EVALUATION METHOD FOR REDUNDANCY OF TRUSS BRIDGE

Eiki Yamaguchi[1], Ryo Okamoto[2], Keita Yamada[2]

Abstract

Partial failure of a bridge may or may not lead to further damage or even to the collapse of the entire bridge. The difference arises from the redundancy of the bridge, and this issue attracts many researchers and engineers in recent years. To this end, the post-member-failure analysis method for a steel truss bridge is studied herein. For the investigation of redundancy, simple analysis is preferred since a number of analyses are required in general. However, the present study reveals that the static analysis yields quite different result from that due to the dynamic analysis. A redundancy analysis method is then proposed. Example problem demonstrates the effectiveness of the proposed method while it requires computational time only as much as the static analysis does.

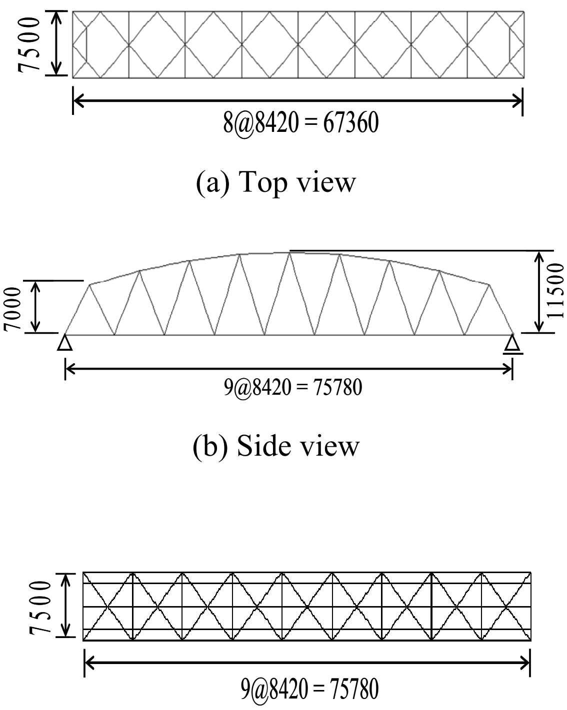
Introduction

In 2007, a truss bridge in USA, Minnesota I-35W, collapsed completely. Fracture of a gusset plate appears to have led to the collapse of the whole structure. In the same year, a truss bridge in Japan was found to have a severed member due to corrosion. Fortunately the bridge escaped the complete collapse. In 2010, a concrete bridge in Japan lost one of its bridge piers due to scour, but still held on.

These experiences imply the necessity of the investigation into the structural behavior when a part of the structure fails. Especially important is the identification of the fracture critical member (FCM), the failure of which would lead to the extensive damage of the bridge. Nevertheless, it is not an obvious task, and the redundancy analysis that deals with the post-member-failure analysis of a bridge has attracted many researchers.

Member failure causes dynamic behavior of a truss bridge, and displacement in the dynamic behavior can exceed that in the static behavior. Therefore, the dynamic analysis would be relevant for evaluating the behavior of a truss bridge after the member failure. Yet dynamic analysis requires much computational time, and the redundancy investigation usually requires a large number of analyses in each of which the failure of a different member is assumed, since the member to fail cannot be singled out in general. Therefore, a simpler redundancy analysis method would be preferred in practice. This is a reason that the static analysis is often employed for predicting the post-member-failure behavior

[1] Professor, Dept. of Civil Engineering, Kyushu Institute of Technology, Kitakyushu
[2] Graduate Student, Dept. of Civil Engineering, Kyushu Institute of Technology, Kitakyushu

