Reliable Condition Assessment of Structures Using Field Measurements and Uncertainty Analyses

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Abstract: The failure of structural systems has significant societal and human consequences. Therefore, there is a crucial need to assess the structural condition of in-service and aging structures which is a major cost and management consideration, particularly in cases with unknown design validation. However, structural condition assessment, when conducted according to state-of-the-art protocols, produces very subjective and highly variable results. This can be attributed to the presence of uncertainty in structural measurements as well as lack of objective condition assessment tools also capable of considering those uncertainties in their analytical procedures.

In this work, a new method with a hybrid experimental/analytical framework for condition assessment and life prediction of existing structures is developed. This objective hybrid framework combines experimental structural measurements (e.g., results from non-destructive tests or routine performance and/or inspection data for structure's response) and theoretical structural uncertainty analyses (interval finite element method). This method uses the structural measurements, with consideration of uncertainties, in structural uncertainty analyses, for estimating the condition of a structure. Application of structural measurement data, integrated with an enhanced structural analysis scheme, and with consideration of uncertainties provides the necessary information to make decisions regarding inspections, rehabilitation and repairs. As a case study, the method is applied for a failed sign support structure and the damage as well as lifetime of the structure is determined.

Keywords: Structural Condition Assessment, Structural Reliability, Structural Health Monitoring, Interval Finite Element Method

1. Introduction

The safety and mobility of the population is dependent on the integrity of existing structures. In order to achieve this integrity, there is a need to perform structural condition assessment which is a major cost and management issue related to safety of structures. As funding available for rehabilitation of aging structures is limited, there is a crucial need for initiatives that can be used effectively for objective evaluation of aging structures in order to guarantee the structural safety and integrity over the lifetime of the structure and, for decision making on an optimum and cost-effective solution in prioritizing structures for repair, rehabilitation and replacement. However, in many cases, the application of results obtained by field measurements is limited.

Moreover, the conventional deterministic structural analyses are incapable of considering uncertainties in measurements, material properties and, applied loads; thereby resulting in errors when estimating the condition of a structure.

In this work, a new method for condition assessment and life prediction of existing structures is developed. This method applies the results from field measurements, for structural uncertainty analyses, in an effort to offer a more robust process for estimating the condition of a critical structure. Having the ability to use structural measurement data, integrated with an enhanced structural analysis scheme as well as consideration of uncertainties, produces the necessary information to make knowledgeable decisions regarding inspections, rehabilitation and repairs. The developed hybrid framework in this method combines experimental structural measurements (e.g., results from non-destructive tests or routine performance and/or inspection data for structure's response) and theoretical structural uncertainty analyses (interval finite element method). The procedure is employed to:

1. Obtain the existing structure's static and/or dynamic response data, using field measurements.
2. Incorporate the presence of uncertainties or impreciseness in data (e.g. due to measurement or sensor errors) by quantification of the experimental data as intervals of uncertainty.
3. Perform interval finite element analyses using the updated measured data for the existing structure in order to obtain the bounds on each structural component's internal strains and/or stresses.
4. Identify the state and extent of damage to the structural components based on their maximum induced stresses leading to determination of safety and integrity of the entire structure.

As an illustrative example, the method is applied for a failed sign support structure. First, the structure's response from previous health assessment procedure was used to construct uncertain interval responses. Then, using these interval responses as input parameters, an interval finite element method was performed. The results of the analysis verify and correlate with the failure location of the actual structure. Moreover, the lifetime assessment of the structure obtained from this method is the lower bound of, and correlates with, the actual failure time of the structure.

This work represents the synthesis of two historically independent fields, structural condition assessment and interval-based structural uncertainty analysis. In order to represent the background for this work, first, a review of development of both fields is presented. Next, the new hybrid method is introduced. Finally, the case study using the developed method is presented that are followed by observations and conclusions.

2. Structural Condition Assessment

The structural health and condition of in-service structures is usually assessed through visual inspections and nondestructive testing and evaluation (NDT/NDE) methods conducted on a pre-set schedule. In general, attempts to quantify the performance of older structures using visual inspection have resulted in subjective and relatively unorganized protocols [1]. Objective evaluation of system level behavior of aging structures is desirable when prioritizing the limited funding available for structural rehabilitation [2-4].

