Maintenance Strategy for Bridges using Reliability Concept and Analytical Hierarchy Process

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Abstract

Civil infrastructure in most of countries is getting old and therefore, there is a tremendous need to assess their safety levels. Among civil infrastructure, bridges are one of the main components and there is a need to study more on their safety and durability to minimize the maintenance cost and to avoid sudden failures. This paper presents bridge maintenance strategy which consists of two parts: (1) reliability based condition assessment procedure and; (2) analytical hierarchy process (AHP) based resources prioritization. In reliability based assessment, safety margins are initially proposed depending on the types of bridges. It is assumed that load and strength are random variables. Elementary reliability indices and thereby elementary failure probabilities are estimated for each safety margins. Then, system failure probability of the bridge is calculated for the time of consideration. Finally, this system failure probability is used to get system reliability index of the bridge and it is used as an index to express the condition of the bridge for the considered time. Secondly, AHP is implemented to identify the order of resources prioritization among set of bridges. The selected criteria are safety, cost of maintenance actions and relative importance of the bridge. Relative importance varies depending on historical importance, age and route of bridge location. The proposed methodology is applied to a collection of five bridges in Sri Lanka to estimate their safety levels and resources prioritization in bridge maintenance.

Keywords: Reliability, analytical hierarchy process, bridge maintenance

1. Introduction

Most of current condition assessment procedures are based on visual inspections made by bridge inspectors at varying time intervals (Sommer et al. 1993). Visual inspection is labor-intensive, tedious, expensive, inconsistent and objective (Koh and Dyke 2007). Since human inspection depends on the individual inspector, there exists a degree of uncertainty in results itself. Therefore, absolute dependence on visual inspection reports is not reliable and may often lead to incorrect decision-making, which causes high maintenance costs for bridge owners and sudden bridge failures such as recent Minnesota I-35W bridge failure. These losses in terms of financial, physical, and other resources are unacceptable, irrespective of the wealth of a country. In fact, human experience should always be incorporated into maintenance decisions, but with sufficient subjective knowledge. Only then, any strategy has acceptable performance. The complexity of structural condition assessment of bridge maintenance has energized researchers into formulating general methods of condition assessment for bridges. Thus, any proposed condition assessment procedure should be based on results of field studies as well as subjective understandings accepted by practicing engineers. Since there are many uncertainties existing in current procedures, a probabilistic approach is advantageous over deterministic approaches (Estes and Frangopol 2005). In this situation, reliability based methods can provide a rational approach to use scarce resources efficiently while maintaining a prescribed level of reliability of a structure throughout its designated service life.

In addition, there should be a proper method for resource allocation among a set of bridges when decisions are to be made on their resources prioritization. In most of countries, resource prioritization is not clearly defined. This insufficiency of decision making tools results some of bridges are virtually getting no resources. Therefore, there should be a sound and logical meaning of resources allocation of bridges so that most practicing engineers can be in agreement. The analytical hierarchy process (AHP) is a structured technique for dealing with complex decisions and it has been successfully used in many complex decision making problems (Satty 2001). Therefore, this paper introduces the application of AHP based resource prioritization of bridges.

2. Proposed maintenance strategy

Proposed maintenance strategy consists of two sections. First, the section outlines the reliability based condition assessment procedure for bridges. Then, second section explains the application of AHP in resource prioritization.

2.1 Reliability based assessment procedure

Bridges can fail due to a number of critical failure modes, depending on the type of bridge. For steel bridges, fatigue is the dominant failure mode. But corrosion also has a considerable impact on the life of steel bridges. Reinforced concrete bridges are influenced by moment and shear. In masonry arch bridges, load carrying capacity is generally considered as the main criteria the main criterion. In wooden deck bridges, tensile strength of planks is the main criterion.