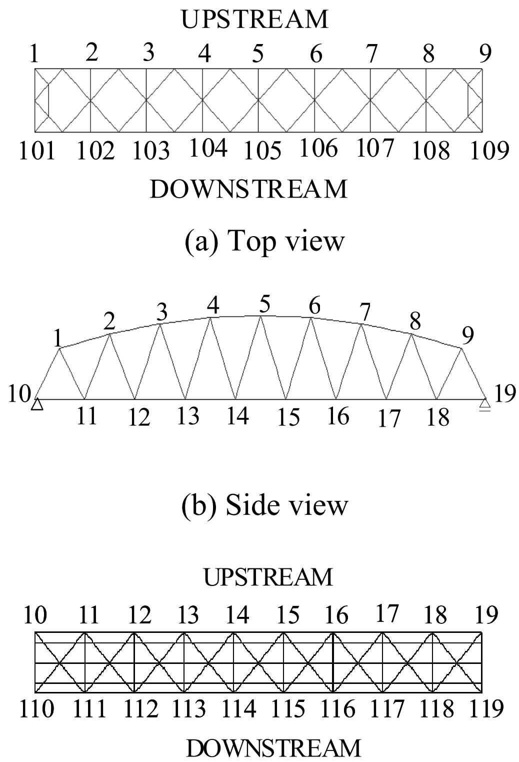


(a) Top view

(b) Side view

(c) Bottom view

Figure 1. Truss bridge model.



(a) Top view

(b) Side view

(c) Bottom view

Figure 2. Node numbers.

(Nagatani et al. 2008).

In the present study, the static analysis is conducted for investigating the post-member-failure behavior of a steel truss bridge from the viewpoint of redundancy. The main objective of the present study is to investigate redundancy analysis method rather than the redundancy of a specific truss bridge. To that end, the dynamic analysis is also carried out, and the effectiveness of the static analysis is discussed by comparing the two sets of numerical result.

Truss Bridge Model

The truss bridge model to be analyzed herein is constructed by referring to an existing steel truss bridge whose diagonal members were corroded. The schematic of the bridge model is given in Figure 1. The node numbers are assigned, as indicated in Figure 2. The member is specified by using two node-numbers at the member ends in the present study.

Since the main objective of the present study is the investigation of redundancy analysis method, only one member failure is considered herein. Observing the internal force distribution in the original state, Member 1-11 is selected as a severed member since it is subjected to rather large internal force so that the influence on the force redistribution due to the member failure can be large.

This is a simply-supported steel truss bridge with the span of 75.780 m. It has a reinforced concrete slab in which a part of every diagonal member is embedded. The thickness of the slab is 165 mm, and the plate thickness of the portion of each diagonal member embedded in the slab is assumed half, as this portion of the existing steel truss bridge was badly corroded. Young's Modulus of steel is assumed 2.0×10^5 N/mm^2, while 1/7 of that value is employed for concrete. Yield stress of steel is 235 N/mm^2. Only the dead load is considered for the external loading in the present study.

The analysis of the bridge model is carried out by the finite element method using Y-FIBER3D (2000). 2-node beam elements of fiber type are employed, and 8 elements are used in modeling each truss member except a lateral member that is modeled by 4 elements. 1364 beam elements are used in total.

Simulation of Member Failure

The member failure of a steel truss bridge is usually simulated as follows (Goto et al. 2010; Nagatani et al. 2008):

(1) Decide which member is to fail.
(2) Compute the internal force acting in that member in the original state of the truss bridge.
(3) Remove the member and apply the internal force as the external load instead at the nodes to which the failed (removed) member was connected, so that the structural deformation remains the same. The external load thus applied is called "the initial load."
(4) Apply another external load in the opposite direction to that of the initial load so as to simulate the member failure. This additional external load is called "the failure load."

This simulation procedure is also employed in the present study.

