

# Reliability of Using Modal Curvature Method in Long Span Cable Stayed Bridges

Dhanya S Remesan<sup>1</sup>, Rahul Leslie<sup>2</sup>, Ashok Mathew<sup>3</sup>

<sup>1</sup>M Tech Scholar, Department of Civil Engineering, Sree Buddha College of Engineering, Alappuzha, Kerala, India

<sup>2</sup>Assistant Director, Buildings Design, DRIQ Board, PWD, Thiruvananthapuram, Kerala, India

<sup>3</sup>Assistant Professor, Department of Civil Engineering, Sree Buddha College of Engineering, Alappuzha, Kerala, India

**Abstract:** *Dynamic damage detection methods have received considerable attention in all branch of engineering. Damage is identified by comparing the typical dynamic properties of the damaged and undamaged structure. In the present work, method based on modal curvature difference is employed for identifying and locating damage in various structural elements of a cable stayed bridge. In order to verify the suitability for implementing the technique, eigen value analyses are carried out on finite element models of cable stayed bridge and the eigen vectors for different cases are extracted. Damage is considered as a localized reduction in structural stiffness. It is observed that the sensitivity of locating damage in a particular cable stayed bridge depends on the location of damage, type of structural element and severity of damages.*

**Keywords:** Cable stayed bridge, Dynamic damage detection, Modal curvature, Structural health monitoring

## 1. Introduction

Structural systems, such as buildings, bridges, planes, trains or any other, are susceptible to sudden damage, deterioration and aging. Therefore, a health monitoring system that is able to detect and identify any damage in real time in its earliest stage is essential to maintain the structural stability, integrity and to maximize the life span of the structures as much as possible. A complete structural health monitoring (SHM) system incorporates performance metrics, sensing, signal processing, data analysis, transmission and management for decision-making purposes. Damage detection in the context of SHM can be successful by employing a collection of robust and practical damage detection methodologies that can be used to identify, locate and quantify damage or, in general terms, changes in observable behavior [6].

Many damage detection methods have been developed over the years, and the local methods such as ultrasonic and X-ray methods are the most popular methods at present. All of these techniques have a drawback in needing the vicinity of the damage to be known a priori and that the portion of the structure being inspected is readily accessible by a labor or machine, which makes automation process almost impossible to perform, not mentioning that these methods are very time consuming and costly.

However the vibration based damage detection methods have an advantage that lies in their global behavior, in which the damage can be identified in a system without regard to size or accessibility, in addition a system of automated real time damage identification becomes possible. Vibration based damage identification techniques are based on the idea that damage modifies both the physical properties of a structure (stiffness and damping) as well as its dynamic characteristics (natural frequency, damping and mode shapes). Therefore by examining the dynamic properties of a structure from

structural vibration, any damage, including its location, and severity, can be identified [2, 9].

In this paper, reliability of modal curvature method for locating damage in a cable stayed bridge is presented with the help of a numerical model of Quincy Bay View Bridge, USA. Several damage scenarios were simulated with different location and severity of damage in order to check the sensitivity of the damage identification method to both the location and the severity of damage.

## 2. The Damage Detection Method

### 2.1 Modal Curvature Method

Curvature mode shapes are related to the flexural stiffness of beam cross sections [2]. Curvature at a point is given by,

$$v_i'' = \frac{M}{EI} \quad (1)$$

In which  $v_i''$  is the curvature at a section, M is the bending moment, E is the modulus of elasticity and I is the second moment of cross sectional area. If a crack or other damage is introduced in a structure, it reduces flexural rigidity (EI) of the structure at the cracked section or in a damaged region, which increases the magnitude of curvature at that section of the structure. The changes in the curvature are local in nature and hence can be used to detect and locate a crack or damage in the structure. The change in curvature increases with reduction in the value of flexural rigidity, and therefore, the amount of damage can be obtained from the magnitude of change in curvature.

