MODAL FLEXIBILITY-BASED DAMAGE DETECTION OF TRUSS BRIDGES: A CONCEPTUAL FRAMEWORK

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ABSTRACT

This paper presents a conceptual framework to locate the damages and diagnose the type of damage. The proposed framework is based on flexibility difference method. The considered structural damages in the framework are categorized as the significant loss of section due to corrosion, cracks due to fatigue or fracture and interaction effect of corrosion-fatigue. The framework consists of a location specified damage index, which is determined by in-situ measurements of vibration modal parameters. The degree of damage is determined proportions to the magnitude of the damage index. The framework provides guidelines to locate the damage or deteriorated region for detailed investigation. A finite element simulation based approach is newly proposed to diagnose the type of damage. Initially paper presents the theoretical derivation of damage index based on flexibility difference. Then the methodology the locate the damages are discussed in detail. Finally, a new approach is proposed to diagnose the type of damage. The scope of this framework is limited to the steel/metal truss bridges. The proposed methodology is comprehensively discussed and is illustrated in a flowchart. The damages or deteriorations due to fully section loss of members, which are difficult to access for visual inspections, can be accurately located by the proposed conceptual framework.

Keywords: structural health monitoring, modal flexibility, steel truss bridges, fatigue damage.

1 INTRODUCTION

Significant attention has been given during last few years to develop structural health monitoring (SHM) and life extension methods to maintain ageing structures more efficiently. Ageing of structures is characterized by deterioration, which is caused mainly by fatigue and corrosion. The detailed inspections of ageing bridges in the marine environment revealed damages such as cracks and fractures, severe deterioration due to corrosion of members, some of which already reached a complete loss of the cross section of the member [1]–[4]. Some of these damages are located in the regions, where it is difficult to access for visual inspections. Thus, it is important to use precise SHM methods to detect the damages or deterioration before it is too late to attend for necessary detailed inspection or maintenance.

The vibration measurement based damage detection techniques are developing as one of the precise SHM method [5], [6]. Due to loss of material due to corrosion and any damage of the structure, the structural stiffness changes and makes the structure more flexible. This concept associated modal flexibility method is designated as one of the precious damage detection methods [6]. The method is based on vibration measurement based modal parameters (i.e. natural frequencies and mode shapes). The method has been verified by simple structural components [7]. The application of was later extended to existing structures specially bridges [8]–[10]. However, applications of above method are not found to determine the degree of structural degradation due to corrosion and corrosion-fatigue interaction.

To overcome above problem to some extent, this paper proposes a model flexibility method based framework to locate the damage and diagnose the type of damage. This consists of a time dependent damage index, which describes the overall structural degradation. The framework provides guidelines to locate the damage or deteriorated region for detailed inspections. The scope of this framework is limited to the steel/metal truss

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bridges. The damages or deterioration due to fully section loss of members, which are difficult to access for visual inspections, can be more precisely located by this proposed damage index.

2 FLEXIBILITY DIFFRENCE METHOD-BASED DAMAGE INDEX

The presence of a crack or a localized damage in structures reduces the structural stiffness. Hence, the flexibility of the structure may increase, as the flexibility is the inverse of stiffness. Therefore, the difference of modal flexibility is affected by presence of damage. Therefore, the degree of change of flexibility can be used as a damage index of structures. The modal flexibility matrix of the structure can be expressed as [11]–[13],

$$[F] = [\emptyset][\Lambda]^{-1}[\emptyset]^T = \sum_{i=1}^{n} \frac{1}{\omega_i{}^2} \emptyset_i \emptyset_i{}^T, \quad (1)$$

where $[\emptyset]$ is the *nxn*-dimensional mode shape matrix of the structure. The $\emptyset_i$ is the mass normalized i^{th} mode shape vector of the structure. The $[\Lambda]$ = diag $(\omega_i{}^2)$ is the eigenmatrix and ω_i is the i^{th} modal frequency. The n is the number of degrees of freedom in overall structure.