Critical failure modes are initially identified for the considered bridge. These failure modes are expressed in mathematical formulae to evaluate the structural health of bridges. Such mathematical formula is defined as safety margin or limit state function. The safety margin M_i for the i^{th} mode of failure of the bridge is defined as:

$$M_i = Z_{R_i} - Z_{S_i} \qquad i = 1,2...,n \tag{1}$$

where Z_{R_i} is the strength variable and Z_{S_i} is the load variable. When $Z_{R_i} > Z_{S_i}$, the bridge is in a safe state and when $Z_{R_i} < Z_{S_i}$, the bridge is in a failure state. If the means and standard deviations of the resistance and load variables are known, then a reliability index can be found for the i^{th} failure mode as (Christensen and Baker 1982; Christensen and Murotsu 1986):

$$\beta_i = (\mu_{ZRi} - \mu_{ZSi}) / \sqrt{(\sigma_{ZRi}^2 + \sigma_{ZSi}^2)} \qquad i = 1,2,...,n \tag{2}$$

In Eq. (2), μ_{ZRi} and σ_{ZR_i} are the mean and the standard deviation of the strength variable, while μ_{ZSi} and σ_{ZS_i} are the mean and the standard deviations of the load variable. The reliability index expresses the condition of a bridge as the mean value of the safety margin divided the standard deviation of the safety margin. Generally, the higher the value of reliability index, the better the condition of the bridge. It is assumed here that both strength and load variables are normally distributed. The assumption of normality in variables simplifies calculation of failure probability while maintaining a satisfactory accuracy.

If the reliability index is known, failure probability P_{f_i} can be calculated as:

$$P_{f_i} = \phi(-\beta_i) \qquad i = 1,2...,n \tag{3}$$

where ϕ is the standard unit normal distribution. Substituting Eq. (2) into Eq. (3) yields (Christensen and Baker 1982; Christensen and Murotsu 1986):

$$P_{f_i} = 1 - \phi\left[(\mu_{ZRi} - \mu_{ZSi}) / \sqrt{(\sigma_{ZRi}^2 + \sigma_{ZSi}^2)}\right] \qquad i = 1,2,...,n \tag{4}$$

The physical meaning of the failure probability is that it conveys the idea of how close the failure state is. Hence, higher values for failure probabilities imply greater chance of failure.

According to Eq. (4), for each failure mode (*i =1,2,….n*), the elementary reliability index and the elementary failure probability are calculated. The next step is to calculate the system failure probability. The actual failure of a bridge can be attributed to several failure modes. Thus, a system model has to be built up. In this context, it is assumed that all failure modes are combined with a series system. Hence, it is possible to calculate the system failure probability from a simple bound as (Christensen and Baker 1982; Christensen and Murotsu 1986):

$$\underset{i=1,2}{\overset{n}{Max}} P_{f_i} \le P_F \le 1 - \prod_{i=1}^{n} (1 - P_{f_i}) \tag{5}$$

The lower bound of Eq. (5) represents the situation where all n failure modes are uncorrelated and the upper bound represents the case when all n failure modes are correlated. Having found the system failure probability, it is possible to convert it to get a system reliability index as follows:

$$\beta_S = -\phi^{-1}(P_F) \tag{6}$$

This system reliability index can be used to express the present condition of the bridge. If $\beta_s \ge \beta_{accp.}$, the bridge condition is safe whereas $\beta_s < \beta_{accp.}$, the bridge condition is not safe to operate.

It is necessary to estimate acceptable reliability index ($\beta_{accp.}$) of the bridge to estimate its service life. The selection of a reasonable value for the acceptable reliability index of a bridge should depend on many safety and economic considerations such as type of failure, importance of bridge, human and property loss, and economic consequences. There are few studies that are focused on estimating acceptable reliability indices of existing bridges. In this study, the acceptable reliability index proposed by Nordic committee on building regulation (Sarveswaran and Roberts 1999) is used for the acceptable reliability index ($\beta_{accp.}$). The method considers both the structural performance and economic considerations of a civil structure. Further, it has been successfully applied to assess a corroded reinforced concrete bridge by Sarveswaran and Roberts and short span bridges by Carlsson 2002.