From displacement mode shapes, obtained from the finite element analysis, curvature mode shapes were obtained numerically by using a central difference approximation as,

$$v_i'' = \frac{(v_{i+1} - 2v_i + v_{i-1}))}{h^2} \quad (2)$$

Where,  $h$  is the length of the elements.

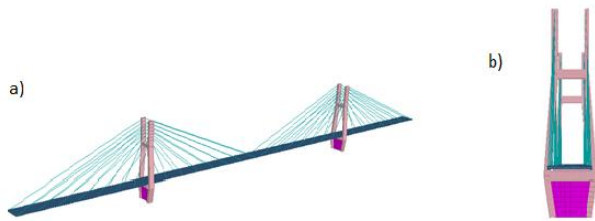
The modal curvature difference for the  $j^{\text{th}}$  mode is defined as,

$$C_j^d(i) = |C_j^d(i) - C_j^u(i)| \quad (3)$$

Where  $C_j^d(i)$  and  $C_j^u(i)$  are the modal curvature of the  $j^{\text{th}}$  mode at the  $i^{\text{th}}$  segment corresponding to the intact and damaged structure respectively.

### 3. Description of model

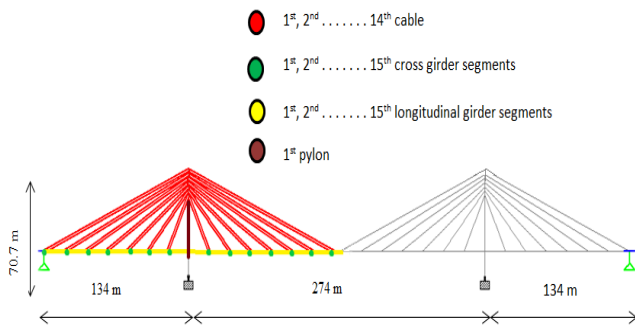
The bridge model used in this study is that of the Quincy Bay View Bridge crossing the Mississippi River at Quincy, USA. The bridge consists of two H-shaped concrete towers, double plane semi-harp type cables and a composite concrete-steel girder bridge deck. A simplified lumped mass finite element (FE) model of the bridge considered for the work is modeled using the analysis package of STAAD.Pro (fig.1)



**Figure 1:** (a) FE model (b) Pylon's elevation

The bridge is symmetrical about the vertical centroid axis. The bridge has a central span of 274m flanked by two side spans of 134m each. The total height of the tower is 70.7m. Depending on the geometry; the towers are divided into three parts. There are 56 stay cables; 14 pairs supporting the main span and 7 pairs supporting each side span. The cables are spaced at 2.75m at the upper part of the towers and are equally spaced at deck level on the side span as well as the main spans. The left and right anchor supports are kept as hinged supports. The towers are considered to be fixed at the base. After discretization, the model consists of 404 nodes.

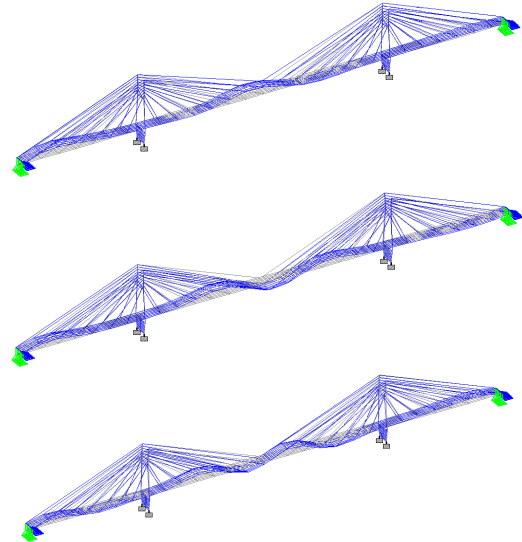
### 4. Simulated Damage Scenario



**Figure 2:** Damage scenario

Due to the symmetry of the bridge about its midspan, defects were introduced only on the left half of the bridge for the study. Damage in each structural element has been simulated by reducing its modulus of elasticity by 30%, 60% and 90% percentages. The simulated damage scenarios are shown in fig. 2. Modal analysis was conducted on the FE model and the first forty eight mode shapes were extracted for both

