{-6}/ ℃$, have been analyzed. In each of the analysis, a target shape x_{tar} is first identified. The truss structures with x_{tar} is then analyzed subjected to given patterns of temperature changes. The resulting member strain ε_c are the adopted as the constraints. Shape analysis is then started with the initial shape x_0 in which the joint coordinates are deviated uniformly from x_{tar} by three different levels of percentage: 1%, 3% and 5%. Iterative calculation is then carried out until either the convergent criteria is satisfied and maximum number of iteration specified is exceeded. The online version of the volume will be available in LNCS Online. Members of institutes subscribing to the Lecture.

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A. Numerical Example 1 : a three-number plane truss

Fig. 2 shows a three-member plane truss which has been adopted as the first example in which $\Delta t_1=10$ ℃ and $\Delta t_2=20$ ℃. The target shape and prescribed member strains are tabulated in Table 1 and 2 respectively.
Results of analysis are shown in Table 3and 4. Ite. In Table 3 and hereafter denotes number of iteration required to achieve convergence. Percentage deviation in both Table 3, 4 and hereafter denotes amount with which initial shape is deviated from target shape.

Table 1. Joint coordinates of the target shape for numerical example 1

Node	Coordinates (x,y)
1	(0,0)
2	(8,3)
3	(20,0)
4	(10,0)

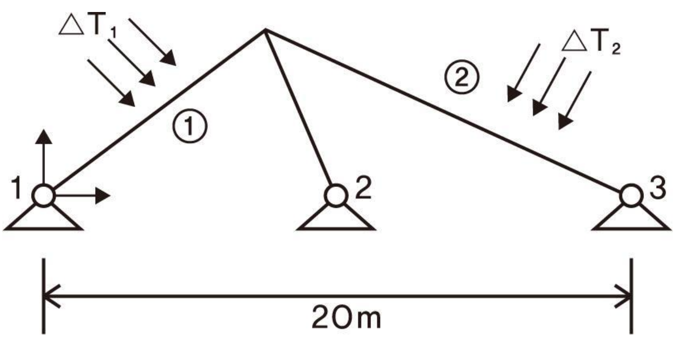

Fig. 2. Numerical example 1: a three- member truss

Table 2. Prescribed member strains for numerical example 1

Member	**Prescribed member strain**
1	**-23.72170×10^{-6}**
2	**31.93136×10^{-6}**
3	**121.30050×10^{-6}**

Table 3. Results of shape analysis for numerical example 1 : coordinates of joint 2

Percentage deviation	**Initial shape**	**Converged shape**	**Target shape**
1.0 (ite.=1)	**X=8.08 Y=3.03**	**X=8.000 Y=3.001**	**X=8.00 Y=3.00**
3.0 (ite.=1)	**X=2.4 Y=3.09**	**X=8.001 Y=3.012**	**X=8.00 Y=3.00**
5.0 (ite.=1)	**X=8.40 Y=3.15**	**X=8.002 Y=3.034**	**X=8.00 Y=3.00**

Table 4. Results of shape analysis for numerical example 1 : member strain

Percentage deviation	**Member**	**Member stains in converged shape**
	1	**-23.72×10^{-6} (-23.722×10^{-6})**
1.0	**2**	**31.95×10^{-6} (31.9312×10^{-6})**
	3	**121.3×10^{-6} (121.301×10^{-6})**

3.0	**1**	**-23.68×10^{-6} (-23.722×10^{-6})**
	2	32.06×10^{-6} (31.9312×10^{-6})
	3	121.5×10^{-6} (121.301×10^{-6})
5.0	1	-23.63×10^{-6} (-23.722×10^{-6})
	2	32.31×10^{-6} (31.9312×10^{-6})
	3	121.9×10^{-6} (121.301×10^{-6})

