# Static Methods for Redundancy Analysis of Steel Truss Bridges

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## 1. Introduction

Static methods for redundancy analysis of steel truss bridges include linear analysis and nonlinear analysis methods. (URS 2006) presents a linear redundancy analysis of I-35W Bridge through member strength checking. (Yamaguchi 2011) proposes a method of combination of linear and eigenvalue analysis to evaluate the redundancy level. It is visible that nonlinear redundancy, which is believed in higher accuracy, is not studied much.

In practical applications, linear approach is traditionally employed because of its simple required work. However, this approach results in limited accuracy. This study attempts to investigate both linear and nonlinear redundancy methods for steel truss bridges following Japan Specifications for Highway Bridge (JRA 2002). Result in nonlinear redundancy, the approach traditionally believing in high accuracy, is used as a norm to evaluate accuracy of linear redundancy.

## 2. Methods

### General procedure

Redundancy analysis needs many analysis efforts. The analysis generally proceeds in three steps as detailed in **Fig. 1**. Step 1 verifies the performance of the intact bridge before any damages. Finite element (FE) models shall consider the varying of structural configuration during construction stages from erection of truss skeleton to installation of deck. Step 2 identifies candidates for Fracture Critical Members (FCMs), tensile members, whose failure would be expected to results in the collapse of the bridge. Members whose failure leading yield in remaining members could be good candidates. Damages are simulated in FCMs candidates by one candidate at a time. In order to perform exactly behavior of member failure, dynamic effect of sudden failure should be considered.

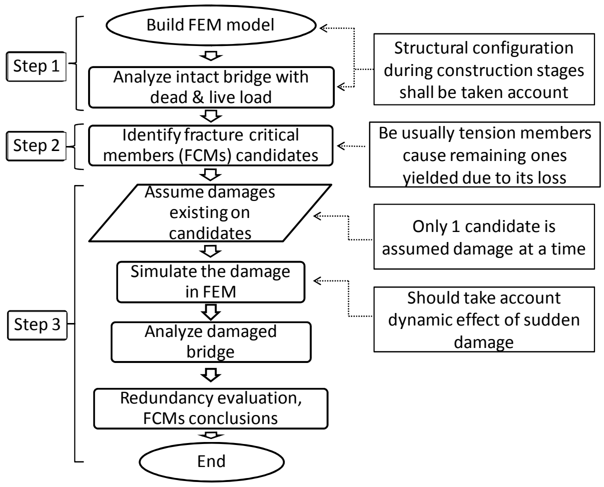


**Fig. 1** General flowchart of redundancy analysis

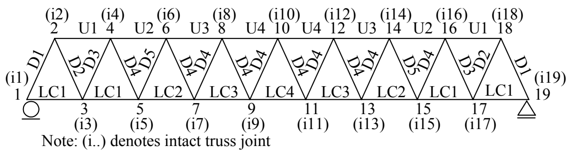


**Fig. 2** Member layout of objective bridge

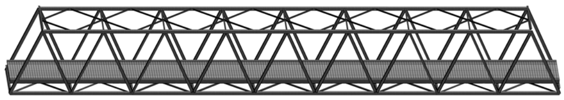

**Fig. 3** FE model in 3D

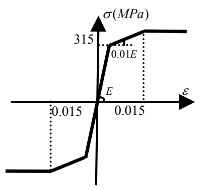


**Fig. 4** Steel SM490A

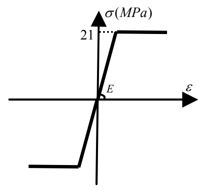


**Fig. 5** Reinforced Concrete

### FE models

A typical steel truss-type bridge is used to illustrate the researched points. Its members are named as shown in **Fig. 2.** The bridge is modeled in 3D model with beam, shell elements and rigid truss joints. Isotropic plasticity material is employed to model both steel and concrete materials. Young's modulus of steel is $E = 2\times10^5 MPa$, and the one of concrete is $E = 0.23\times10^5 MPa$. Yield stress of steel and concrete are 315MPa and 21MPa respectively. Because redundancy analysis takes interest in maximum resistance of structure, steel is only allowed to develop stress to the point which test load reaching peak in material test. For steel SM490A, using in the bridge, peak is reached when strain is about 0.015. Hence, its hardening curve is going up linear until strain of 0.015 before it proceeds horizontally.