intact and damaged cases. For further application in modal curvature method, only the vertical modes are considered (fig. 3). From extracted modal displacements of intact and damaged models, absolute curvature difference plot has been made along span of the bridge. Then sensitivity plot has been made in order to study the variation in absolute curvature difference for different locations for different levels of damage.



**Figure 3:** Mode shapes corresponding to 32<sup>nd</sup>, 34<sup>th</sup>, 36<sup>th</sup> mode of bridge

### 5. Numerical Results

#### 5.1 Cables

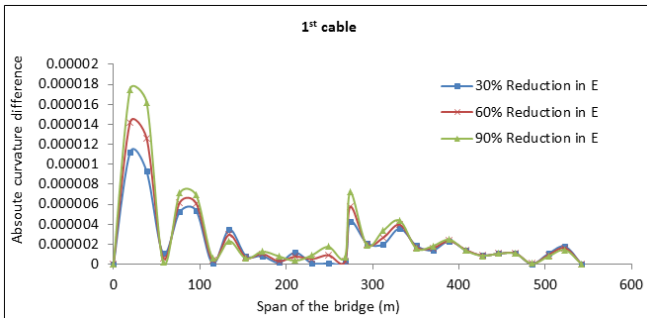
Cases of damages in 14 cable pairs (in the left side of the midspan of the bridge) are studied. Damages are introduced in each cable pairs by reducing their modulus of elasticity by 30%, 60% and 90%. From modal curvature difference plots, it is difficult to find exact damage locations except two or three cases. Even in cases where a maximum peak is present at the damage locations; there also exist peak at the centre span of the bridge. In the case of 7<sup>th</sup> and 8<sup>th</sup> cable pairs near pylon, the graph shows a region of damage instead of getting successive peaks. The different severities of damage at a particular location show same pattern of curve, also height of the peak is proportional to the severity of damage. In all cases, damage severity can be identified. Fig. 4, 5 and 6 are the curvature plots for 1<sup>st</sup>, 7<sup>th</sup> and 14<sup>th</sup> cable pairs, determined using modes 36, 32, and 32 respectively.

The sensitivity in locating damage for cable pair locations (ie., the graph connecting the peaks at the cable location of curvature plot of the 'defect in cable pairs' cases from 1<sup>st</sup> to 14<sup>th</sup>) are represented in fig. 7. The magnitude of curvature difference corresponding to 1<sup>st</sup>, 7<sup>th</sup> and 8<sup>th</sup> cable pair shows comparatively minimum value. The maximum values are obtained for 2<sup>nd</sup>, 4<sup>th</sup> and 12<sup>th</sup> cable pairs.

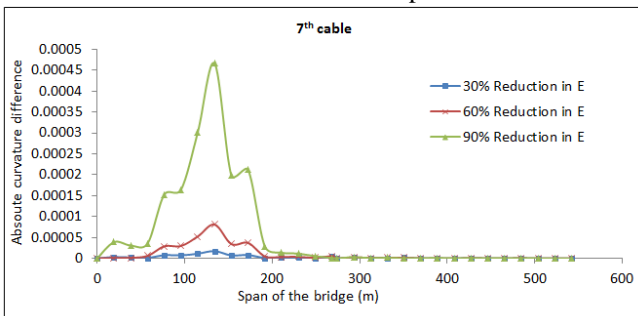
#### 5.2 Cross Girders

Similar study was conducted for the 15 cross girder segments. Compared to curvature plots for cable defects, the curvature plots for cross girders are more easily identifiable.