The value of modal flexibility is dominating in the lower-frequency modes of the structure due to its inverse relationship to the square of the modal frequencies [14]. The lower mode shapes and frequencies can be measured or can be estimated by finite element analysis [15]. If the modal parameters (i.e. natural frequencies and mass normalized mode shapes) can be determined for both undamaged (i.e. healthy) and damaged structures, then by using eqn (1), the flexibility matrix $[F]$ for both states can be obtained. Then the change of flexibility matrix $[\Delta F]$ can be determined as,

$$[\Delta F] = [F]_H - [F]_D, \quad (2)$$

where $[F]_H$ and $[F]_D$ are the flexibility matrices for the undamaged and damaged states respectively. In general, it is very much difficult to measure the mode displacements of rotational degrees of freedoms; the translational degrees of freedom related measurements are only considered for modal flexibility matrix.

The absolute maximum value of the element in the j^{th} column in the change of flexibility matrix [ΔF] is defined as [12],

$$\delta_j = Max\ |\delta f_{ij}|, j=1,2,3,....n, \quad (3)$$

where δf_{ij} is the elements in change of flexibility matrix. The δ_j is used as the measure of damage closer to the j^{th} degrees of freedom of the structures. Damage in a structure will result higher δ_j values for the degrees of freedoms (DOF) near the damage locations. Hence, the damage index at j^{th} DOF is defined as,

$$DI_j = \frac{\delta_j}{f_{ij}} \times 100\ \%, j=1,2,3,....n, \quad (4)$$

where f_{ij} is the corresponding elements in the undamaged model flexibility matrix $[F]_H$. The above proposed damage indicator associated damage detection method is comprehensively discussed in the following sections.

3 PROPOSED METHOD TO LOCATE DAMAGES

This section proposes a method to locate the damage of the members of truss bridges. The considered damage is categorized as the significant loss of section due to corrosion, cracks due to fatigue or fracture and interaction effect of corrosion-fatigue.

3.1 Structural appraisal

Since the ageing bridges have been subjected to different degradation conditions, initially an inspection has to be carried out to assess the present geometric condition, alternations/modification and damages of the bridge. This can be done by collecting and screening of the recorded data and visual inspection of the bridge to identify present geometric details, damages and the state of corrosion. Then laboratory tests should be carried out to determine the current mechanical properties and chemical composition of the bridge materials. Then static and dynamic load testing are recommended as the next major step to study the real behavior of the bridge under various load combinations. The vibration measurement should also be performed. The bridge should be instrumented with accelerometers placed at all most all the joints to measure acceleration in three directions. In order to measure free vibration, accelerations should be recorded after the trucks/trains crossed the bridge. The measurements should be taken at least for period of 12 hours. Hence, natural periods of each mode are determined for each heavy truck/trains passed the bridge. The modal analyses should be conducted to obtain the natural periods for each mode. Hence, the average value of corresponding natural frequencies should be predicted respectively for vertical and lateral first two modes. The mode displacements can be obtained by fast fourier transformation of measured accelerations in respective mode direction. However, the appraisal is not necessary for fairly new structures as far as those have not been subjected to damages, deterioration and any alternation/modification as ageing structures. Refer the framework shown in Fig. 1 for more details.

3.2 Development of validated FE model

The obtained data from the step 1 is used to develop a proper finite element (FE) model. Then the structural performance should be evaluated by performing FE analysis of the bridge under test loadings. Material properties which are obtained through laboratory tests and current geometric properties obtained from condition assessment are applied to the FE model for more realistic outputs. The validation of the FE model has to be done by comparing the results from analysis with those from field tests. The analytical modal parameters (i.e. natural frequencies and mode shapes) should be compared with the experimentally determined modal parameters which was obtained in section 3.1. The FE model, which gives better comparison to load test results and vibration measurement is nominated as 'validated FE model'. Finally, the validated FE model can be used to obtain current modal flexibility of the bridge in the next step. Refer the framework shown in Fig. 1 for more details.