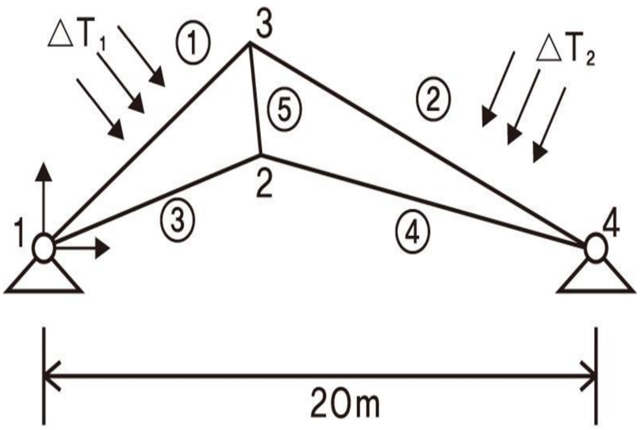

Fig. 3. Numerical example 2 : a five- member truss

B. Numerical Example 2 : a five-mumber truss

Fig.3 shows a five-member plane truss which has been analysis as the second example in which $\Delta t_1=10$ ℃ and $\Delta t_2=20$ ℃. Coordinates of both joints 2 and 3 are used as design variables. The target shape and prescribed member strains are tabulated in Table 5 and 6 respectively.

Results of analysis showing joint coordinates and member strains in converged shape are shown in Table 7 and 8 respectively.

Table 5. Joint coordinates of the target shape for numerical example 2

Node	Coordinates (x,y)
1	**(0,0)**
2	**(8,3)**
3	**(7,2)**
4	**(10,0)**

Table 6. Prescribed member strains for numerical example 2

Member	Prescribed member strain
1	**74.59469×10^{-6}**
2	**86.32100×10^{-6}**
3	**$190.21551\times\times10^{-6}$**
4	**91.15596×10^{-6}**
5	**23.79050×10^{-6}**

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Table 7. Results of shape analysis for numerical example 2 : coordinates of joint 2 and 3.

Percentage deviation	Node	Initial shape	Converged shape
1.0 (ite.=1)	2	X=8.04 Y=1.01	X=8.004(8.0) Y=1.001(1.0_
	3	X=7.07 Y=2.02	X=7.004(7.0) Y=2.003(2.0)
3.0 (ite.=1)	2	X=8.24 Y=1.03	X=8.000(8.0) Y=1.000(1.0)
	3	X=7.21 Y=2.06	X=6.997(7.0) Y=2.001(2.0)
5.0 (ite.=1)	2	X=80.40 Y=1.05	X=7.999(8.0) Y=1.001(1.0)
	3	X=7.35 Y=2.10	X=6.998(7.0) Y=2.002(2.0)

(Figures in parenthesis under the column member strains in converged shape represent target values)

Table 8. Results of shape analysis for numerical example 2: member strain

Percentage deviation	Member	Member stains in converged shape
1.0	1	7.59×10^{-6} (7.595×10^{-6})
	2	86.32×10^{-6} (86.321×10^{-6})
	3	190.2×10^{-6} (190.216×10^{-6})
	4	91.15×10^{-6} (91.156×10^{-6})
	5	23.81×10^{-6} (23.791×10^{-6})
3.0	1	74.59×10^{-6} (74.595×10^{-6})
	2	86.32×10^{-6} (86.321×10^{-6})
	3	190.2×10^{-6} (190.216×10^{-6})
	4	91.17×10^{-6} (91.156×10^{-6})
	5	23.80×10^{-6} (23.791×10^{-6})
5.0	1	74.59×10^{-6} (74.595×10^{-6})
	2	86.32×10^{-6} (86.321×10^{-6})
	3	190.2×10^{-6} (190.216×10^{-6})
	4	91.19×10^{-6} (91.156×10^{-6})
	5	23.83×10^{-6} (23.791×10^{-6})

(Figures in parenthesis under the column member strains in converged shape represent target values)

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C. Numerical Example 3 : a 11-mumber truss

Fig.4 shows a 11-member plane truss which has been analyzed as the third example. In this example, only coordinates of nodes 3 and 5 are allowed to change. Coordinates of nodes 2, 4 and 6 remain fixed during the analysis. Joint coordinates and prescribed member strains are given in 9 and 10 respectively. Here, $\Delta t_1=10$ ℃, $\Delta t_2=20$ ℃ and $\Delta t_3=30$ ℃.

The results of analysis showing the joint coordinates and member strains of the converged shape are shown in Table 11 and 12 respectively. In Table 12. only the results correspond to percentage deviation 5% are listed.

