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After fracture redundancy analysis of steel truss bridges in Japan

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ABSTRACT: After fracture redundancy of a steel truss bridge is investigated through a case study for a 3 span continues bridge designed by Japanese Highway Public Cooperation in 1980. The FE analysis is employed to evaluate the load-carrying capacity after a failure of a member of the truss bridge. The applicability of linear analysis to the redundancy analysis is examined by comparison with the nonlinear analysis results.

1 INTRODUCTION

I-35W bridge collapse in Minnesota killed 13 people and injured 145. In Japan, almost at the same time, a diagonal member of two steel truss bridges in national roads was fractured due to corrosion. Furthermore, a steel truss bridge over border between Tokushima and Kagawa prefectures collapsed in Nov. 2007. Fortunately, nobody was injured by this collapse, but bridge maintenance becomes a mater of considerable concern to everybody in Japan. The Tokushima-Kagawa border bridge is considered to be a particular case, because the bridge owner is not clear even now and maintenance of the bridge had not been carried out since its construction. However, the member fracture occurred in two truss bridges, which are expected to be inspected following the maintenance specifications for the national road. This suggests that the maintenance scheme preparing a possible member fracture should be reconsidered.

From this background, Japanese Steel Bridge Research Association (JSBRA) lunched a special committee on steel bridge maintenance. This paper reports a case study for after fracture redundancy analysis of a Japanese truss bridge conducted by the JSBRA special committee. The after fracture redundancy means the capability of a bridge superstructure to continue to carry loads after the damage or the failure of one of its members (Ghosn and Moses, 1998).

2 MODEL BRIDGE AND DAMAGE SCENARIO

Figure 1 shows a model bridge employed in the case study. The model bridge was designed in 1980 using Japanese Specifications of Highway Bridges (JSHB). In a after fracture redundancy analysis, only one member is assumed to fracture at once, and the assumed fracture members are shown in Figure 2. For each redundancy analysis, the dead load and live load (TT-43) are considered, and the live load is applied so as to maximize the axial force of the assumed fracture member in the intact bridge system. In the subsequent chapters, first a linear redundancy analysis is reported. Second, a nonlinear redundancy analysis is carried out to examine adequacy of the linear redundancy analysis.

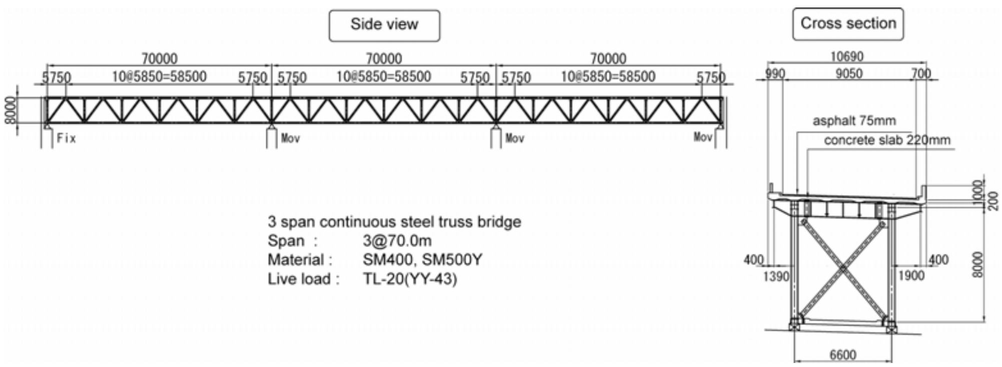

Figure 1: Model bridge for redundancy analysis (JH, 1981)

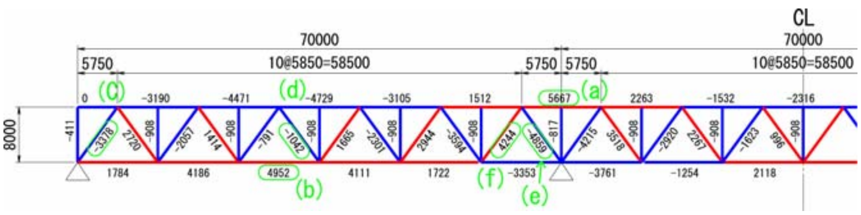

Figure 2: Assumed fracture members (a)-(f) and design axial forces in intact state. The red members stand for tensile members, while blue for compressive members.