2.1 SENSOR-BASED STRUCTURAL MEASUREMENTS

The goal of sensor-based structural measurements is to employ sensing instruments to provide information pertaining to the condition of the structure [5]. The current practice of structural measurements involves a host of structural parameters. For those parameters, the sensor-based data is compiled either continuously or intermittently. The availability of compact data acquisition systems along with the wireless technology has made the process of data compilation more affordable and convenient. It is envisioned that in the near future, more engineers and owners will take the advantage of the wireless instrumentation and data acquisition process in developing systems that can continuously be used to monitor the state of the structures. However, the challenge to this process will be the efficient use of the compiled data and development of a process via which the actual condition of a structure can be assessed accurately and the results be used reliably. This will determine what decisions need to be made in regards to the structures' need for repair, retrofit or reconstruction. There are several existing techniques to measure the parameters in structures. There are contact methods that place various sensors, such as strain gauges, accelerometers and Fiber Bragg Grating (FBG) sensors along a structure. Conversely, there exist non-contact methods such as Laser Doppler Vibrometer (LDV), Global Positioning System (GPS), and Terrestrial Laser Scanning (TSL) [6].

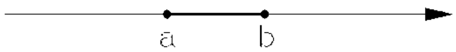
3. Structural Uncertainty Analysis

Engineering analysis has two main steps, simulation/analysis and optimization/design. The reliability of these two steps depends on how effectively the system behavior is predicted and how successfully the optimal solutions are achieved. Engineering uncertainty analysis requires that the procedures for analysis accommodate different sources of errors. One engineering computing tool for uncertainty is interval analysis. A key to this endeavor is the inclusion of uncertainties in engineering systems via the concept of performing analysis using interval quantities. Interval analysis approach has previously been used for damage identification of structures. Moreover, interval analysis has been used for FE model updating [7-10]. As more structures start using a monitoring system in their routine operation, there will be a need for an efficient method to incorporate the uncertainty in the condition assessment and decision making on the status of a structure. An efficient method to account for the effect of uncertainty will result in a more refined and reliable process in situations when specific and critical decision will need to make in regard to the health condition of a structure and its need for immediate repair and/or reconstruction.

3.1 INTERVAL VARIABLE

A real interval is a closed set defined by extreme values as [11]:

$$\tilde{Z} = [z^l, z^u] = \{z \in \Re \mid z^l \le z \le z^u\} \tag{1}$$



$$\tilde{z} = [a, b]$$

Figure 1. Shows an interval variable schematically. In this work, the symbol (~) represents an interval quantity.

3.2. Interval Arithmetic Operations

Assume $\tilde{X} = [a,b]$ $\tilde{X} = [a,b]$ and $\tilde{Y} = [c,d]$, the interval arithmetic operation is as follows:
Addition:

$$\tilde{X} + \tilde{Y} = [a+c, b+d] \tag{2}$$

Subtraction:

$$\tilde{X} - \tilde{Y} = [a-d, c-b] \tag{3}$$

Multiplication:

$$\tilde{X} \times \tilde{Y} = [\min(\mathrm{ac, ad, bc, bd}), \max(\mathrm{ac, ad, bc, bd})] \tag{4}$$

Division:

$$\tilde{X} \div \tilde{Y} = \left[\min(\frac{\mathrm{a}}{\mathrm{c}}, \frac{\mathrm{b}}{\mathrm{c}}, \frac{\mathrm{a}}{\mathrm{d}}, \frac{\mathrm{b}}{\mathrm{d}}), \max(\frac{\mathrm{a}}{\mathrm{c}}, \frac{\mathrm{b}}{\mathrm{c}}, \frac{\mathrm{a}}{\mathrm{d}}, \frac{\mathrm{b}}{\mathrm{d}})\right], (0 \notin [c,d]) \tag{5}$$

