# Damage Evaluation of Truss Bridges Using a Reliability-Based Assessment Technique

Y.Q. NI, K.F. WAT, J.M. KO AND X.G. HUA

**ABSTRACT:**

This paper presents an investigation on damage evaluation of truss bridges using long-term measurement data of strain. A reliability-based method is proposed for structural damage evaluation, in which the safety index of each structural member is assessed making use of the long-term monitoring data of strain and reliability analysis; subsequently an examination of the change in safety index before and after damage is made to identify the damaged member(s). The proposed method possesses two salient merits: (i) it directly uses long-term measurement data of strain for damage evaluation without need of structural model, and (ii) it provides quantitative information to bridge managers for decision making on optimizing and prioritizing bridge inspection and maintenance. This paper focuses on the study of: (i) the effect of damage on structural member safety index for determinate and indeterminate truss bridges, respectively, (ii) the influence of inconsistent loading levels before and after damage on the evaluated safety index, and (iii) the influence of different probability distribution types (normal, lognormal, and mixed) of the load effect and resistance on the evaluated safety index. Some important conclusions are obtained from the study.

## INTRODUCTION

Structural health monitoring has become an important tool for diagnosing structural health and conditions of bridges [1, 2]. Successful implementation and operation of long-term structural health monitoring systems on bridges has been reported worldwide. When a bridge is instrumented with a structural health monitoring system, the bridge managers want to know how the monitoring system benefits the inspection, maintenance, and management of the bridge, and how to use the monitoring data for bridge health and condition assessment. While the development of structural health monitoring methods for the detection of damage occurrence, location

Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong. E-mail: ceyqni@polyu.edu.hk (Y.Q. Ni).

and severity has now attained some degree of maturity, the application of the monitoring data for instructing bridge inspection, maintenance and management is still in its infancy [3]. A gap between health monitoring technology and bridge inspection, maintenance and management exercises exists currently which impedes bridge managers to benefit from the monitoring system. Research efforts are increasingly devoted to exploring monitoring data for improved operational efficiency of structures, safety/reliability enhancement, and lower maintenance costs.

In the present study, a reliability-based method is proposed for structural health and safety evaluation of truss bridges. Following the proposed method, the safety index of each structural member is assessed making use of the long-term monitoring data and reliability analysis, and then an examination of the change in safety index before and after damage is made to identify the damaged member(s). This method directly uses strain/stress measurement data for safety index and damage evaluation without need of structural model, and also accounts for uncertainty and randomness inherent in the measurement data and structure. More importantly, it is able to provide quantitative information to bridge managers for decision making on optimizing and prioritizing bridge inspection and maintenance. After examining the performance of the proposed method to determinate and indeterminate truss bridges, the present study is devoted to investigating the effects of inconsistence in the applied loads before and after damage and different probability distribution types of the response and resistance on the safety index evaluation accuracy.

**RELIABILITY-BASED EVALUATION METHOD**

According to reliability theory, the failure probability $P_f$ of a structural component can be evaluated by considering both the member resistance (capacity) $R$ and the load effect $S$ as random variables:

$$P_f = \iint_{r-s<0} f_R(r) f_S(s) dr ds \tag{1}$$

where $f_R(r)$ and $f_S(s)$ are probability density functions of $R$ and $S$. In the proposed method, the probability density function of the load effect $S$ is obtained directly from continuously measured strain or derived from continuously measured strain. When the measured stress distribution varies due to structural damage or loading condition, the probability density function $f_S(s)$ thus obtained will be changed accordingly. The probability density function of the resistance (capacity) $R$ for a structural member is determined using the mean and standard deviation of material strength prescribed in provisions or obtained by in-situ material testing.

