ILLINOIS INSTITUTE OF TECHNOLOGY

Reliable Condition Assessment of Structures Using Field Measurements and Uncertainty Analyses

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Condition Assessment of Infrastructures

The safety and mobility of the population is dependent on the structural integrity of existing infrastructures.

The failure of structural systems has significant societal and human consequences.

To achieve this integrity, there is a need to perform structural condition assessment for infrastructures to guarantee their safe and reliable operation.

Condition Assessment of Infrastructures (Cont.)

Condition assessment is a major cost and management issue related to existing infrastructures.

However, the current protocols for structure's condition assessment typically produce very subjective and highly variable results.

Condition Assessment of Infrastructures (Cont.)

Attributed to:

1) The application of results obtained by health monitoring of a structure is limited due to presence of errors and uncertainties.

2) The conventional structural analysis schemes are incapable of considering uncertainties in experiments, system properties, data compilation, and loads.

Thereby resulting in error when estimating the structure’s health.

Research Objective

To develop a framework for condition assessment of infrastructures by incorporating engineering uncertainty analyses with structural health monitoring outcomes.

The goal is to achieve a more robust procedure for result interpretation and follow-up engineering decision-making process geared for management of existing infrastructures.

Procedure

To establish a hybrid protocol that combines experimental structural health monitoring (performance of non-destructive tests for structure’s response) and theoretical structural uncertainty analyses (interval finite element analysis).

Presentation Outline

- Structural health monitoring procedure
- Fundamentals of uncertainty analyses
- Introducing the framework for developed methodology
- Case Study
- Conclusions

Structural Health Monitoring

The health and condition of in-service structures is usually assessed through visual inspections and nondestructive testing & evaluation (NDT/NDE) methods conducted on a pre-set schedule.

The goal of structural health monitoring system is to employ sensing instruments to provide information pertaining to the condition of the structure.

(Chang 2003)

Structural Health Monitoring (Cont.)

The today's practice of structural health monitoring involves a host of structural parameters for which the 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.

Structural Health Monitoring- Challenges

- The efficient use of the compiled data.
- Development of a process for accurately assessing the actual condition of a structure.
- The results of this process be used reliably.
- Decision making in regards to the structure’s need for repair, retrofit or reconstruction.

Engineering Uncertainty Analysis

- Formulation

Modifications on the representation of the system characteristics due to presence of uncertainty

- Computation

Development of schemes capable of considering the presence of uncertainty throughout the solution process

Uncertainty Analysis Schemes

considerations

- Consistent with the system’s physical behavior
- Capable of performing analysis with limited information
- Computationally feasible

Uncertainty

Inability to predict the future.

Categories:

- Aleatoric

The system has an intrinsic random or stochastic nature and it is not predictable.

- Epistemic

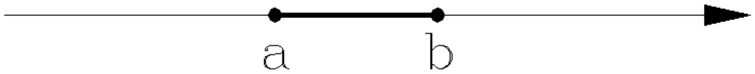
The uncertainty induced by the lack of information and it is predictable.

Interval Uncertainty

The set-theoretic (unknown but bounded) or interval representation is one method to quantify the uncertainty present in a physical system.

In this representation, the uncertain parameter varies within the interval defined by extreme values.

Interval Variable



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

A real interval is a set of the form:

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

Archimedes (287-212 B.C.)

$$3\frac{10}{71} < \pi < 3\frac{1}{7}$$

Interval Arithmetic Operations

Considering two interval numbers: $\tilde{X} = [a,b]$ and $\tilde{Y} = [c,d]$

Addition:

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

Multiplication:

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

Subtraction:

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

Division:

$$\frac{\tilde{X}}{\tilde{Y}} = [a,b] \times [\frac{1}{d}, \frac{1}{c}], (0 \notin [c,d])$$

Sub-distributive Property:

$$(\tilde{X} + \tilde{Y}) \times \tilde{Z} \subset \tilde{X} \times \tilde{Z} + \tilde{Y} \times \tilde{Z}$$