Table 1: Acceptable reliability index from Nordic committee on building regulations

Failure consequences	*Ductile failure with reserve strength*	*Ductile failure without reserve strength*	*Brittle failure*
Not serious	*3.09*	*3.71*	*4.26*
Serious	*3.71*	*4.26*	*4.75*
Very serious	*4.26*	*4.75*	*5.20*

The flowchart of the reliability based condition assessment procedure is shown in Figure 1.

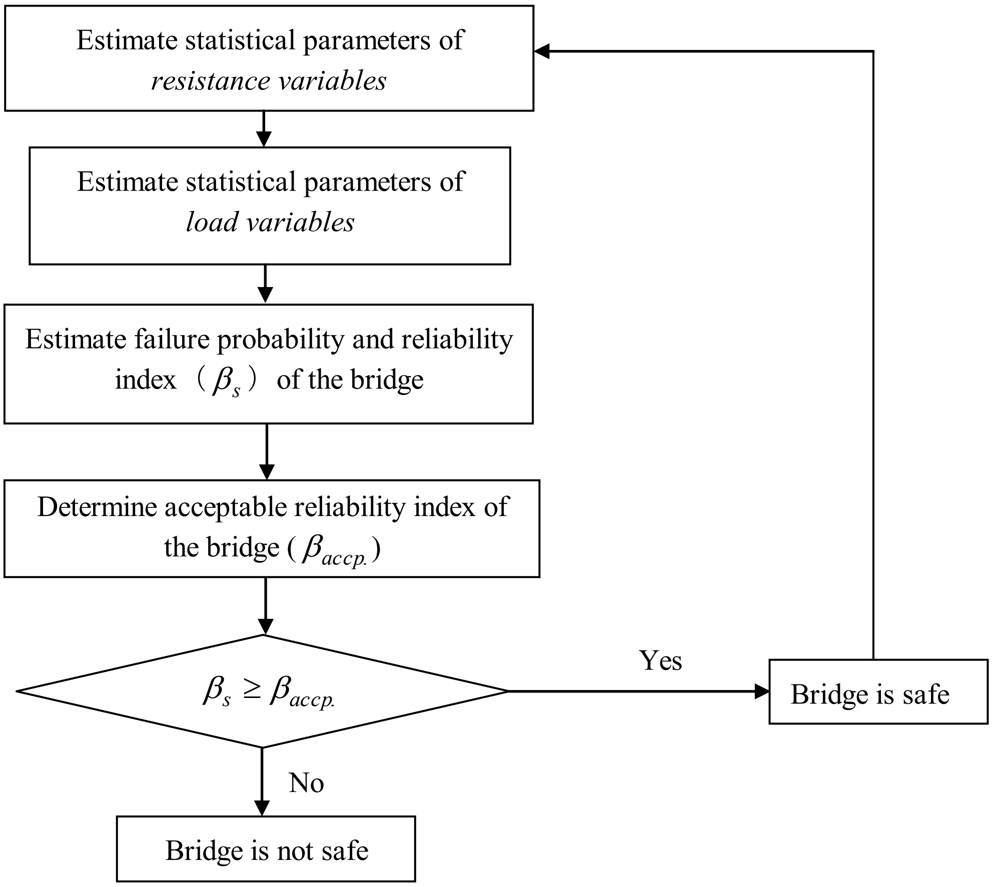

Figure 1: Flowchart of the assessment of bridges by reliability concept

2.2 Analytical hierarchy process based resources prioritization

The AHP is a structured technique for dealing with complex decisions. Problems are decomposed into a hierarchy of criteria and alternatives. Rather than prescribing a "correct" decision, the AHP helps decision makers find one that best suits their goal and their understanding of the problem. Based on mathematics and psychology, the AHP was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions.

In bridge maintenance, prioritization of resources allocation is one of the main problems for bridge authorities. This problem is even more highlighted as funding for bridge maintenance is limited and not sufficient. Unless resources are allocated in more logical and meaningful way, authorities are faced with ever increasing deficient bridges. Currently, most of countries adopt their own methodologies for resources allocations. Most of such methods are without logical reasoning and therefore makes lot of problems to bridge authorities.