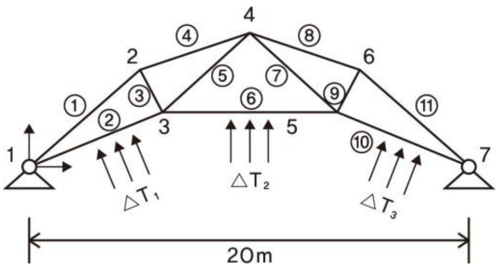

Fig. 4. Numerical example 3 : a 11- member truss

Table 9. Joint coordinates of the target shape for numerical example 3

Node	Coordinates (x,y)
1	(0,0)
2	(4,4)
3	(6,3)
4	(10,5)
5	(14,3)
6	(16,4)
7	(20,0)

Table 10. Prescribed member strains for numerical example 3

Member	Prescribed member strain
1	130.73110×10^{-6}
2	262.42893×10^{-6}
3	-129.1900×10^{-6}
4	210.86089×10^{-6}
5	-94.20543×10^{-6}
6	58.66208×10^{-6}
7	-44.13117×10^{-6}
8	165.45533×10^{-6}
9	-101.37098×10^{-6}
10	214.49785×10^{-6}
11	71.88832×10^{-6}

Table 11. Results of shape analysis for numerical example 3:Joint coordinates of converged shape

Percentage deviation	Node	Initial shape	Converged shape
1.0 (ite.=1)	3	6.06 3.03	6.000(6.0) 3.000(3.0)
	5	14.14 3.03	14.00(14.0) 3.000(3.0)
3.0 (ite.=1)	3	6.18 3.09	6.000(6.0) 3.000(3.0)

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	5	14.42 3.09	14.00(14.0) 3.000(3.0)
5.0 (ite.=1)	3	6.3 3.15	6.000(6.0) 3.000(3.0)
	5	14.7 3.15	14.00(14.0) 3.000(3.0)

(Figures in parenthesis under the column converged shape represent target values)

Table 12. Results of shape analysis for numerical example 3 : member strain in converged shape

Percentage deviation	Member	Member stains in converged shape
5.0	1	130.8×10^{-6} (130.731×10^{-6})
	2	262.5×10^{-6} (262.429×10^{-6})
	3	-129.2×10^{-6} (-129.190×10^{-6})
	4	210.9×10^{-6} (210.861×10^{-6})
	5	-94.25×10^{-6} (-94.205×10^{-6})
	6	58.65×10^{-6} (58.662×10^{-6})
	7	-44.11×10^{-6} (-44.131×10^{-6})
	8	165.5×10^{-6} (165.455×10^{-6})
	9	-101.4×10^{-6} (-101.371×10^{-6})
	10	214.5×10^{-6} (214.498×10^{-6})
	11	71.89×10^{-6} (71.888×10^{-6})

(Figures in parenthesis under the column member strains in converged shape represent target values)

IV. DISCUSSION AND CONCLUSIONS

From the results presented, it can be seen that convergence has been achieved after 1 iteration for numerical example 1, 2(Table 3 and 7) and after 2-4 iteration (Table 11) for numerical example 3. Comparison between joint coordinates and member strains of converged shape with the corresponding values of target shape for all three numerical examples have shown that the solution algorithm yield results with high accuracy (Table 3,4,7,8,11,12).

Shape analysis of truss structures under thermal loading with constraints in member strains has been studied. A solution algorithm involving the use of generalized inverse and Newton-Raphson iteration scheme has been adopted and its applicability investigated. Results obtained from analysis carried out on three simple plane truss structures have shown that the solution algorithm adopted yield solutions with sufficient accuracy. Based on the above, it can be concluded that the accuracy. Based solution algorithm is applicable to shape analysis problems and worthy of further development.

Among areas that need further research works are as follows :

(a) Verification of applicability of solution algorithm to problems with higher degrees of freedom including 3D problems.
(b) Investigation in sensitivity of final converged shape with respect to initial assumed shape.
(c) Potential extension of the solution algorithm to problems involving shape control of truss structures with member strains as constraints.

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