**Cases of study**

In addition to dead load *D*, the bridge was tested with effect of live load *L* prescribed in (JRA 2002). Truck load located in positions inducing largest axial force to target member. **Fig. 6** and **Fig. 7** detailed alignment of truck in cross section and a specific truck load for target D2 members in longitudinal direction. Investing the healthy case of bridge, two tensile members, D2(2-3) and D4(4-5) are selected as FCMs' candidates, and one compressive member U4(8-10) is also selected as candidate of compressive fracture critical members which is vital compressive ones. Hence three damaged bridge cases, *Case 2,3,4*, and one healthy case, *Case1*, are studied.

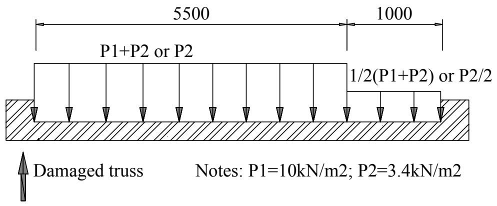


**Fig. 6** Truck load alignment in cross direction

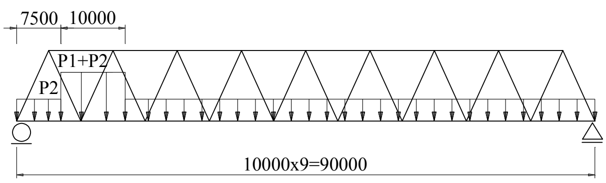


**Fig. 7** Specific truck load alignment for D2 members

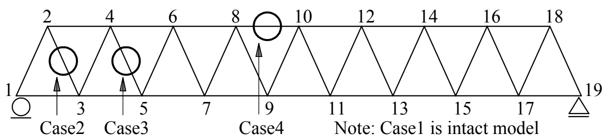


**Fig. 8** Cases of study

**Simulations of damaged member in FE model**

In reality, the member failure can appear at any load level and by various factors as corrosion, cracks. This study assumes that when failures existing on a certain member, that member, in all types of damages, will lose its function. Hence, the failure one can be released out of FE model. A static simulation of damaged Condition A at certain load level *D+aL* with *a* is attributed factor, is superposition of Condition B and C as in **Fig. 9**. Because this research purposes to study method of redundancy analysis, is not a single redundancy analysis of a specific bridge, the failure is simple assumed to appear at *D+0.5L.* This load level is also minimum requirement for an adequately redundant bridge as stated in (NCRHP-406 1998). The bridge was loaded until this assumed load through phased analysis in order to simulate stages of construction. By this phased analysis, the members constructed in later stage do not receive any forces from weight effect of members installed in former stages.

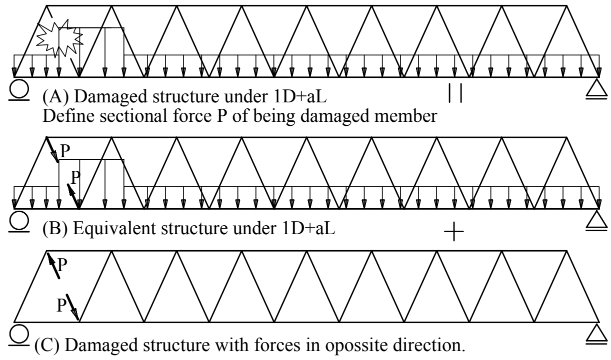


**Fig. 9** Simulation of member failure

$$u(t) = U\left[1 - e^{-\zeta\frac{2\pi}{T\sqrt{1-\zeta^2}}t}\left(\cos\frac{2\pi}{T}t + \frac{\zeta}{\sqrt{1-\zeta^2}}\sin\frac{2\pi}{T}t\right)\right]$$

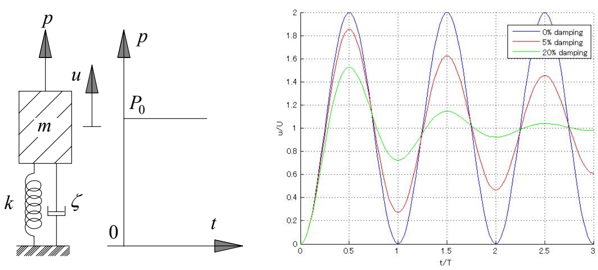


**Fig. 10** Dynamic response of a SDOF system

Furthermore, because dynamic effect due to sudden failure of members always exits, a magnified factor *I* which should be multiplied with Condition C is used for accounting the dynamic effect. (URS 2006) proposes *I* should be *1.854* by idealizing bridges a single degree of freedom (SDOF) system under typical acceptable *5%* damping. However, (Y. Goto 2011) concludes that magnified factor *I* is almost ranging from *1.4* to *1.8* under *5%* structural damping. This study used two values of magnified factor, including *1.0* and *1.854* for analysis.