Dependency of Intervals

Considering two independent interval numbers: $\tilde{X} = [-2,2]$ and $\tilde{Y} = [-2,2]$

- Independent Interval Multiplication:

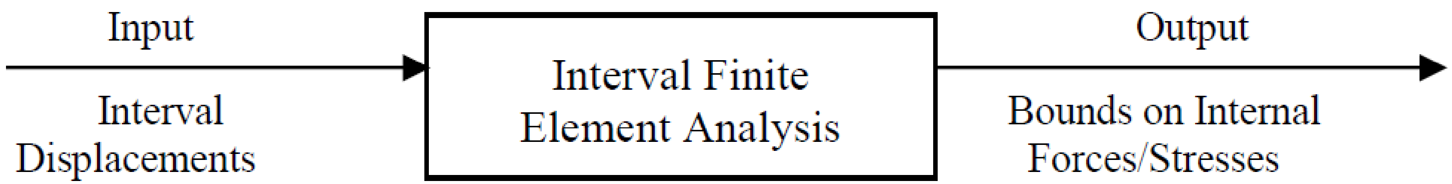
$$\tilde{X} \times \tilde{Y} = [-4,4]$$

- Dependent Interval Multiplication:

$$\tilde{X} \times \tilde{X} = [0,4]$$

Interval Finite Element Method

An enhanced method of finite element analysis that is capable of considering the presence of interval uncertainty in the input parameters.



This results in obtaining the analysis output as interval values whose bounds can be used for decision-making and design.

Methodology Framework

Node 1

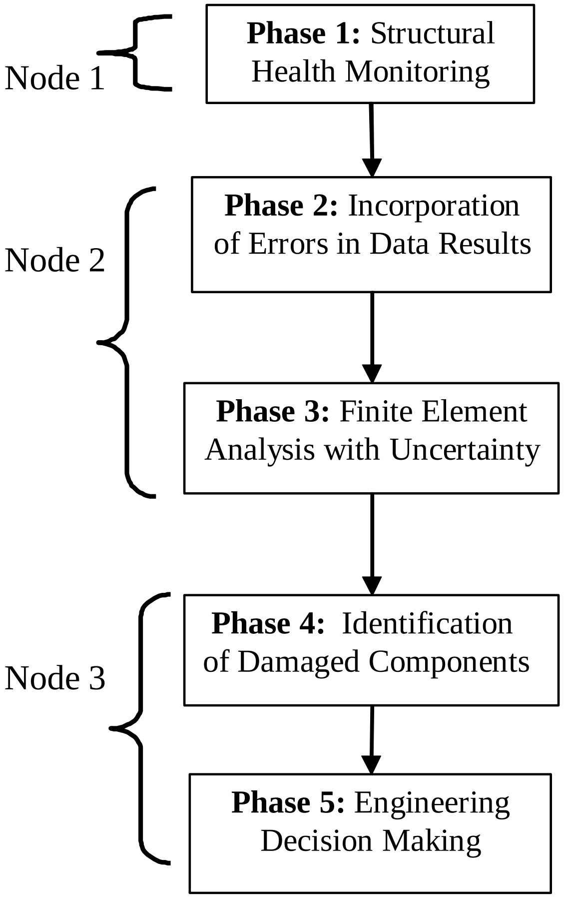
Data Acquisition

Node 2

Structural Uncertainty Analysis

Node 3

Results Evaluation and Decision-Making



Node 1: Data Acquisition

Phase 1: Structural Health Monitoring

The displacement and/or other response data in several identified key performance parameters for existing structures are obtained.

For example, stress ranges will be an important parameter in investigation of cracks in critical components of a steel girder in a bridge.

The information for these parameters needs to be translated from data that may only be available for strain and acceleration of the structure.

Node 2: Structural Uncertainty Analysis

Phase 2: Incorporation of Errors in Data Results

The presence of any uncertainty or impreciseness in data (for example, due to measurement or sensor errors) is incorporated through quantification of the experimental data as intervals of uncertainty.

The quantification of uncertainties is performed through the analysis of variation in the data, reported senor errors, sampling errors, and uncertainties related to sensor locations.