3.3 Modal flexibility of undamaged/current structure: Intact modal flexibility

The modal flexibility matrix $[F]_H$ can be determined for first two modes by using the measured modal parameters or analytical modal parameters which can be derived by validated FE model mentioned in section 3.2. The mass normalized mode shape vector and natural frequencies for first two modes can directly obtained by the validated FE model as discussed in section 3.2. The experimental mode displacements for respective mode directions can be obtained by fast Fourier transformation of measured accelerations at each node. The mass normalized mode shape vector should be obtained as follows by using the mass matrix obtained from validated FE model.

$$[I] = [\emptyset]^T [M][\emptyset], \tag{5}$$

where $[I]$ is the $n \times n$ identity matrix and $[M]$ is mass matrix. If it is difficult to measure each and every joint (i.e. node in FE model), it is advisable to measure reasonable number of joints which are more susceptible to fracture, fatigue or corrosion. The measurement locations should be required to represent the overall structural mode displacements and corresponding flexibility. Refer the framework shown in Fig. 1, for more details.

3.4 Periodical measurement of vibration and modal flexibility of damaged structure

The periodical vibration measurements are required to determine the current/damage modal flexibility of the bridge. The bridge should be instrumented with accelerometers placed at all most all the joints to measure all three directions accelerations as mentioned in section 3.1. As mentioned in section 3.1, the natural frequencies and mode shape vector for should be determine for first vertical and horizontal modes. Refer the framework shown in Fig. 1 for more details. The measurement can also be done only for most critical members of the bridge. But, it is compulsory to have the fair amount of measurement locations (i.e. joint DOFs) closer to the critical members. For truss bridges, it can be separately considered the trusses and deck (i.e. cross girders and stringers). The current modal flexibility matrix $[F]_D$ can be determined for first two modes by using the measured modal parameters.

3.5 Determination of damage index/ degree of damage /identification of damaged locations/joints/members

The damage index for every measured location can be calculated using eqns (2)–(5). The differences between damage and undamaged modal flexibilities are governing the damage index. This damage index should be compared with allowable damage index as shown in Fig. 1. There will be a change of flexibility due to numerical errors and/or usual structural degradation. The allowable damage index has been defined to capture the above change of flexibility. Therefore, the allowable damage index should be determined for particular types of members (i.e. truss main chord, truss diagonal, cross girders and stringers) of the bridge. The higher damage index gives the indication of presence of cracks or localized damages close proximity to measured locations (i.e. higher change of flexibility). These locations and closer areas should be selected for detailed investigations/analysis. The next section proposes a new method to identify the types of damage.

4 PROPOSED APPROACH TO DIAGNOSE DAMAGES

Selection of appropriate non-destructive testing (NDT) methods or inspection techniques depend on the types of the damage scenario/deterioration. For optimized inspection planning process, it is very much important to pre-identify the damage scenario before planning the inspection. This is much beneficial for the locations, which are difficult to access for visual inspections. To overcome this problem to some extent, the following method is proposed. The proposed method consists of two major steps, i.e. diagnose of the damage by theoretically and detailed inspection followed by NDT.

4.1 Identification of critical failure scenarios

The selected damage members/joints, should be carefully check for critical failure modes. Some of the members are more vulnerable for ductile fracture, buckling, fatigue or combination of above two or all. A detailed design checks in ultimate limit state should be conducted based on the action effect or stresses (i.e. local stresses) which were obtained by the FE analysis. Time dependent structural degradation due to corrosion may also a critical failure scenario. Identification of possible type of corrosion (i.e. uniform, patch or localized corrosion) is also primarily important. Refer the framework shown in Fig. 1 for more details.