**Static redundancy evaluation methods**

*Linear redundancy:* The resistance of structure is evaluated by member-strength checking through sectional forces from FE linear analysis. The tensile members and compressive members are treated separately by formula (1) and (2). $N_p$ and $M_p$ are plastic axial force and full plastic moments in in-plane and out-plane correspondingly. $N_u$ and $N_E$ are respectively ultimate compressive strength in consideration of buckling and buckling load. $M_{eq}$ is equivalent moment to convert linear varying moment to uniform moment case. These above constants are defined based on concept of yield stress, 315MPa for SM490A, without any safety factors. If any member gives $R \geq 1$, that member is considered as failure.

$$R = \frac{N}{N_p} + \left(\frac{M}{M_p}\right)_{out\text{-plane}} + \left(\frac{M}{M_p}\right)_{in\text{-plane}} \tag{1}$$

$$R = \frac{N}{N_u} + \left(\frac{1}{1-\frac{N}{N_E}}\right)\left(\frac{M_{eq}}{M_p}\right)_{out\text{-plane}} + \left(\frac{1}{1-\frac{N}{N_E}}\right)\left(\frac{M_{eq}}{M_p}\right)_{in\text{-plane}} \tag{2}$$

*Nonlinear* redundancy*:* If the bridge response in nonlinear analysis with physical nonlinearity and geometry nonlinearity passes the peak, it may conclude that the bridge collapses by load at the peak.

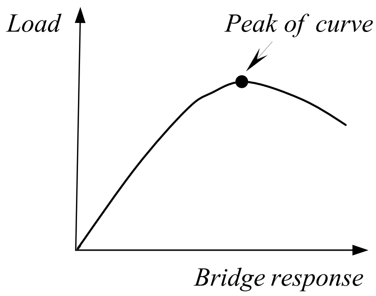


**Fig. 11** Collapse definition in nonlinear redundancy

## 3. Results

### Linear redundancy analysis

The member's strength checking confirms that all members giving R values much lower than 1.0 at load *1.0D+1.0L* in *Case1*. The largest value, *R=0.53*, appears on D2(2-3), one of FCM's candidate. Then, in this case first *R=1.0,* which occurring in D2 members, was yielded at load *1.0D+3.11L.* On the other hand, the damage of a member as in *Case2,3,4* results in many of remaining members giving *R>1.0*. These members are subsequently failed in strength due to a member loss, so the bridge is collapsed consequently. The subsequently strength-failed members are located nearby virtually break. **Table1** counts number of subsequently strength-failed members and shows largest *R* values in three post-damaged cases. All of 3 candidates cause subsequent collapse of the bridge due to their loss. The larges R values in case of accounting dynamic effect of sudden failure of a member is sharply larger than those in case not accounting that effect. *Case4* is giving a largest value in *Rmax* as well as number of subsequently strength-failed members.

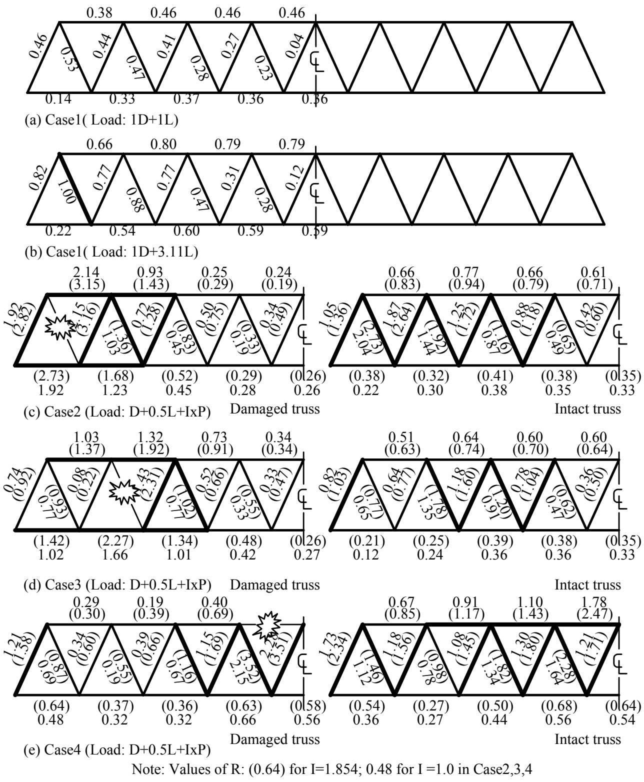


**Fig. 12** R values in studied cases

**Table 1** Summary of linear redundancy

| Cases | *I=1.00* | | *I=1.854* | |
|---|---|---|---|---|
| | *N°* | R max | *N°* | R max |
| *Case2* | *5* | *1.22* | *9* | *1.97* |
| *Case3* | *0* | *0.96* | *4* | *1.55* |
| *Case4* | *3* | *1.05* | *14* | *2.09* |

