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Comparative Study on Condition Estimation of Masonry Arch Bridges

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1. Introduction

The history of masonry arch bridge construction goes back some 3000 years. From Sumerians in Mesopothemia to modern days, it has appeared in different civilizations and in different geographical regions in the world. At present, the increase in loading, traffic frequency and age of these structures has resulted in structural decay. Hence, safety estimation in terms of remaining load carrying capacity has become very important issue in masonry arch bridge management. As pointed out by some researchers (Ng. & Fairfield 2002), it cannot be predicted in a reliable manner because of time dependent effects, environmental effects, participation of non-structural elements and etc. Thus, bridge authorities still consider them as difficult to rate due to high degree of uncertainties involved.

At present, there are number of methods in condition estimation of masonry arch bridges. MEXE method is one of the commonly used deterministic methods of condition estimation. Despite its popularity, it is considered to be more conservative approach for determining permissible axle load. In this paper, new methodology is introduced to find permissible axle load based on structural reliability theory, which can account aforementioned uncertainties of masonry arch bridges.

A case study was selected from the national bridge network of Sri Lanka and it was evaluated both by MEXE method and the proposed reliability method. Both results are compared and the use of MEXE method in masonry arch bridges is validated.

2. Methodology

2.1 MEXE method

The MEXE method was developed during World War II (1939-1945) at the military engineering experimental establishment in the UK, and it has subsequently been widely used throughout the world. The method was initially designed to provide army officers with a quick and simple means of assessing the abilities of bridges to carry out abnormal loadings during the war, being developed from a permissible stress analysis of a centrally loaded two pinned parabolic arch. Various modifying factors are applied to account for differing geometries, materials, conditions, etc. It can be used to estimate load carrying capacity of single span masonry arches with spans up to 18 *m*, and it is considered to give conservative values when the arch span is over 12 *m*. It is recommended that this method should not be used when the arch is deformed or flat. Further, it should be used only when the fill is compacted well and it should not be used for open spandrel arch bridges. This is fast and easy to use and according to the department of transport in UK, MEXE method should be tried before using a more sophisticated method.

2.2.Proposed reliability based methodology-involving coefficient of variation of provisional axle load

In condition estimation of the masonry arch bridges, load carrying capacity is the dominant requirement to be satisfied. Based on the load carrying capacity, arch bridges are generally rated. Hence, reliability model should be based on the load carrying capacity. Mathematically, the proposed reliability model is given in Equation (1) below:

$$M = PAL - AAL \quad (1)$$

M is the safety margin. PAL is the Provisional Axle Load in kN and AAL is the Actual Axle Load in kN. Both PAL and AAL are assumed to behave as normally distributed random variables.

Using well-known rules for subtraction (addition) of normal variables, the mean of the safety margin can be written as a combination of the mean values of PAL and AAL as follows:

$$\mu_M = \mu_{PAL} - \mu_{AAL} \quad (2)$$

Then, the uncertainty of the PAL can be represented with the term called Coefficient Of Variation (COV) of the PAL. The COV of the PAL is the ratio of the standard deviation of the PAL to the mean of the PAL as in Equation (3):

$$COV = \sigma_{PAL} / \mu_{PAL} \quad (3)$$

The COV value can be used to find the σ_{PAL}:

$$\sigma_{PAL} = COV \times \mu_{PAL} \quad (4)$$

Then, $\sigma_M^2 = (COV \times \mu_{PAL})^2 + \sigma_{AAL}^2 \quad (5)$

In the above Equations, μ_M, μ_{PAL} and μ_{AAL} represent the mean values of the safety margin, the PAL and the AAL respectively. In addition, σ_M, σ_{PAL} and σ_{AAL} represent the standard deviations of the safety margin, the PAL and the AAL respectively.

Based on these parameters, reliability index of the bridge can be found. The reliability index (β) of the bridge is a measure of its soundness. It can be mathematically represented as follows (Christensen and Murotsu 1986):

$$\beta = \frac{\mu_M}{\sigma_M} \quad (6)$$

By substituting values:

$$\beta = (\mu_{PAL} - \mu_{AAL}) / \sqrt{\left((COV \times \mu_{PAL})^2 + \sigma_{AAL}^2\right)} \quad (7)$$

As the reliability index is found, it can be used to find the failure probability of the bridge. Failure probability of a bridge is a measure its closeness to the failure. Thus, it can be presented as follows:

$$P_f = \phi\left[\frac{-(\mu_{PAL} - \mu_{AAL})}{\sqrt{\left((COV \times \mu_{PAL})^2 + \sigma_{AAL}^2\right)}}\right] \quad (8)$$

Where ϕ is the standard unit normal distribution function. When $P_f < (P_f')_{acc.}$, the condition of the bridge is satisfactory in terms of the load carrying capacity. Here, $(P_f')_{acc.}$ represents the acceptable failure probability of the bridge. When $P_f \geq (P_f')_{acc.}$, major maintenance should be carried out to improve the condition of the bridge.