Eq. (1) can be alternatively expressed as

$$P_f = P(R - S < 0) = \iint_{R<S} f_{R,S}(r,s) dr ds \tag{2}$$

where $f_{R,S}(r,s)$ is the joint probability density function of $R$ and $S$. Because both $R$ and $S$ are the functions of a set of basic random variables $X = \{X_1, X_2, \cdots, X_n\}^T$ that represent material properties, geometrical parameters, loads, etc., a limit state function $g(X) = 0$

describing the failure surface that separates the survival region from the failure region can be defined. Thus Eq. (2) can be further expressed as

$$p_f = \int \cdots \int_{g(X)<0} f_{X_1,X_2,\cdots,X_n}(x_1, x_2, \cdots, x_n)dx_1dx_2\cdots dx_n \tag{3}$$

where $f_{X_1,X_2,\cdots,X_n}(x_1, x_2,\cdots,x_n)$ is the joint probability density function of the basic random variables. Because of difficulty in analytical solution, various approximation methods have been developed to solve Eq. (3). Among others the first-order reliability method (FORM) is the most commonly used one [4]. FORM approximates the limit state function using a linearized hyper-plane at the design point in the transformed standard normal space $u$ and the safety index (reliability index) $\beta$ is interpreted as the minimum distance from the origin to limit state surface in this space. That is

$$\beta = \left(u^{*T}u^*\right)^{\frac{1}{2}} \tag{4}$$

where $u^*$ is the design point in the $u$-space. Provided that the limit state is well-behaved, the probability of failure can be obtained by

$$P_f \approx \Phi(-\beta) \tag{5}$$

where $\Phi(\ )$ is the distribution function of the standard normal variate.

When the safety indices of structural components are evaluated at regular intervals using the long-term monitoring data, structural damage is alarmed if a notable change in safety indices is observed, and the structural member with the maximum reduction in safety index is identified as the damaged member. Additionally, with the evaluated safety indices, it is easy to decide bridge inspection/maintenance strategy because the correspondence between the safety index and the required maintenance action has been investigated and formulated by several researchers [5, 6]. Table 1 gives such a correspondence adopted in the present study. Thus a linkage among the structural health monitoring, bridge safety assessment, and decision making on bridge inspection and maintenance has been established.

Table 1: Relationship between safety state and maintenance action.

| Safety State | 5 | 4 | 3 | 2 | 1 |
|---|---|---|---|---|---|
| Safety Index | $\beta > 9.0$ | $9.0 > \beta > 8.0$ | $8.0 > \beta > 6.0$ | $6.0 > \beta > 4.6$ | $4.6 > \beta$ |
| Attribute for Safety | excellent | very good | good | fair | unacceptable |
| Maintenance Action | no action | preventive inspection | detailed inspection | possible strengthening | rehabilitation |

## APPLICABILITY TO TRUSS BRIDGES

The applicability of the proposed method to determinate and indeterminate truss bridges is first examined. Figure 1 shows a statically determinate truss bridge (bridge 1) and a statically indeterminate truss bridge (bridge 2). The material and geometrical properties and the applied loads of the two structures are as follows: Young's modulus of each member is $E = 200$ GPa; cross-section area of each member is $A = 0.01$ m$^2$;

mass density is $\rho = 7800$ kg/m$^3$; superimposed dead load is 10 KN/m; yield stress $F_y$ is determined from design provisions as a normal variable with the mean of 252.5 MPa and the standard deviation of 29 MPa [7, 8]; the applied live loads $V$ are uncorrelated normal variables with the mean of 120 kN and the standard deviation of 12 kN.