4. Interval Finite Element Method

An interval finite element analysis (as proposed in this work) to perform on a structure (e.g. existing) with displacements/rotations and strains defined as interval variables:

$$[K]\{\tilde{U}\} = \{\tilde{F}\} \tag{6}$$

where, $[K]$ is the stiffness matrix, $\{\tilde{U}\}$ is the interval displacement vector and $\{\tilde{F}\}$ is the interval external force vector. Also, the induced state of stress in each element is obtained as:

$$\{\tilde{\sigma}\} = [C][B]\{\tilde{u}\} \tag{7}$$

where, $\{\tilde{\sigma}\}$ is the element interval state of stress, $[C]$is the constitutive (material) matrix as a function of modulus of elasticity and Poisson ratio, $[B]$ is the strain-displacement matrix, and $\{\tilde{u}\}$ is the vector of element interval displacements. The results of these analyses include the upper and lower bounds on the internal forces and stresses. The bounds on the internal stresses will then be used in the structural condition assessment.

In general, in order to attain guaranteed and nearly sharp results for a system of equations with interval parameters (e.g. computation of structural stresses), interval global optimization techniques may be used. For example, parameterizing and consideration of dependency of intervals tremendously decreases the overestimation that may occur throughout the analysis. And as such, all possibilities in the intervals are considered and gross overestimations are avoided.

5. Methodology Framework

The framework for the developed methodology will be through five steps described as follows:

Step 1: ***Data Acquisition and Structural Measurements***
In this step, displacement and/or other response data in several identified key performance parameters for existing structures is compiled. Furthermore, for a specific structure, several key performance parameters are identified. For example stress ranges will be an important parameter in investigation of cracks in steel-framed structures. The information for these parameters needs to be translated from data that may only be available for strain and acceleration at limited locations within the structure. Therefore, this step involves extracting information for key performance parameters from what is available through structural measurements and data acquisition processes.

Step 2: ***Incorporation of Errors in Input Data***
In this step, the presence of any uncertainty or impreciseness in data (e.g. due to measurement or sensor errors) is incorporated through quantification of the experimental data as intervals of uncertainty used in finite element analyses with uncertain input (Step 3). Step 2 involves a critical review of compiled data and use of statistical analyses to determine the various levels of uncertainties that may be inherent in the data. The quantification of uncertainties are performed through the analysis of variation in the data, comparison with expected norms, reported sensor errors, sampling errors, and uncertainties related to sensor locations. The uncertainty in the method of analysis often develops when the available data needs to be translated into information for the key performance parameters of the structure as explained earlier. In obtaining such information, common engineering methods are employed, which are based on approximations and modeling limitations; and as such, they cause uncertainties in the final results.

Step 3: ***Finite Element Analysis with Uncertainty***
In this step, an interval finite element analysis is performed that utilizes the updated uncertain experimental data for the structure (interval input), in order to obtain the bounds on the induced components' forces and stresses in each component of the structure (upper-bounds of interval output). Figure 2 shows the analysis scheme in Step 3 schematically. The results of this task are used in identification of damage (Step 4).

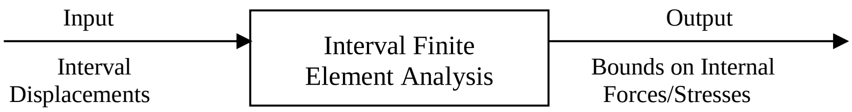


Figure 2. Interval Finite Element Scheme.

Step 4: ***Identification of Damaged Components***
In this step, based on the induced stresses in existing structure's components (Step 3), it is determined whether the induced stresses in each element meet the initial design criteria or, it must be labeled as failed and/or damaged. This identifies the status of the individual elements leading to determination of the safety and reliability of each component locally and the entire structure globally. The results obtained in this step are used to detect the existence and extent of the damaged components in the structure and whether the structure has suffered enough damage in its elements that for practical purposes has reached a failure state.

6. Numerical Example

In order to illustrate the capability of the developed method, the structural damage assessment, using the present method is conducted on a failed sign support structure previously mounted on an interstate highway bridge in Ohio (Figure 3). The location of the failure was adjacent to the end of the girder truss, at the weld between the branch and chord member. The crack propagated circumferentially around the chord member until the complete separation (Figure 4).

Figure 3. Failure location of the sign support structure.

Figure 4. Detailed view of the failure.