AHP is applied with the decomposition of the maintenance problems into objective, criteria and alternatives. The considered criteria are safety, cost of the maintenance actions and importance of the bridge. Considered group of bridges (*N*- number of bridges) are assigned as alternatives. The objective, criteria and alternatives are schematically shown in Figure 2.

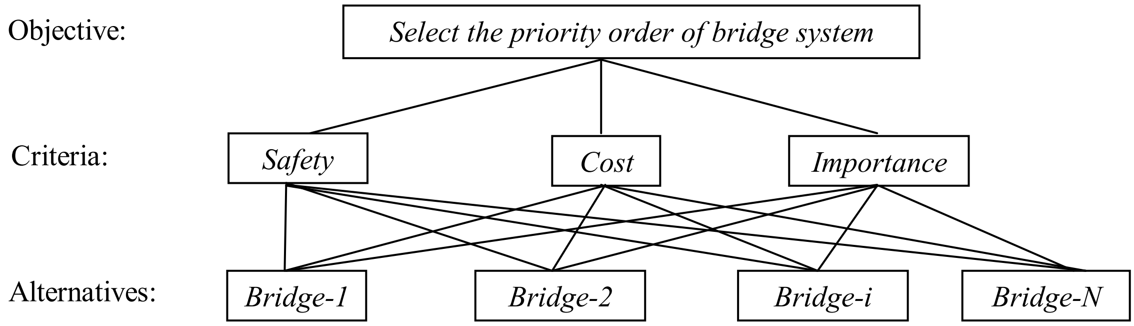

Figure 2: Schematic representation of AHP in resources prioritization

Initially, the criteria are compared pairwise with the objective of problem to obtain their relative significance. For this comparison, a number is selected from a numerical scale of 1-9 as shown in Table 2 (Triantaphyllou and Mann 1995).

Table 2: Scale for relative significances

Intensity of importance	*Definition*	*Explanation*
1	*Equal importance*	*Two activities contribute equally to the objective*
3	*Weak importance of one over another*	*Experience and judgment slightly favor one activity over another*
5	*Essential or strong importance*	*Experience and judgment strongly favor one activity over another*
7	*Demonstrated importance*	*An activity is strongly favored and its dominance demonstrated in practice*
9	*Absolute importance*	*The evidence favoring one activity over another is of the highest possible order of affirmation*
2, 4, 6, 8	*Intermediate values between the two adjacent judgments*	*When compromise is needed*
Reciprocals of above nonzero	*If activity i has one of the above nonzero numbers assigned to it when compared with activity j. Then j has reciprocal value when compared with i.*	

Using the scale, pairwise comparison is mathematically expressed in the form of a matrix. Eigen vector give the relative significance of criteria quantitatively. Secondly, alternatives (bridges) are compared considering one criterion at one time. For this comparison, real data sets can be used. On other hand, if there is not such available data, numerical values given in Table 2 are used. Thirdly, these two numerical results are combined to get the priority order of bridges for resources allocation. Therefore, the highest resources priority is given to the bridge having highest numerical value and the least resources priority is given to the bridge having least numerical value.

One of the most practical issues in the AHP methodology is that it allows identifying non-consistent pairwise comparisons. The matrix is considered to be adequately consistent if the corresponding consistency ratio (CR) is less than 10%. First consistency index (CI) needs to be estimated. This is done by adding the columns of matrix and multiplying the resulting vector by the values of Eigen vector. This yields an approximation of the maximum Eigen value, denoted by $\lambda_{\max}$. Then, the CI value is calculated by using following formula:

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)} \tag{7}$$

where n is the number criteria in the problem. Then, CR is obtained by dividing the CI value by random consistency index (RCI). RCI is given in Table 3.

Table 3: RCI values for different values of n

n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
RCI	*0*	*0*	*0.58*	*0.90*	*1.12*	*1.24*	*1.32*	*1.41*	*1.45*

3. Case study

Five bridges from the national bridge network were selected to demonstrate the proposed methodology. One bridge is a railway bridge while others are freeway bridges. The views of the bridges are shown in Figure 3. The geometric details of the bridges are given in Table 4.