(a) Statically determinate truss bridge (bridge 1)



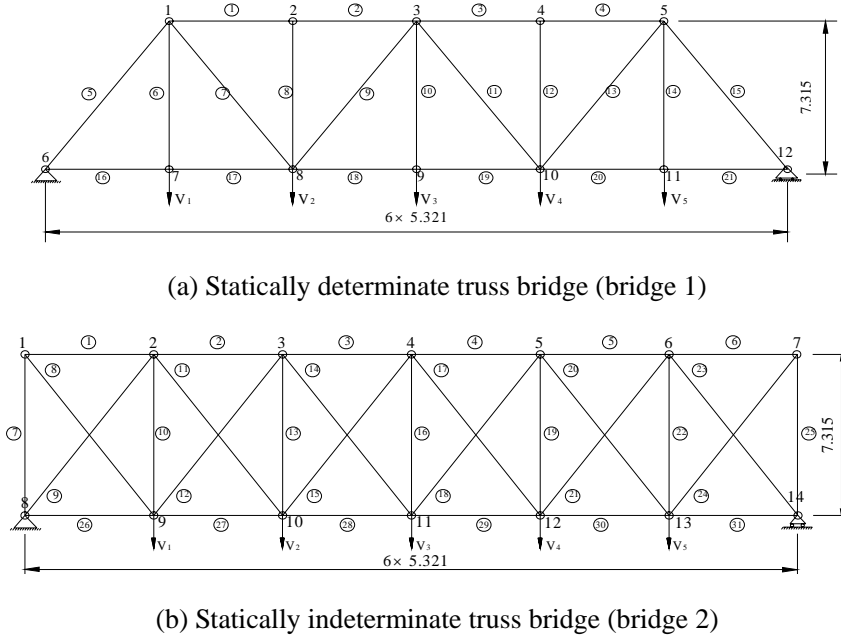(b) Statically indeterminate truss bridge (bridge 2)

Figure 1: Two truss bridges.

The determinate structure (bridge 1) is first studied. When a bridge is instrumented with a long-term monitoring system, the stress of structural members under normal operational conditions can be measured. In this study, the stress measurement data (history) for each member is simulated by applying the random loads $V$ to a finite element model of the structure. With the 'measured' statistical properties of the stress, the safety indices for all structural members of the intact (healthy) bridge are obtained by FORM. Figure 2(a) shows such obtained safety indices of bridge 1 in healthy state, which indicate the real safety reserve of each structural member when the bridge is built.



(a) Safety index of intact structure   (b) Safety index versus damage extent
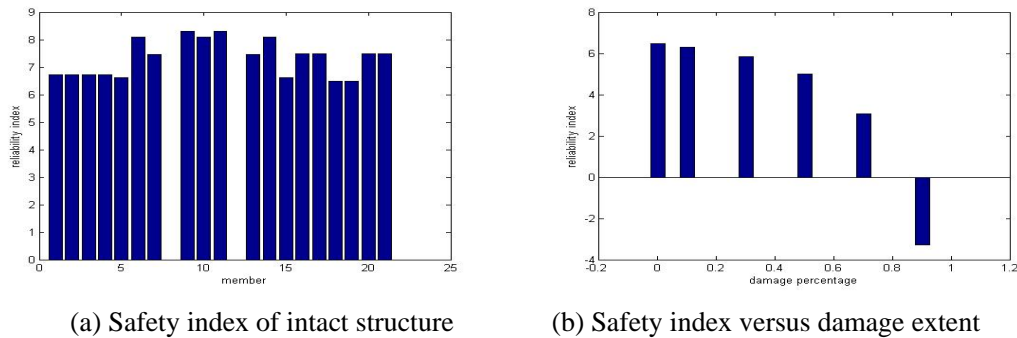
Figure 2: Safety index of intact structure and its change with damage extent (bridge 1).

Two damage scenarios are considered. The first scenario is the single-damage case with damage occurring at member 18, and the second scenario is the multi-damage case with damage occurring at both members 9 and 18. The damage extent is assumed as 10%, 30%, 50%, 70% and 90% reduction respectively in the cross-section area of the concerned members. The safety indices for all structural members are re-evaluated in each damage case. It is found that for the determinate structure, the damage only causes reduction of the safety indices for damaged members while the safety indices for undamaged members remain unchanged. Figure 2(b) shows the safety index versus damage extent for member 18 in the single-damage case. It is evident that the safety index of the damaged member decreases gradually with increasing damage extent. When the evaluated safety index is lower than the thresholds given in Table 1, proper strengthening and rehabilitation should be acted. It is concluded that for determinate truss bridges, the damaged member(s) can be accurately identified by the proposed method and the damage extent is reflected by reduction in the safety index.