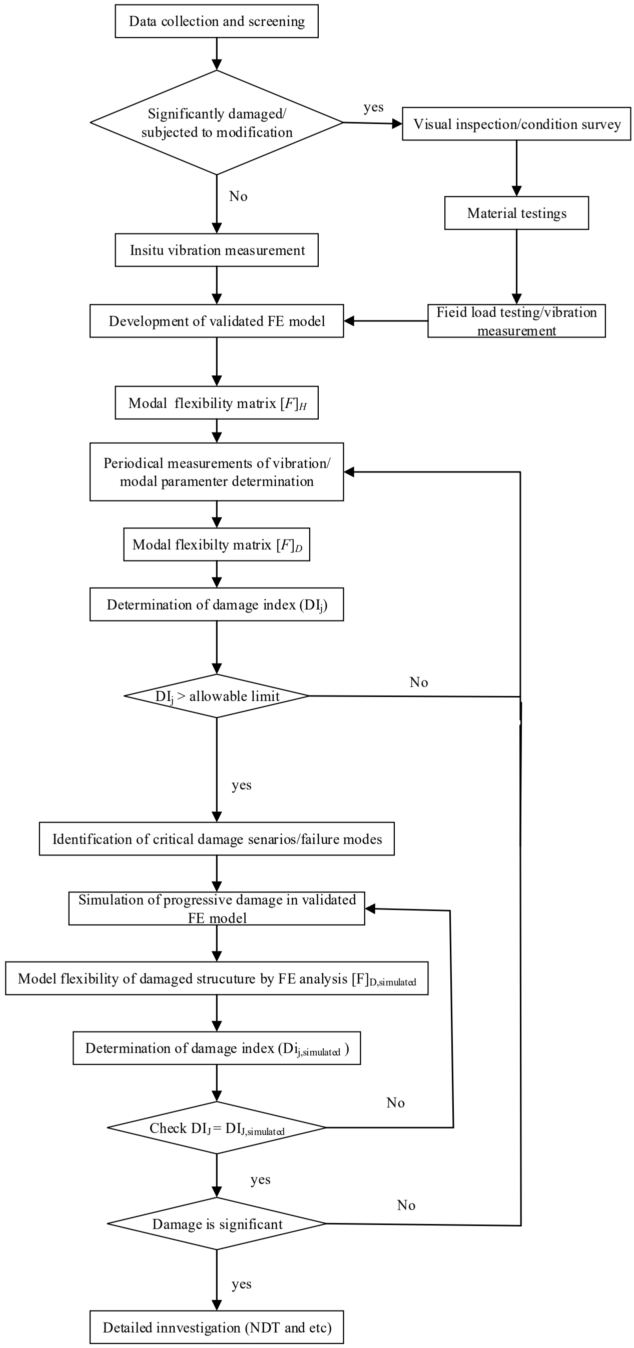

Figure 1: Proposed framework for damage detection and diagnosing damage type.

4.2 Finite element simulation based approach

The change of flexibility is the measure of damage. If there is high degree of flexibility change (i.e. large value for damage index), it is very important to pay attention of these members for detailed damage assessment by NDT [16]. Then identify the possible/critical damage scenario which applicable to particular member (i.e. crack due to fatigue/fracture, localized corrosion near the joint/connection and uniform/patch corrosion). Simulation of each damage should be done by either progressive change of sectional properties or change of modulus of elasticity (cracks) or complete removal of the member of validated FE model obtained in section 3.2. The reduction of joint rigidities/ losing of rivets/ reduction of clamping forces can be simulated by introducing releases and changing the rotational stiffness progressively. The time-dependent cross sectional properties due to corrosion can be obtained by author's previous article [17]. Previously obtained validated FE model is utilized for this progressive analysis. The damage index for every joints/nodes should be calculated for every progressive stage by considering the difference of modal flexibility, which were obtained by undamaged and damaged FE models. Then simulated damage index ($DI_{j,simulated}$) should be compared with damage index (DI_j). The progressive simulation should be performed until above damage indices becomes close each other as shown in Fig. 1. Once these damage indices are closer, significance of the damage should be discussed. If the damage is significant, the detailed NDT based site investigations are recommended to perform diagnose the damage as shown in Fig. 1.

4 CONCLUSIONS

The paper proposed two new frameworks to locate the damage and to diagnose type of damage. A flow chart of the proposed frameworks has been presented to illustrate the procedure more clearly. This consists of vibration measurement based determination of damage index and damage simulation technique by FE analysis. The paper provides a clear guidance to simulate crack due to fatigue/fracture, localized corrosion near the joint/connection and uniform/patch corrosion. It is recommended to highlight the significance of proposed frameworks on existing ageing bridges through case studies.

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