Node 2: Structural Uncertainty Analysis

Phase 3: Finite Element Analysis with Uncertainty

Interval finite element analysis is performed using the updated experimental data for the structure in order to obtain the bounds on the induced components' forces and stresses.

This interval finite element analysis utilizes the data with uncertainty, quantified by interval representation, to establish bounds for the results used in engineering decision-making.

Node 3: Results Evaluation and Decision-Making

Phase 4: Identification of Damaged Components

Based on the induced stresses in existing structure’s components, it is determined whether, those components meet the initial design criteria or, they must be labeled as failed and/or damaged.

This evaluation determines the safety of each component of the structure based on induced stresses in the elements and, whether the structure has suffered significant damage in its elements that for practical purposes has reached a failure state.

Node 3: Results Evaluation and Decision-Making

Phase 5: Engineering Decision Making

The quantity and intensity of the damage or failure of the structure’s components is used to establish a framework for decision making on whether to repair or replace the structure based on both safety and economical considerations.

Case Study

A sign support structure :

The studied sign support structure was mounted on I-480 Interstate bridge in Cleveland, Ohio.

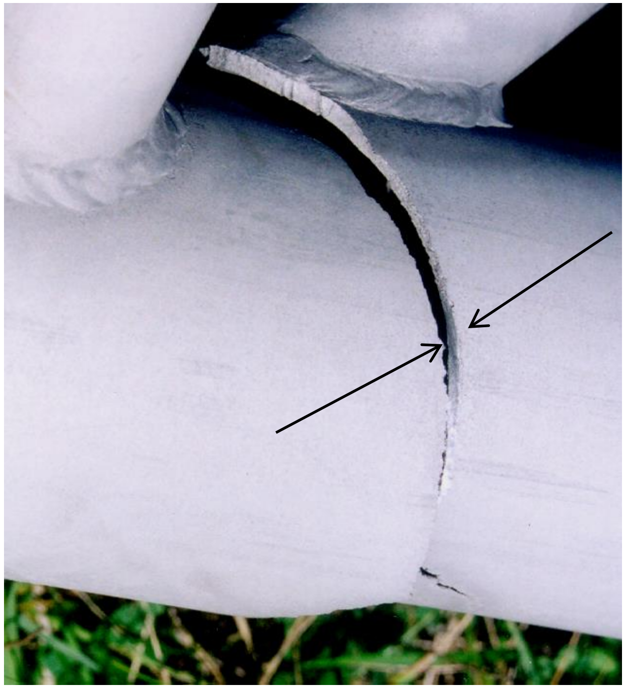
Structure Specifications

	Towers		Truss girder	
Members	Orthogonal Members	Diagonal members	Orthogonal members	Diagonal Members
Material	Steel pipes	Aluminum Pipes	Aluminum pipes	Aluminum pipes
Outer diameter	6.18 in	2.0 in	4.75 in	2.0 in
Thickness	0.239 in	.1875 in	0.1875 in	0.1875 in

Structural Failure

The location of a failure was adjacent to the end of the girder truss, at the weld between the branch and chord member after 36 years.

Structural Failure (Cont.)