*N° is number of members have R>1*

### Nonlinear redundancy analysis:

By same load protocol, *Case1* is analyzed until final collapse of whole bridge. The member strain is observed during analysis. **Fig. 13** draws strain curve of D2(2-3) in analysis. This D2 member is always giving largest strain comparatively the others during analysis. At load

*1D+7.13L* the curve passes peak point, and the bridge is collapse. In additionally, in *Case2,3,4,* the being damaged member is gradually released by increasing load factor in Condition C from 0 to 1.854. **Fig. 14** shows strain curves in *Case2,3,4*. These curves are also drawn from member which giving largest strain during analysis. Load factor *I=1.0* means that virtual damaged member is fully released. All of curves do not proceed to their peak, so the bridge is not collapse due to the member loss even the dynamic effect is taken into account or not.

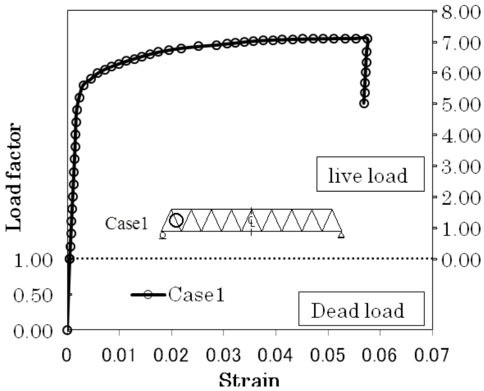


**Fig. 13** Load-strain curve in *Case1*

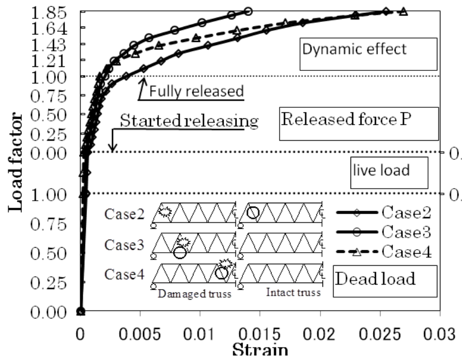


**Fig. 14** Load-strain curves in *Case2,3,4*

## 4. Discussions

**Table 2** compares conclusions of linear redundancy and nonlinear redundancy. It shows none of candidates is identified as FCMs by nonlinear redundancy while most of them are FCMs indentifying by linear redundancy. If the dynamic effect is not taken into account, the D4(4-5) is not a FCM. The bridge is rated as non-redundant by linear redundancy while it is classified as redundant by nonlinear redundancy.

The sectional forces of members are observed to clarify why difference exists between two approaches. **Fig. 15** plotted a comparison of section forces of being damaged D2(2-3) member in *Case1*. The other cases are going in same tendency. Before load factor 4.0 or load *1D+4.0L* in other word, axial force and moment in linear and nonlinear redundancy proceed in same line. However, linear redundancy result said that this D2 started yielding R=1.0 at *1D+3.11L*. Hence, the formula (1) and (2) may underestimate the strength of member.

**Table 2** Comparison between two approaches

| **Cases** | **I=1.000** | | **I=1.854** | |
|---|---|---|---|---|
| | Linear | Nonlinear | Linear | Nonlinear |
| FCM | *D2 ,U4* | *None* | *D2,D4,U4* | *None* |
| Redundancy | *No* | *Yes* | *No* | *Yes* |

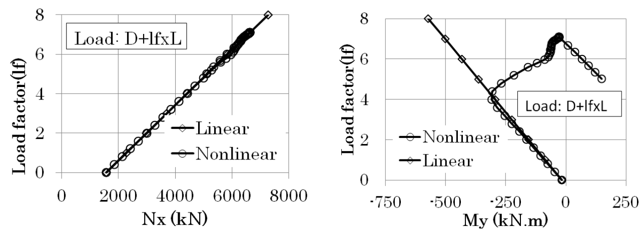


**Fig. 15** Sectional forces of D2(i1-13) in *Case 1*

## 5. Conclusion

Both linear and nonlinear redundancy methods are investigated in this study. A comparison between them shows that two approaches result in different identification of FCMs. The linear redundancy method gives a lower redundant rating than nonlinear method does.

## 6. References

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