The indeterminate structure (bridge 2) is also studied by considering the single-damage and multi-damage cases. It is found that for the indeterminate structure, the damage not only causes reduction of the safety indices for damaged members, but also induces change of the safety indices for undamaged members. This is due to the fact that the stresses in all members of a statically indeterminate structure are redistributed when one member incurs damage. Figure 3 shows safety index versus damage extent for the five members which have the largest change in safety index. It is seen that when single-damage occurs at member 29, the safety index has much larger reduction for the damaged member than for undamaged members; when multi-damage occurs at both members 4 and 17, it results in a significant reduction of the safety index for member 4 but affects member 17 insignificantly when the damage is not severe. It is concluded that for indeterminate truss bridges, one damaged member can be identified by observing the greatest reduction in safety index. However, considering the safety index reduction in other members may result in false-positive damage identification in single-damage case, while inferring only the greatest safety index reduction may result in false-negative damage identification in multi-damage case.
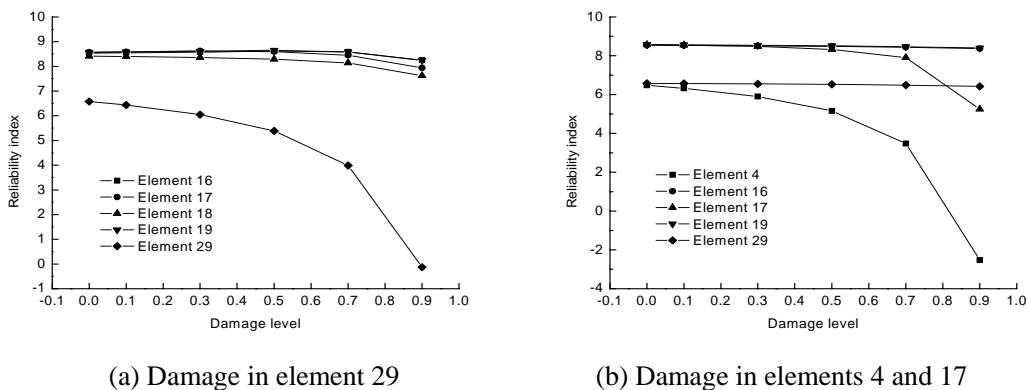


(a) Damage in element 29                    (b) Damage in elements 4 and 17

Figure 3: Safety index versus damage extent (bridge 2).