Verification of Member Safety

Following the work of Nagatani et al. (2008), the safety of the member is to be verified when the following criterion is satisfied:

$$R_t = \left(\frac{N}{N_y}\right) + \left(\frac{M}{M_p}\right)_i + \left(\frac{M}{M_p}\right)_o < 1.0 \qquad \text{when the axial force is tensile}$$

$$R_c = \left(\frac{N}{N_{cr}}\right) + \frac{1}{1-(N/N_E)_i} \cdot \left(\frac{M_{eq}}{M_p}\right)_i + \frac{1}{1-(N/N_E)_o} \cdot \left(\frac{M_{eq}}{M_p}\right)_o < 1.0 \qquad (1)$$

when the axial force is compressive

where N and M are the axial force and the bending moment acting in the member, respectively. N_y is the squash force, M_p the fully plastic moment, N_{cr} the load-carrying capacity in axial compression as a column, N_E the Euler buckling strength, and M_{eq} is the equivalent bending moment of the member computed by the formula given in Japan (2002) when the bending moment varies along the member. The subscripts i and o indicate the in-plane and out-of-plane quantities, respectively. Except the diagonal members, N_E is obtained theoretically without much difficulty by assuming the effective buckling length is equal to the member length, and N_{cr} is evaluated by the design equation in Japan (2002).

N_E and N_{cr} of the diagonal members are computed by the finite element method using ABAQUS (2006). Due to symmetry, only four different dimensions of diagonal compressive members are used in the truss bridge. Therefore, four members, Members 1-10, 2-11, 3-12 and 4-13, are analyzed by ABAQUS to obtain N_E and N_{cr}. The evaluation of N_E requires only the buckling eigenvalue analysis while material and geometrical nonlinearities need be considered together with initial geometrical imperfection and residual stress for computing N_{cr}. The influence of the corrosion on N_E turns out to be insignificant while the influence on N_{cr}. is rather substantial.

The member that satisfies Equation (1) is safe. Otherwise the member is judged damaged.

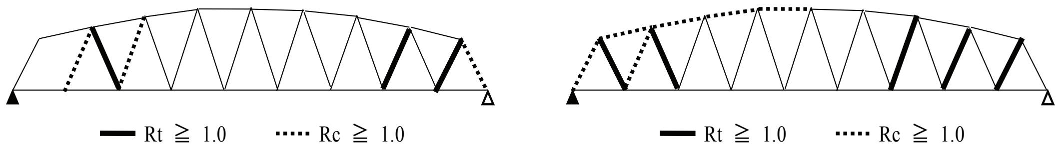
Numerical Results

Table 1 presents the numerical results where V_1 is the vertical displacement of Node 1. The table indicates that Member 102-103 is judged damaged when V_1 is 5.1 mm in the static analysis. On the other hand, Member 2-11 is found damaged when V_1 is 8.8 mm in the dynamic analysis. The last column of the table, Damage type, shows whether the axial force in the subsequently damaged member is tension or compression.

The dynamic analysis reveals that Node 1 reaches the vertical position corresponding to V_1 = 39.6 mm before it starts moving downward. Figures 3 and 4 show

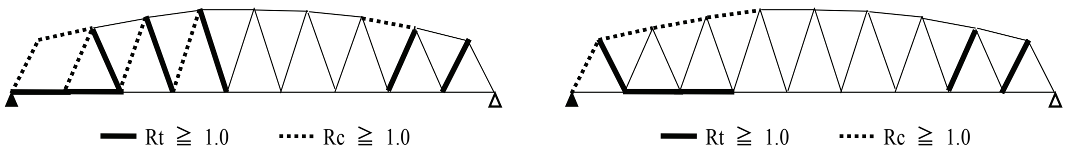
Table 1. Numerical results.

Analysis	V_1 (mm)	Damaged member(s)	Damage type
Static	5.1	Member 102-103	$R_c \geq 1.0$
	39.6	Figure 3	
Dynamic	8.8	Member 2-11	$R_c \geq 1.0$
	39.6	Figure 4	
Proposed	7.8	Member 2-11	$R_c \geq 1.0$
	39.6	Figure 6	



(a) Upstream side (b) Downstream side

Figure 3. Damaged members (static analysis at V_1= 39.6 mm).