3 LINEAR REDUNDANCY ANALYSIS

In the linear redundancy analysis, all steel members were modeled with beam-column elements, and the concrete deck with shell elements. In the original design, this truss bridge was designed as a non-composite bridge. However, slab anchors installed between floor beams and the concrete slab serve as shear connectors. The composite action is considered thereby installing spring elements at the position of the slab anchors to connect the floor beams and the concrete deck.

The dead load including the weight of wet concrete is applied to the steel truss bridge without the concrete deck. Then, the concrete deck is installed into the steel truss, and the superimposed dead load and the live load are applied to the composite section. Finally, an assumed fracture member is removed to reproduce an after fracture state.

3.1 *Member capacity*

In the linear redundancy analysis, the after fracture redundancy is estimated in terms of the member capacity based on the stress resultants obtained from the liner analysis (URS corporation, 2006). The following interaction equation for the axial force P and bending moments M is employed to check the member capacity for tensile members:

$$R = \left(\frac{P}{P_p}\right) + \left(\frac{M}{M_p}\right)_{ip} + \left(\frac{M}{M_p}\right)_{op} \leq 1.0 \qquad (1)$$

where the subscript *ip* and *op* stand for in-plane and out-of-plane, respectively. P_P and M_P are the yield axial force and the full plastic bending moment, respectively. For compressive member, the interaction equation accounted for the member buckling is used

$$R = \left(\frac{P}{P_u}\right) + \frac{1}{1-(P/P_E)}\left(\frac{M_{eq}}{M_P}\right)_{ip} + \frac{1}{1-(P/P_E)}\left(\frac{M_{eq}}{M_P}\right)_{op} \leq 1.0 \qquad (2)$$

where P_u is the ultimate buckling force defined in JSHB (JRA, 2002), and P_E is the Euler buckling force, and M_{eq} denotes the equivalent bending moment accounting for variation of bending moment distribution within a member (JRA, 2002).

3.2 *Results of linear redundancy analysis and fracture critical member*

The linear redundancy analysis results of totally 12 cases are summarized in Table 1 including 2 load cases (dead and live loads referred to as "D+L" and dead load only as "D") and 6 cases for different assumed fracture members (a-f). In the cases that Upper Chord (a) and Lower Chord (b) assumed to be fracture, *R* values for all member are less than 1.0, and accordingly there is no ultimate member. On the other hand, in the cases that the assumed fracture member is Diagonal (c), (e) and (f) under dead and live load, the maximum *R* value becomes more than 1.0. In particular Diagonal (e) case, totally 3 members attains to the ultimate state.

AASHTO LRFD defines the Fracture Critical Member (FCM) as the component in tension whose failure is expected to result in the collapse of the bridge or the inability of the bridge to perform its function. According to this definition, Diagonal (f) becomes a FCM.

Table 1: Number of ultimate members and maximum *R* value

Load case		Assumed fracture member					
		U.Chord (a) tension	L.Chord (b) tension	Diagonal (c) comp.	Diagonal (d) comp.	Diagonal (e) comp.	Diagonal (f) tension
D+L	R_{max}	R<1	R<1	1.18	R<1	1.49	1.61
	U. Chord	0	0	1	0	2	1
	L. Chord	0	0	0	0	0	0
	Virtical	0	0	0	0	1	0
	Diagonal	0	0	0	0	0	0
D	R_{max}	R<1	R<1	R<1	R<1	R<1	1.02
	U. Chord	0	0	0	0	0	1
	L. Chord	0	0	0	0	0	0
	Virtical	0	0	0	0	0	0
	Diagonal	0	0	0	0	0	0

4 NONLINEAR REDUNDANCY ANALYSIS

4.1 *Method of nonlinear analysis*

The material and geometrical nonlinearity is considered in the nonlinear redundancy analysis. The fiber beam element is employed to account for the material nonlinearity in a beam element. For steel, the bilinear stress-strain curve with a second stiffness of $E/100$ is used, where E is the Young's modulus. For concrete, a tensile strength is assigned to 2 MPa. After tensile cracking, only re-bars in concrete resist the tensile stress. The slab anchor connecting floor beams and concrete slab is also modeled as a nonlinear spring based on a push out test. All joints of members are considered as a rigid connection. The phase analysis accounting for unshored construction and the member fracture is used, and the load control method is employed in the

4.2 *Comparison with liner redundancy analysis result*

In the comparison of the linear and nonlinear redundancy analyses, Diagonal (f), which is judged as a FCM with the linear redundancy analysis, is assumed to fracture.