## TOLERANCE TO INCONSISTENCE IN LOADING LEVELS

The level of applied loads on a real structure in its intact (healthy) state may be different from that in damage state. The effect of inconsistence in loading levels before and after damage on the evaluated safety index is studied for both the determinate truss bridge (bridge 1) and the indeterminate truss bridge (bridge 2). The damage for bridge 1 is assumed to occur at member 18 with 10% to 90% reduction in the cross-section area, and the damage for bridge 2 is assumed to occur at member 29 with 10% to 90% reduction in the cross-section area. Figure 4 shows the evaluated safety index versus damage extent for the damaged members (member 18 in bridge 1 and member 29 in bridge 2) in the following three cases: (i) the mean of random applied loads after damage is the same as that before damage (but different load sequences), (ii) the mean of random applied loads after damage is 10% less than that before damage, and (iii) the mean of random applied loads after damage is 10% larger than that before damage. It is observed from Figure 4 that for both the determinate and indeterminate structures, the difference of the evaluated safety indices obtained under consistent load levels and obtained under inconsistent load levels is insignificant. It means that the proposed method is robust and tolerant to the inconsistence (difference) in loading levels before and after damage.
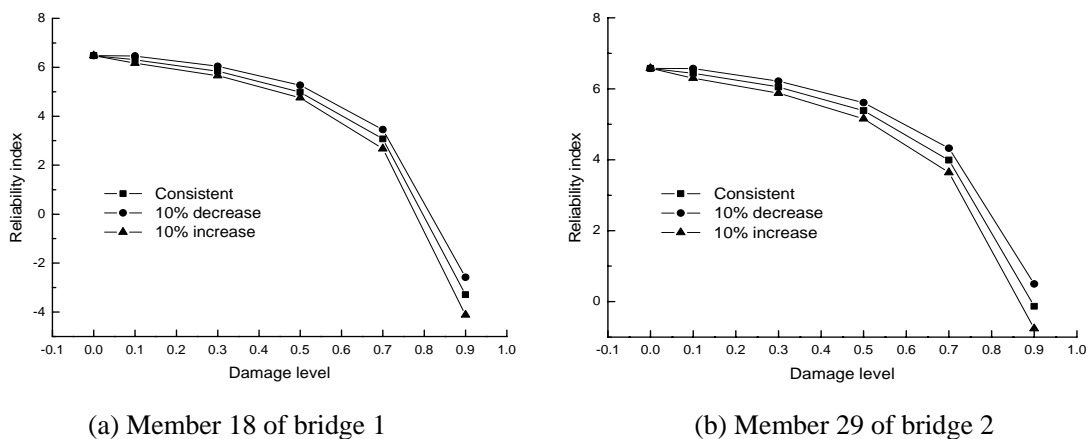


(a) Member 18 of bridge 1        (b) Member 29 of bridge 2

Figure 4: Effect of inconsistence in loading levels on evaluated safety index.

## INFLUENCE OF PROBABILITY DISTRIBUTION TYPE

In the above simulation study, both the applied forces and yield stress are assumed to comply with normal probability distributions. For a real structure, the statistical properties (mean, standard deviation, and probability distribution type) of both the load effect and resistance can be determined using long-term monitoring and material testing data. With the long-term measurement data, the mean and standard deviation of a random variable are obtained via statistical analysis, and its probability distribution type is estimated by trying different probability distribution functions and figuring out the best-fitted one. In the following, the influence of probability distribution type of

the applied loads and yield stress on the evaluated safety indices of structural members is examined. The determinate truss bridge (bridge 1) is taken as an example, where the damage is assumed to occur at member 18 with 10% to 90% reduction in the cross-section area.

With the fixed mean and standard deviation for both the applied loads and yield stress same as before (the applied loads have the mean of 120 kN and the standard deviation of 12 kN, and the yield stress has the mean of 252.5 MPa and the standard deviation of 29 MPa), the following three cases are considered: (i) both the applied loads and yield stress comply with normal probability distributions, (ii) both the applied loads and yield stress comply with lognormal probability distributions, and (iii) the applied loads and yield stress comply with normal and lognormal probability distributions (mixed), respectively. Table 2 shows a comparison of the evaluated safety index values of member 18 in healthy state, obtained by assuming different probability distribution types (normal, lognormal, and mixed). Figure 5 illustrates the safety index values of all structural members in healthy state and the change in the safety index of member 18 with damage extent, obtained under different probability distribution types. It is observed that the evaluated safety index of a structural member under the same mean and standard deviation but different probability distribution types for the applied loads and yield stress is significantly different. In order to accurately evaluate the safety index, the probability distribution types of the load effect and resistance should be correctly identified.