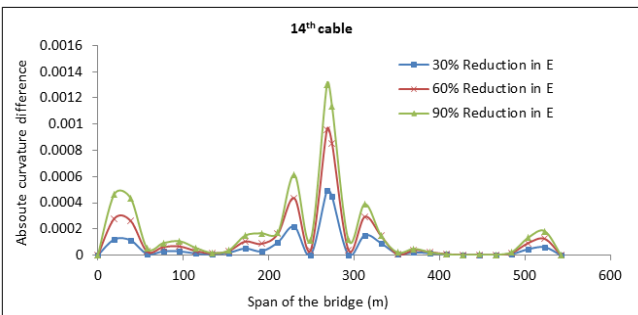
The plot obtained for 1<sup>st</sup> cross girder segment has two successive peaks, but maximum peak obtained is exactly at the damage location. All other damage locations clearly identified in three cases of damage severities. Curvature plot for 1<sup>st</sup>, 7<sup>th</sup> and 15<sup>th</sup> cross girders determined using modes 32, 36 and 32 respectively are shown in fig. 8, 9, 10. The magnitude of curvature peaks for each damage locations (i.e. the graph connecting the peaks at the girder location of curvature plot of the 'defect in cross girder' cases from 1<sup>st</sup> to 14<sup>th</sup>) are presented in fig. 11. The sensitivity in locating damage is high at 2<sup>nd</sup>, 4<sup>th</sup> and 13<sup>th</sup> cross girders.



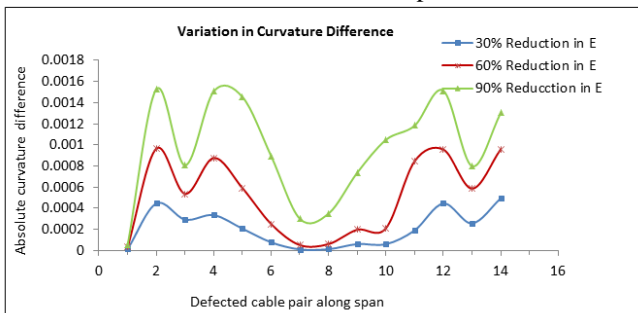
**Figure 4:** Curvature difference plot of bridge with defect induced at 1<sup>st</sup> cable pair



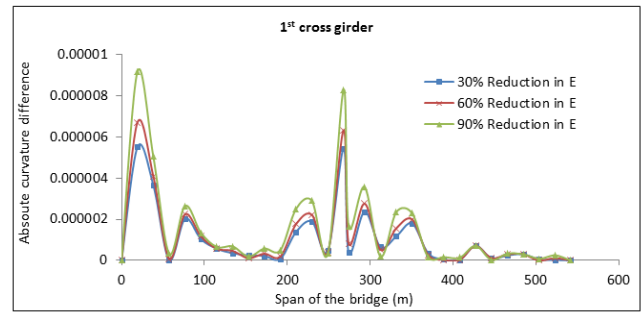
**Figure 5:** Curvature difference plot of bridge with defect induced at 7<sup>th</sup> cable pair



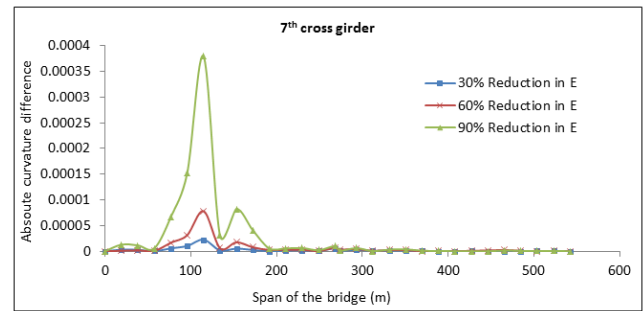
**Figure 6:** Curvature difference plot of bridge with defect induced at 14<sup>th</sup> cable pair