Figure 3 shows a comparison of the load-displacement relationship between the linear and nonlinear analyses. In the first phase, only dead load is applied to the non-composite steel truss. The superimposed dead load and the live load are applied to the composite truss model in the second and third phases, respectively. The difference between the linear and nonlinear analyses is small up to the third phase, where an intact truss bridge system is considered. After Diagonal (f) is fractured, the difference of displacement becomes larger and 7% of the linear analysis result. However, the nonlinear analysis shows that the bridge system after Diagonal (f) fracture does not collapse under the dead and live loads, and still possesses the load carrying capacity, though Diagonal (f) is judged as a FCM with the linear redundancy analysis.

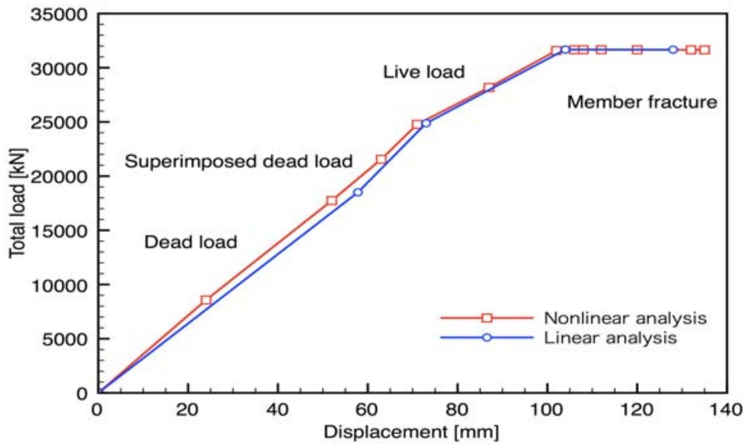

Figure 3: Comparison between linear and nonlinear analysis: Load-displacement curve

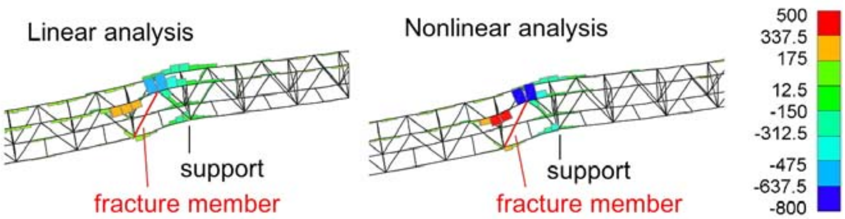

Figure 4: Comparison between linear and nonlinear analysis: In-plane bending moment (unit: kNm).

In an intact truss bridge, the bending moment of members is small comparing with the axial force, and accordingly the bending moment used to be neglected in design practice assuming pin-connection of members. After member fracture, however, the bending moment of members near the assumed fracture member becomes very large as shown in Figure 4.

Figure 5 shows the in-plane bending moment distribution of the upper chord members throughout the bridge. The maximum bending moment obtained from the nonlinear analysis is 1.5 times larger than that from the linear analysis. However, the members whose bending moment difference between the linear and nonlinear analyses results is very large are limited within members connecting the assumed fracture member.

Even in non-composite design bridges, it is well known that the concrete deck substantially supports the load as a part of composite sections. One concern for the linear redundancy analysis is to overestimate the stiffness of the concrete deck, since concrete cracking is not considered in the liner analysis. To clarify this, the stress of the concrete deck in the longitudinal direction is plotted in Figure 6. In the linear analysis result, the maximum tensile stress attains to 10 MPa, while in the nonlinear analysis result the maximum stress is reduced to less than 3 MPa owing to concrete cracking.