Table 2: Safety index of member 18 in healthy state (bridge 1).

| Probability distribution type | | Member 18 in healthy state |
|---|---|---|
| $S$ | $R$ | $\beta$ |
| Normal | Normal | 6.478 |
| Lognormal | Lognormal | 10.965 |
| Normal | Lognormal | 11.813 |



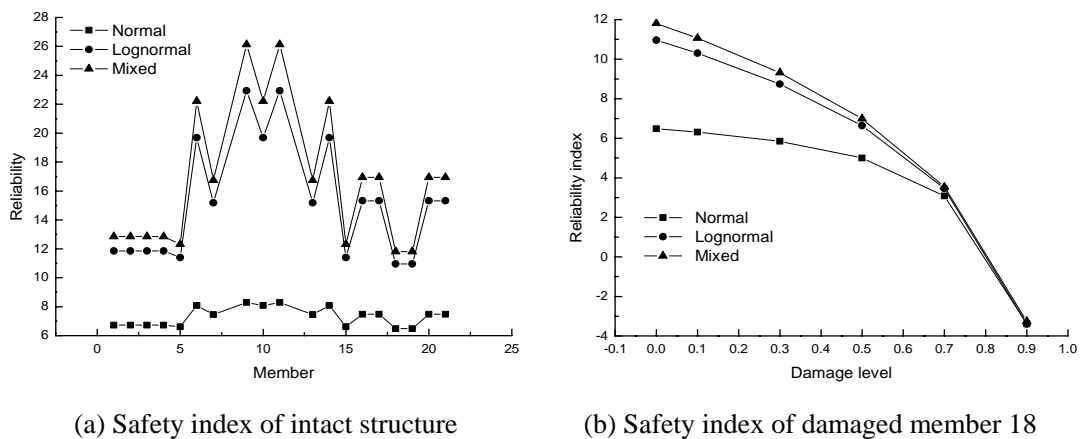(a) Safety index of intact structure      (b) Safety index of damaged member 18

Figure 5: Safety index of bridge 1 under different probability distribution types.

**SUMMARY**

In this study, a reliability-based method is proposed for structural health and safety evaluation of truss bridges. This method uses strain/stress measurement data for safety index and damage evaluation, and accounts for uncertainty and randomness inherent in the measurement data and the structure. It is able to provide quantitative information for bridge inspection and maintenance. The numerical simulation results show that the proposed method can accurately identify both single- and multi-damage scenarios for statically determinate structures. For statically indeterminate structures, the proposed method can unambiguously identify the member incurring the largest damage but may give rise to false-positive or false-negative evaluation results for other members. As a salient advantage, this method is insensitive to difference in loading levels before and after structural damage. The evaluated safety index by assuming different probability distribution types of the load effect and resistance may noticeably differ; as a result, it is essential to properly identify the distribution type of strain/stress based on long-term measurement data.

**REFERENCES**

1. D. J. Pines, and A. E. Aktan. Status of Structural Health Monitoring of Long-Span Bridges in the United States. *Progress in Structural Engineering and Materials*, 4(4), 372-380. (2002)

2. J. M. Ko, and Y. Q. Ni. Technology Developments in Structural Health Monitoring of Large-Scale Bridges. *Engineering Structures*, 27(12), 1715-1725. (2005)

3. B. Yanev. Structural Health Monitoring as a Bridge Management Tool, *in Structural Health Monitoring and Intelligent Infrastructure*, (Editors: Z. S. Wu, and M. Abe). *Balkema*, pp. 87-95. (2003)

4. R. Rackwitz. Reliability Analysis – A Review and Some Perspectives. *Structural Safety*, 23(4), 365-395. (2001)

5. D. M. Frangopol, J. S. Kong, and E. S. Gharaibeh. Reliability-Based Life-Cycle Management of Highway Bridges. *Journal of Computing in Civil Engineering*, ASCE, 15(1), 27-34. (2001)

6. R. J. Lark, and K. D. Flaig. The Use of Reliability Analysis to Aid Bridge Management. *The Structural Engineer*, 83(5), 27-31. (2005)

7. A. S. Nowak. Calibration of LRFD Bridge Design Code. *Report No. UMCE 93-22*, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, USA. (1993)

8. A. C. Estes, and D. M. Frangopol. Repair Optimization of Highway Bridges Using System Reliability Approach. *Journal of Structural Engineering*, ASCE, 125(7), 766-775. (1999)