The sign support structure consisted of two towers 25.4ft and a girder 73ft. The towers' horizontal and vertical members were made of steel pipes with outer diameter of 6.18 in and a thickness of 0.239 in. The horizontal and vertical girder members were made of aluminum pipes with outer diameter of 4.75 in and a thickness of 0.1875 in. The girder and towers diagonal members were aluminum pipes with outer diameter of 2 in and a thickness of 0.1875 in. The modulus of elasticity for steel and aluminum was 29000 ksi and 10900 ksi, respectively. The Poisson's ratio for both the metals was 0.3.

6.1. PROBLEM SOLUTION

The developed method is performed in the damage assessment of the structure by conducting the main steps of the proposed technique.

6.1.1. Structural Measurements

Structural measurements were previously conducted on this structure by measurements on **base accelerations** on the towers induced by the passage of an eighteen-wheel truck [12]. The experiments were performed fourteen times and the induced accelerations were recorded. Figure 5 depicts the result for one of the experiments. In order to obtain the deflections at the base of the towers, the induced acceleration due to truck passage were double integrated. Figures 6 and 7 depict the integration results to obtain the velocity history and the displacement history for one experiment, respectively.

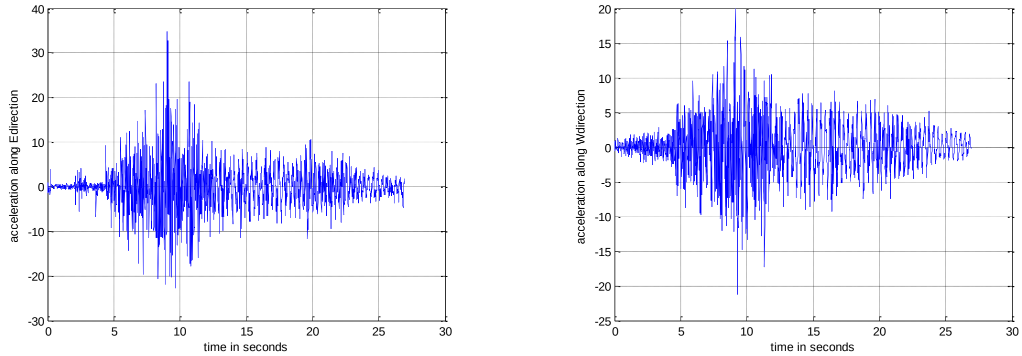


Figure 5. Acceleration history of Test 13 for both towers (Left: East and Right: West).

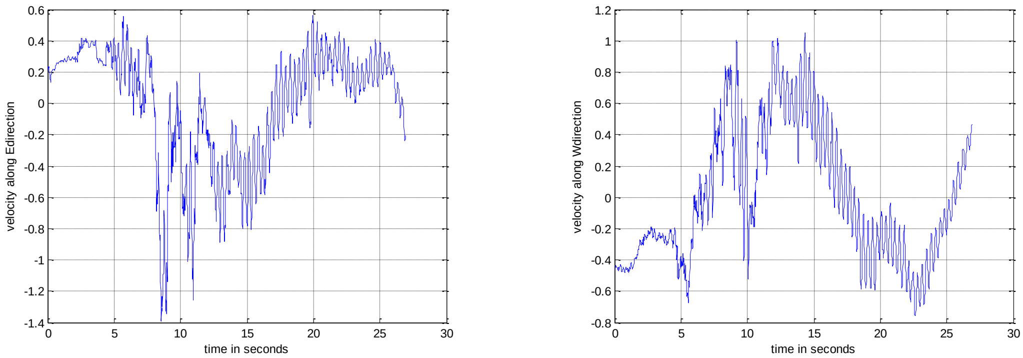


Figure 6. Velocity history of Test 13 for both towers (Left: East and Right: West).