Table 4: Details of the selected bridges

Name	*Class*	*Type*	*Construction year*	*No of spans*	*Bridge span (m)*
Kelani railway bridge	*Railway*	*Steel truss*	*1885*	*8*	*160.0*
Mawanella bridge (A 90/1)	*A*	*Brick arch*	*1833*	*4*	*70.0*
Elahera bridge (B312 43/2)	*B*	*R/F concrete*	*1977*	*1*	*5.4*
Yatiyantota bridge (B482 32/3)	*B*	*Wooden deck*	*1977*	*1*	*18.0*
Hatton bridge (A7 78/3)	*A*	*Stone arch*	*1918*	*1*	*14.0*

(a) (b) (c)

(d) (e)

Figure 3: Views of (a) Kelani railway bridge; (b) Mawanella bridge; (c) Elahera bridge; (d) Yatiyantota bridge; (d) Hatton bridge

3.1 Condition assessment of bridges

Reliability modelling of these bridges has been successfully carried out and already published (Karunananda 2004; Dissanayake and Karunananda 2008; Karunananda et al. 2010). As mentioned in introduction, the fatigue failure was considered the failure criterion for steel truss bridge, moment and shear capacities for reinforced concrete bridges, load carrying capacity for masonry arch bridges and tensile strength for wooden plank deck bridges. Load and strength variables of each failure mode are considered to behave as Gaussian variables. Table 5 summarizes the system reliability indices of five bridges.

Table 5: System reliability of bridges

Bridge name	*System reliability*
Kelani railway bridge	*4.33*
Mawanella bridge (A 90/1)	*4.99*
Elahera bridge (B312 43/2)	*4.14*
Yatiyantota bridge (B482 32/3)	*4.54*
Hatton bridge (A7 78/3)	*4.91*

Acceptable reliability index of a bridge is selected as 4.26. Except Elahera bridge, all others have higher system reliability than acceptable reliability index. However, it is marginally within the limits of acceptable reliability index. Therefore, all five bridges have satisfactory condition.

3.2 Resources allocations using AHP

As shown in Figure 2, safety, cost and importance were considered as the three main criteria for resources allocations. The relative significance of safety over cost was high and therefore a value of 2 was assigned for safety vs. cost. Then, the relative significance of safety over importance was very high and therefore, a value of 5.0 was assigned for safety over importance. The relative significance of cost over importance was appreciably high and therefore, a value of 3.0 was assigned. Then, the matrix for criteria was made as shown in Table 6.

Table 6: Matrix for relative importance of criteria

Criteria	*Safety*	*Cost*	*Importance*
Safety	*1.00*	*3.00*	*7.00*
Cost	*0.33*	*1.00*	*5.00*
Importance	*0.14*	*0.20*	*1.00*

After 3 iterations, Eigen vector of the criteria were determined as shown in Table 7. For this comparison, $\lambda_{\max}$ was obtained as 3.066, CI was 0.033 and RCI was 0.58. Then, CR was estimated as 0.06. This value is less 0.1 and therefore selected values in Table 6 are consistent with each other.

Table 7: Eigen values of criteria

Criteria	*Eigen value*
Safety	*0.6490*
Cost	*0.2790*
Importance	*0.0720*

Then, considering each criterion, Eigen vectors of alternatives are obtained as shown in Tables 8, 9 & 10. Table 8 gives Eigen values for safety criterion. Failure probabilities of each bridge were used in obtaining these values. As Elahera bridge has the lowest system reliability index (Table 5), it has the highest Eigen value for the safety criterion.

Table 8: Eigen values for alternatives considering safety

Bridge	*Eigen value*
Kelani bridge	*0.2626*
Mawanella bridge	*0.0106*
Elahera bridge	*0.6117*
Yatiyantota bridge	*0.0991*
Hatton bridge	*0.0160*

Table 9 gives Eigen values of alternatives for cost criterion. Maintenance costs of each bridge were used and the highest maintenance cost occurs with Kelani bridge followed by Mawanella bridge, Yatiyantota bridge, Elahera bridge and Hatton bridge.