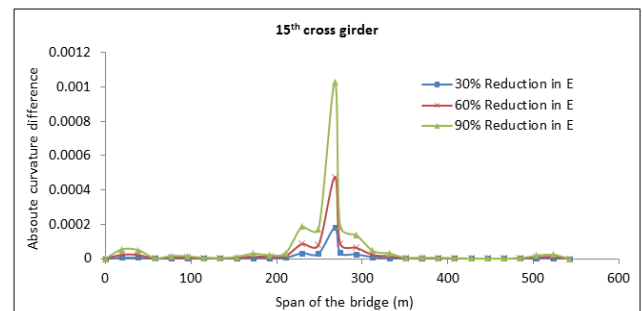
**Figure 7:** Variation in magnitude of curvature difference for different cable locations



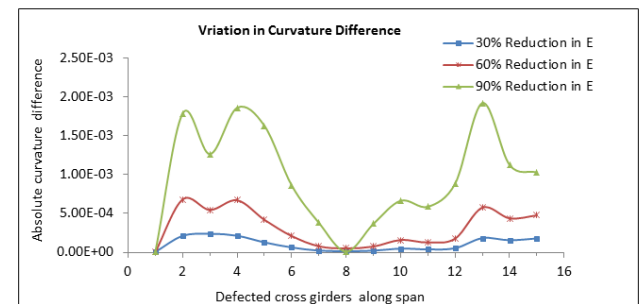
**Figure 8:** Curvature difference plot of bridge with defect induced at 1<sup>st</sup> cross girder segment



**Figure 9:** Curvature difference plot of bridge with defect induced at 7<sup>th</sup> cross girder segment



**Figure 10:** Curvature difference plot of bridge with defect induced at 15<sup>th</sup> cross girder segment

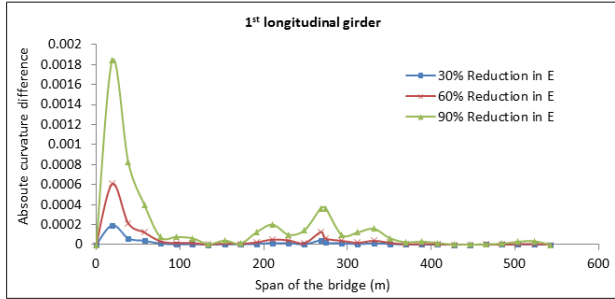


**Figure 11:** Variation in magnitude of curvature difference for different cross girder locations

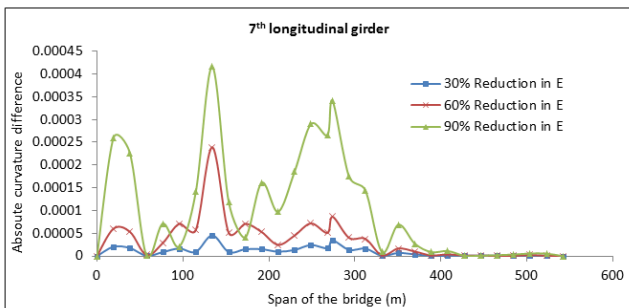
### 5.3 Longitudinal Girders

The curvature plot obtained for 15 longitudinal girders are comparatively confusing in locating damages due to more than one peak in the curvature diagram. The method is found effective only for 1<sup>st</sup>, 2<sup>nd</sup> and 15<sup>th</sup> girder segments only. Curvature peaks obtained for other cases are confusing. For different severities of damage, the pattern of curve obtained is same for all cases. But as expected, the magnitude of curvature increases with increase in severity. Fig. 12, 13 and