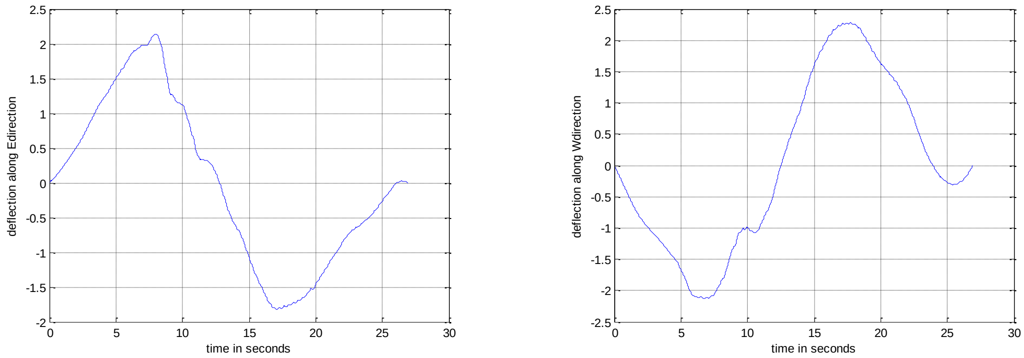


Figure 7. Displacement history of Test 13 for both towers (Left: East and Right: West).

The maximum displacements for each experiment on both towers are determined and shown in Table 1.

Table I. Displacement on towers in fourteen tests

	West Tower Deflection(in)		*East Tower Deflection(in)*	
Test	*Minimum*	*Maximum*	*Minimum*	*Maximum*
1	-0.269	0.4036	-0.1025	0.1766
2	-0.4236	0.6631	-0.2468	0.1283
3	-0.0844	0.1533	-0.0632	0.0649
4	-0.6992	0.9815	-0.4269	0.4506
5	-0.2273	0.1211	-0.5182	0.561
6	-0.375	1.1282	-0.4872	0.4811
7	-0.9154	1.4212	-0.9759	2.6429
8	-0.714	1.2547	-0.9913	2.0486
9	-0.592	0.5622	-0.9831	0.7442
10	-0.3729	0.2666	-0.1528	0.2645
11	-0.5051	0.4234	-0.5006	0.5339
12	-0.1466	0.1516	-0.1719	0.1869
13	-2.1239	2.2826	-1.8241	2.1384
14	-0.4408	0.4757	-0.1991	0.2389

6.1.2. *Incorporation of Uncertainties in Data Results*

The results for fourteen measurements are combined, as the bounding union of all possibilities, to construct the intervals of base deflections for considering the presence of errors and uncertainties including the ones in experiments processes. The intervals for towers' deflections are summarized in Table 2

Table II. Interval Deflections

Tower	*Interval Deflections (in.)*
East	[-1.8241, 2.6429]
West	[-2.1239, 2.2826]

6.1.3. *Interval Finite Element Analysis*

The interval finite element analysis is performed using MATLAB. The proposed procedure is conducted and the structure is modeled using three-dimensional frame elements (2 nodes-6 degree-of-freedom (DOF) per node). The structure model has 92 nodes, 197 elements and 552 DOF's. The prescribed displacements are the vertical nodal displacements at the bases of both towers(Figure 8).

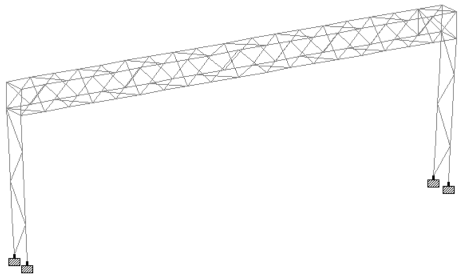


Figure 8. Finite element model of the structure.

For this structure, the analysis is performed using the following steps:

1. Define the structure's mechanical and geometric properties
   - Element stiffness matrix $[K_l]_i$
   - Element rotation matrix $[R]_i$
2. Transform element stiffness matrices from local coordinate system to global coordinate system using the element's rotation matrices:

$$[K_g]_i = [R]_i [K_l]_i [R]_i^T \quad (8)$$

3. Determine the global stiffness matrix of the structure $[K_G]$ by assembling the element stiffness matrices $[K_g]_i$:
   a. Define the Boolean connectivity matrices $[L]_i$ for each element:
   b. Obtain the global stiffness matrix:

$$[K_G] = \sum_{i=1}^{n} [L]_i [K_g]_i [L]_i^T \quad (9)$$

4. Construct the interval equilibrium equation:

$$\begin{pmatrix} P_f \\ P_s \end{pmatrix} = \begin{bmatrix} K_{ff} & K_{fs} \\ K_{sf} & K_{ss} \end{bmatrix} \begin{pmatrix} U_f \\ U_s \end{pmatrix} \quad (10)$$

   where, P_s is the vector of unknown forces, P_f is the vector of applied forces, $\widetilde{U}_s$ is the vector of prescribed interval displacements, K_{ff}, K_{fs}, K_{sf}, and K_{ss} are the partitioned components of global stiffness matrix.