Table 9: Eigen values for alternatives considering cost

Bridge	*Eigen value*
Kelani bridge	*0.6329*
Mawanella bridge	*0.1266*
Elahera bridge	*0.0759*
Yatiyantota bridge	*0.1139*
Hatton bridge	*0.0506*

Table 10 gives Eigen values of alternatives for importance criterion. In obtaining these values, historical significance, class of road on which the bridge is located were used. CR was obtained as 0.05.

Table 10: Eigen values for alternatives considering importance

Bridge	*Eigen value*
Kelani bridge	*0.4799*
Mawanella bridge	*0.2912*
Elahera bridge	*0.0841*
Yatiyantota bridge	*0.0350*
Hatton bridge	*0.1099*

These vectors were used to estimate the final priority list of the bridges. Figure 4 shows the obtained results graphically.

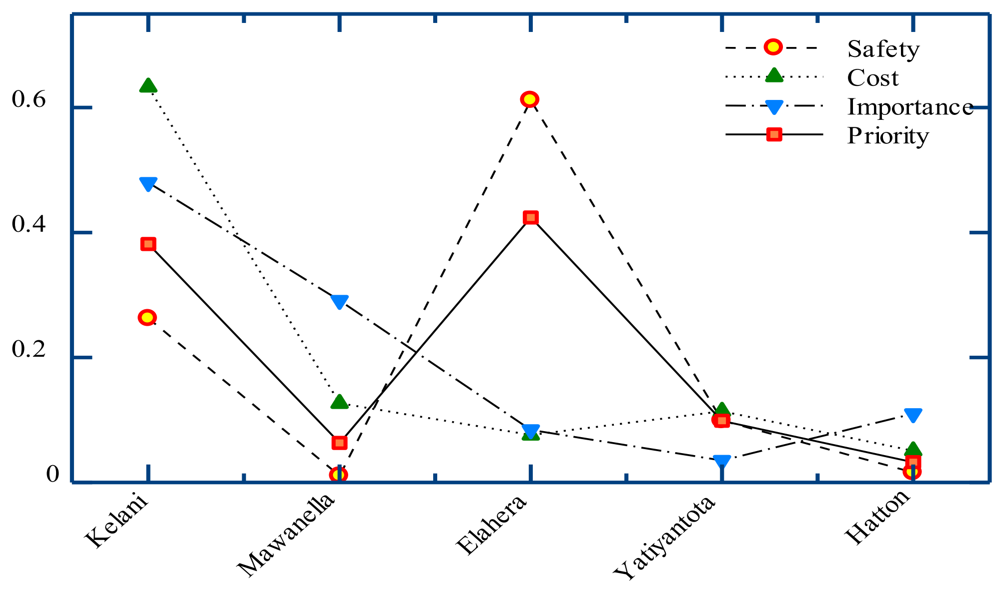

Figure 4: Graphical representation of the obtained results

The obtained results are shown as follows in Table 11.

Table 11: Results of AHP

Bridge	*Calculated value*
Kelani bridge	*0.3816*
Mawanella bridge	*0.0632*
Elahera bridge	*0.4242*
Yatiyantota bridge	*0.0986*
Hatton bridge	*0.0324*

As shown both in Figure 4 and Table 11, Kelani bridge has the highest relative significance for cost and importance criteria whereas Elahera bridge has the highest relative significance for safety criterion. Therefore, the bridge having the highest overall value was given more priority for bridge resources. Thus, Elahera bridge was assigned for the highest priority for resources followed by Kelani bridge, Yatiyantota bridge, Mawanella bridge and Hatton bridge. Appreciably high relative significance of safety criterion over other two criteria (cost and importance) according to Table 7 is the reason for the selected priority order.

4. Conclusions

Reliability based condition assessment procedure and analytical hierarchy process (AHP) based maintenance prioritization was developed for bridge maintenance. The proposed method was successfully applied a group of bridges from the national bridge network of Sri Lanka. The obtained results showed that proposed procedure was more efficient and more reliable than the previous methods. Therefore, the proposed strategy can be used effectively in current condition predictions and resources prioritization in bridge maintenance.

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