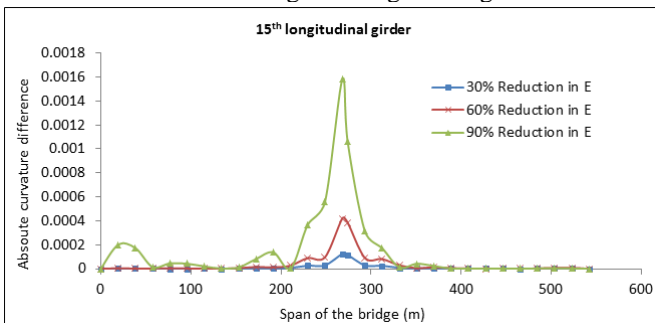
14 are the curvature plot for 1<sup>st</sup>, 7<sup>th</sup> and 14<sup>th</sup> longitudinal girder determined using modes 32, 34 and 32 respectively. The fig. 15 shows variation in curvature difference for different damage locations (ie., the graph connecting the peaks at the girder location of curvature plot of the ‘defect in longitudinal girder’ cases from 1<sup>st</sup> to 14<sup>th</sup>). The sensitivity in locating damage near pylon is poor.



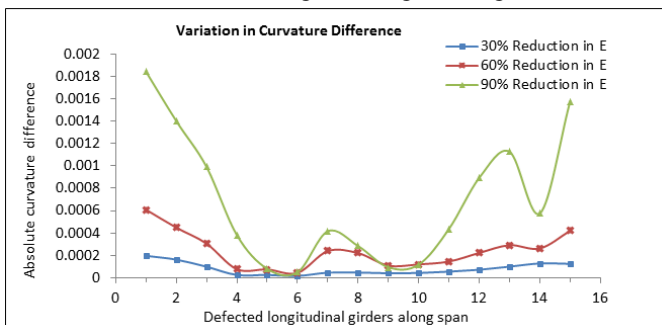
**Figure 12:** Curvature difference plot of bridge with defect induced at 1<sup>st</sup> longitudinal girder segment



**Figure 13:** Curvature difference plot of bridge with defect induced at 7<sup>th</sup> longitudinal girder segment



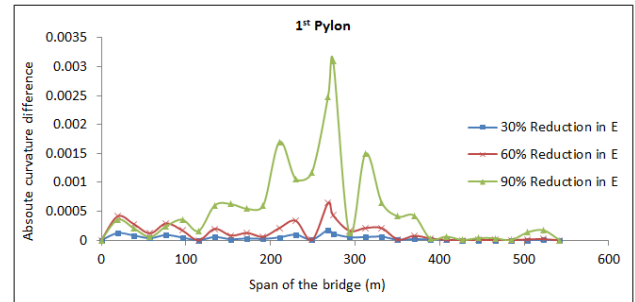
**Figure 14:** Curvature difference plot of bridge with defect induced at 15<sup>th</sup> longitudinal girder segment



**Figure 15:** Variation in magnitude of curvature difference for different longitudinal girder locations

## 5.4 Pylon

For pylon, the method failed to distinguish the damage. The result shows misleading peaks. Fig. 16 shows curvature plot for 1<sup>st</sup> pylon with varying damage severities.



**Figure 16:** Curvature difference plot of bridge with defect induced at 1<sup>st</sup> pylon

## 6. Conclusions

The feasibility of modal curvature damage identification method in cable stayed bridge has been studied in this paper. Three damage severities with different damage locations were investigated for all members. The reliability of method varies with nature of structural element and location of damage severities.

Comparatively, results obtained for cross girders are promising i.e. possessing the peak value at damage location. The height of the peak is proportional to the severity of damage.

For cables and longitudinal girders, the method is successful only two or three damage locations. Although there is a peak at the damage location, other peaks also exist in the curvature diagram. This is confusing for locating damage. The curvature method failed to locate damage in pylon for all severities of damage. The magnitude of curvature difference is proportional to the severity of damage and is minimum near pylon region for all damage cases. The study was limited to the application of modal curvature method for vertical modes. This technique can be extended to treat a complete cable stayed bridge with different modes of vibration (lateral, torsional and coupled modes).

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