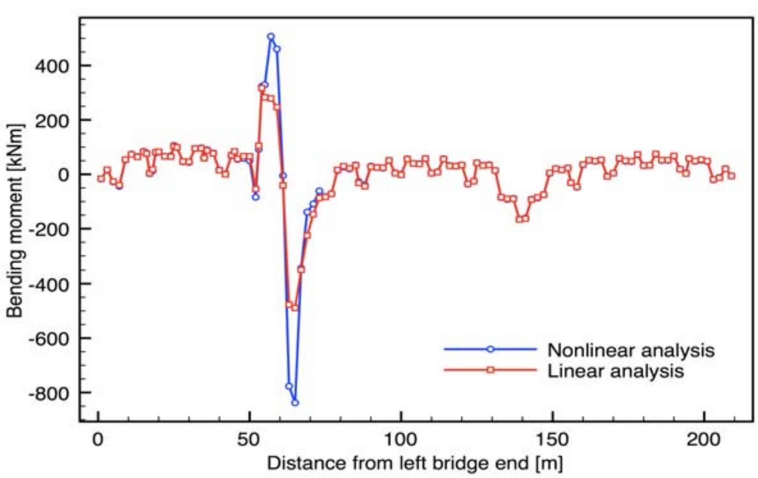

Figure 5: Comparison between linear and nonlinear analysis: Bending moment distribution of upper chord member.

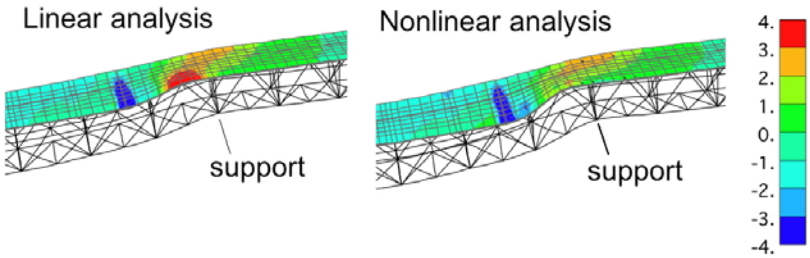

Figure 6: Comparison between linear and nonlinear analysis: Stress in concrete deck (unit: MPa).

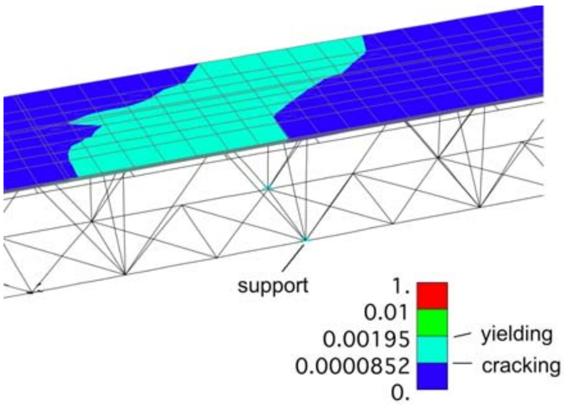

Figure 7: Strain distribution in concrete deck obtained from nonlinear analysis.

In order to investigate damage of the concrete deck, the maximum principal strain of the concrete deck is plotted in Figure 7. In this figure, the dark blue region is intact, while the light blue region stands for concrete cracking. However, yielding of re-bars does not occur. Hence, the concrete deck still possesses the load-carrying capability, which results in stable behavior of the bridge system. In the linear analysis, the concrete deck has the load carrying capability to any extent. In this particular case study, it is considered that the linear analysis gives a result almost consistent with the nonlinear analysis result, because the re-bar yielding does not occur.

5 SUMMARY

A case study of the after fracture redundancy analysis on a Japanese truss bridge is carried out. Based on the liner analysis results, the fracture critical member defined in AASHTO is identified. Furthermore, in order to verify the linear redundancy analysis, the nonlinear analysis accounting for the material and geometrical nonlinearity is carried out. For this particular case study, the liner redundancy analysis identifies a diagonal member as a FCM, while the nonlinear redundancy analysis shows that the member is not a FCM. However, overall behavior, such as displacement and bending moment distributions, of the linear and nonlinear analyses results not so different.

The floor system, such as stringers and floor beams, as well as concrete decks have substantial effect on the after fracture redundancy. In upper concrete deck bridges, even though a upper chord member is fractured, the concrete deck support load, and the collapse of the bridges is avoided in many cases. In the linear redundancy analysis, however, there is a possibility that stress more than the concrete tensile strength occurs in the concrete deck. This leads the overestimation of the after fracture redundancy. To avoid this problem, it is needed to check member capacity of the concrete deck. As pointed out as the main cause of the Minnesota bridge collapse, it is important to check the capacity of joints for estimation of the after fracture redundancy as well.

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