From Equation (8), μ_{PAL} can be found as follows:

$$\mu_{PAL}^2\left\{1-\left[\phi^{-1}(1-P_f)\right]^2 \times COV^2\right\} - 2\mu_{PAL} \times \mu_{AAL} + \mu_{AAL}^2 - \left[\phi^{-1}(1-P_f)\right]^2 \times \sigma_{AAL}^2 = 0 \quad (9)$$

If relevant parameter values are given in above Equation (9), μ_{PAL} can be solved to find permissible axle load. This reliability-based μ_{PAL} value represents the failure strength of the masonry arch bridge given the present loading and presumptive failure probability. In other words, this represents the ultimate load capacity of the masonry arch bridge.

2.3 Acceptable failure probabilities

In order to determine the latest time to repair interventions for bridges, it is necessary to establish an acceptance level of reliability below which the bridge may be considered unsafe. In most of countries, there are no criteria specified in the bridge codes and standards and no guidelines for establishing such acceptance levels.

In this study, a more direct approach for establishing acceptance probability levels based on economic optimization recommended by the Nordic committee on building regulation is used (Sarveswaran & Roberts 1999). It recommends acceptance levels based on the consequences of failures and the nature of the failure mode. Hence, the accetaptable failure probability of 10^{-5} is used for masonry arch bridges which corresponds to failure consequces of not serious and brittle failure situation.

3. Case study

In illustrating the proposed methodology, a single spanned stone arch bridge from the national bridge network of Sri Lanka was selected. This bridge, constructed 1918, is located near central town of Hatton in the A7 route and two views of the bridge are shown in Fig. 1.

It has these geometric details, bridge length = 14 *m*, clear span = 8.8 *m*, thickness of the barrel = 0.55 *m* and height of the compacted fill from the crest of the barrel = 1.50 *m*.

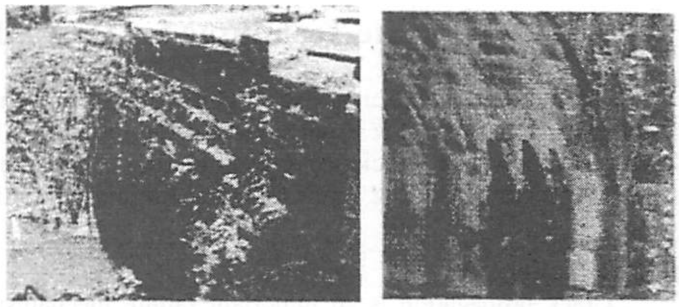

Fig. 1: A view of the selected masonry arch bridge

With the geometric values of the selected arch bridge, initial *PAL* was calculated as 184.03 *kN*. This value has to be modified with five modification factors according to the MEXE method. These five modification factors were calculated and given Table 1.

Table 1: Calculated values of adjustment factors

Adjustment factor	Value
For span/rise	1.0
For profile	0.85
For material	1.75
For joint	0.9
For condition	0.95

These values are multiplied with initial *PAL* and the modified value of *PAL* was calculated as 233.91 *kN*.

From axle load measurements, it was found that the *AAL* has the mean of 50.7 *kN* and the standard deviation of 29.03 *kN*. From the central limit theorem, it can be concluded that *AAL* measurements obey normal distribution even if the parent distribution is not normal. Form these values, using Equation (9), *PAL* was calculated and given in Table 2.

Table 2: Provisional axle load from the reliability method

COV of permissible axle load	0.0	0.1	0.15
Value of *PAL* (*kN*)	174.4	201.2	255.5

4. Conclusions

It is seen from this case study, reliability method gives the permissible axle load as in Table 2. It is interesting to see that the MEXE method gives the value as 233.91 *kN*. Hence, it can be concluded that the MEXE method value of *PAL* is conformed to that of the proposed reliability method that assumes the acceptable failure probability of 10^{-5}.

References

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