5. Obtain unknown interval displacement vector, $\widetilde{U}_f$:

$$\widetilde{U}_f = K_{ff}^{-1}\left(P_f - K_{fs}\widetilde{U}_s\right) \quad (11)$$

6. Determine internal axial forces for each element $\{\tilde{f}\}_i$:

$$\{\tilde{f}\}_i = [K]_i [R]_i^T [L]_i^T \begin{pmatrix} U_f \\ U_s \end{pmatrix} \quad (12)$$

7. Determine the interval axial stress in each element of the structure:

$$\tilde{\sigma}_i = \frac{\{\tilde{f}\}_i}{A_i} \tag{13}$$

where, A_i is area of each element. The results on this phase contain the bounds on induced stresses in each component of the structure.

6.1.4. *Identification of Damaged Member*

The maximum induced interval stress in the girder is:

$\tilde{\sigma}_{max} = [\,-0.5362\,, 0.5313\,]ksi$

Therefore, the upper bound of the maximum induced stress is:

$\sigma_{max} = \max(|\tilde{\sigma}_{max}|) = 536.2\ psi$

This maximum induced stress occurs in the chord member of the girder adjacent to the tower which is the actual failed member (Figures 3 and 4). Therefore, the results from the developed method correlate with the actual structure's behavior. The lifetime of the failed member is also determined based on Miner's damage rule for fatigue analysis as follows.

6.1.5. *Sign Support Truss Lifetime Analysis*

The lifetime of the structure is determined using Miner's rule based on the analytical approximation of the traditional S-N curve as:

$$N_f = \frac{C_f}{S_R^{\ 3}} \tag{14}$$

where, N_f is the number of cycles to failure, S_R is the stress range of the critical member determined, and C_f is a constant dependent on the material and weld detail.

For the truss aluminum weld detail ET, C_f=1,870,000. Then, the stress range for the critical member is: $S_R = width\ (\tilde{\sigma}_{max}) = [0.5313\ ksi - (-0.5362\ ksi)] = 1.0675\ ksi$

Substituting the values to the S-N Equation: $N_f = 1{,}537{,}226\ cycle$. The lifetime of the failed member in terms of truck passage is:

$$Lifetime = \frac{N_f}{365.\, N_{trucks} \cdot N_{cycles}} \tag{15}$$

where, lifetime is calculated in years, N_{trucks} is the number of truck passage per day ($N_{trucks} = 150$) , and N_{cycles} is the number of cycles of stress deviations per truck passage ($N_{cycles} = 1$). The lifetime of the failed member is: $Lifetime = 29\ years$.

The determined lifetime is the conservative measure of the actual failure time (36 years) due to consideration of uncertainties.

Moreover, in order to verify the results obtained using the developed method, a series of Monte-Carlo using uniformly bounded random variables simulations were performed. The results of the simulation, as expected, were the inner-bounds of the interval analysis.

7. Conclusion

This work develops an objective condition assessment tool that integrates finite element models, structural measurements and uncertainty analyses. The developed condition assessment framework is able to use visual inspection reports, collected non-destructive-test measurements, and mathematical modeling with a greater level of confidence due to the inclusion of uncertainty into the protocol. The resulting information can be implemented into structural asset management programs to provide more accurate information to the owners for decision making on the structure's condition. This will improve the planning and process for repair, and rehabilitation of critical aging structures (e.g. buildings and bridges). Furthermore, the use of interval-based finite element modeling offers a more practical procedure than the stochastic-based finite element methodology and an accuracy level that exceeds those in traditional probabilistic-based methods. This is because of the set-based, bounding, non-iterative and computational efficient nature of interval approach when it is compared to traditional those methods.

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