(a) Upstream side (b) Downstream side

Figure 4. Damaged members (dynamic analysis at V_1= 39.6 mm).

the damaged members at the moment of the maximum V_1 (= 39.6 mm) in the static analysis and the dynamic analysis, respectively. These results are obtained ignoring the strength deterioration in the subsequently damaged members, since the objective herein is the comparison between the two analyses.

The results in this section reveal that the static analysis and the dynamic analysis yield considerably different information on the redundancy evaluation.

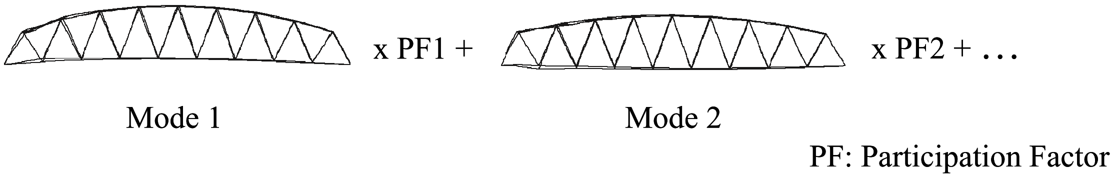


Figure 5. Superposition of natural frequency modes in proposed method.

Proposed Method

Looking into the numerical results closely, the deformed configurations due to the static analysis and the dynamic analysis have been found quite different from each other.

Based on this observation, the following method is proposed:

(1) Conduct eigenvalue analysis of the truss bridge with a failed member (one missing member) so as to obtain natural vibration modes, effective masses and participation factors.
(2) Pick out the natural vibration modes in order of effective mass until the sum of the effective masses of the picked-out modes exceeds 90 % of the total mass.
(3) Superpose the picked-out natural vibration modes multiplied by the corresponding participation factors. The mode thus obtained is assumed to be the deformation mode in the proposed analysis method. (Figure 5 illustrates this procedure.)
(4) Increase the displacement, while retaining the deformation mode obtained in (3), and compute the internal forces in the members to see whether or not the subsequent damage takes place by referring to Equation (1).

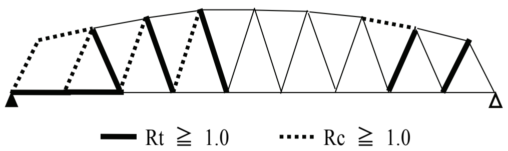
Note that the natural vibration modes in the proposed method are normalized by imposing the following equation:

$$[\Phi]^T[\mathrm{M}][\Phi] = [\mathrm{I}] \tag{2}$$

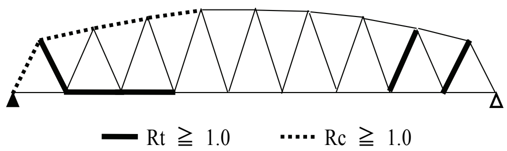
where $[\Phi]$ is the natural-vibration-mode matrix, $[\mathrm{M}]$ is the mass matrix and $[\mathrm{I}]$ is the identity matrix.

Numerical Verification

Table 1 and Figure 6 present the numerical results by the proposed method. The results are in good agreement with those of the dynamic analysis. Slight difference is observed in the value of V_1 at the initiation of the first subsequent damage; otherwise the results due to the proposed analysis and the dynamic analysis are identical with each other.



(a) Upstream side



(b) Downstream side

Figure 6. Damaged members (proposed analysis at V_1= 39.6 mm).

Concluding Remarks

The post-member-failure behavior of a truss bridge was investigated by the static analysis and the dynamic analysis. Large discrepancy between the results due to the two analyses was observed, which was found attributable to the fact that the two analyses resulted in different deformed configurations. Then a method for the redundancy analysis was proposed in an effort to include the dynamic effect in the static analysis.

The effectiveness of the proposed method has been verified by comparing the result with that due to the dynamic analysis. Since the computational time of the proposed method is not much different from that of the static analysis and much less than that of the dynamic analysis, it is believed that the proposed method is promising for the redundancy analysis.

Acknowledgments

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