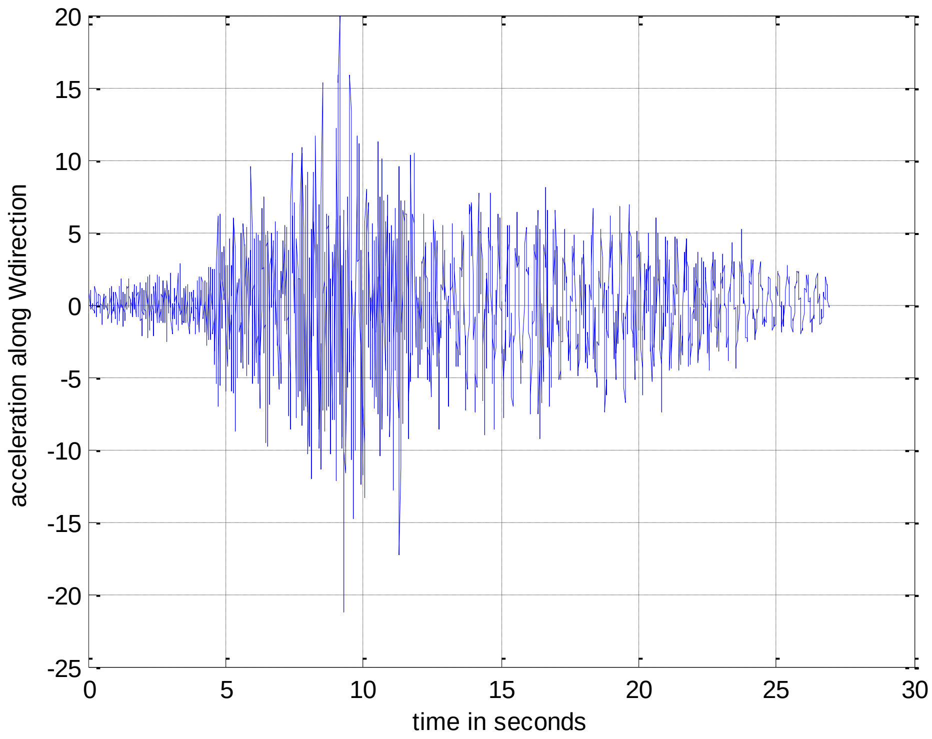
The crack propagated circumferentially around the chord member until complete separation.

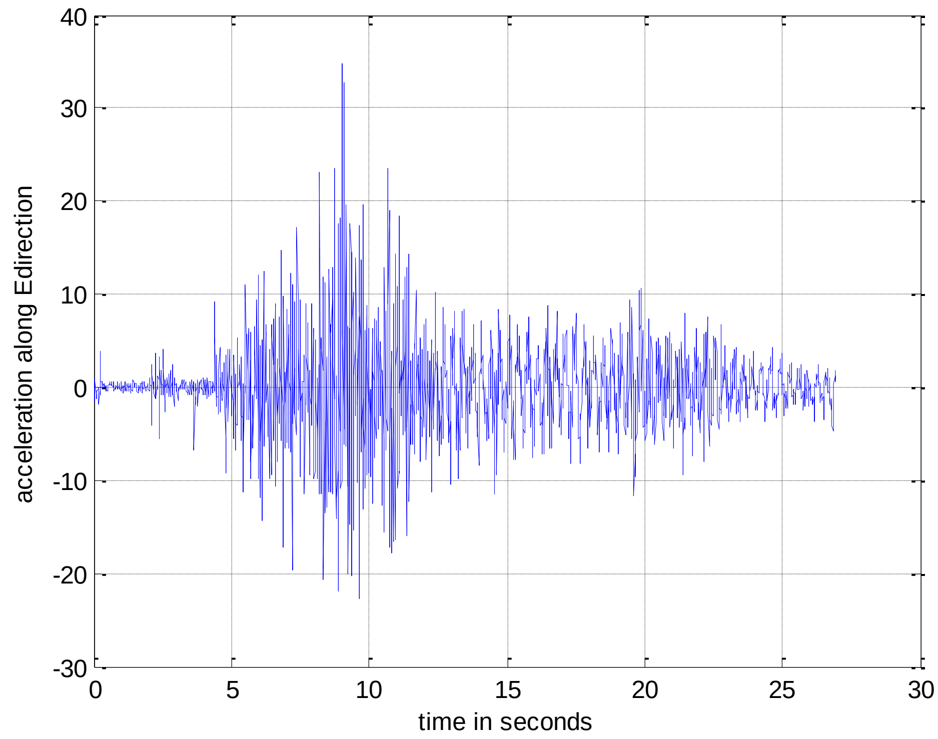
Structural Health Monitoring

- The failed sign support was replaced by an identical structure.
- The dynamic response of the structure was previously determined by the passage of eighteen-wheel truck.
- Base acceleration on the towers due to the passage of truck was measured using accelerometers.
- The experiments were performed fourteen times.

Processed Measured Acceleration

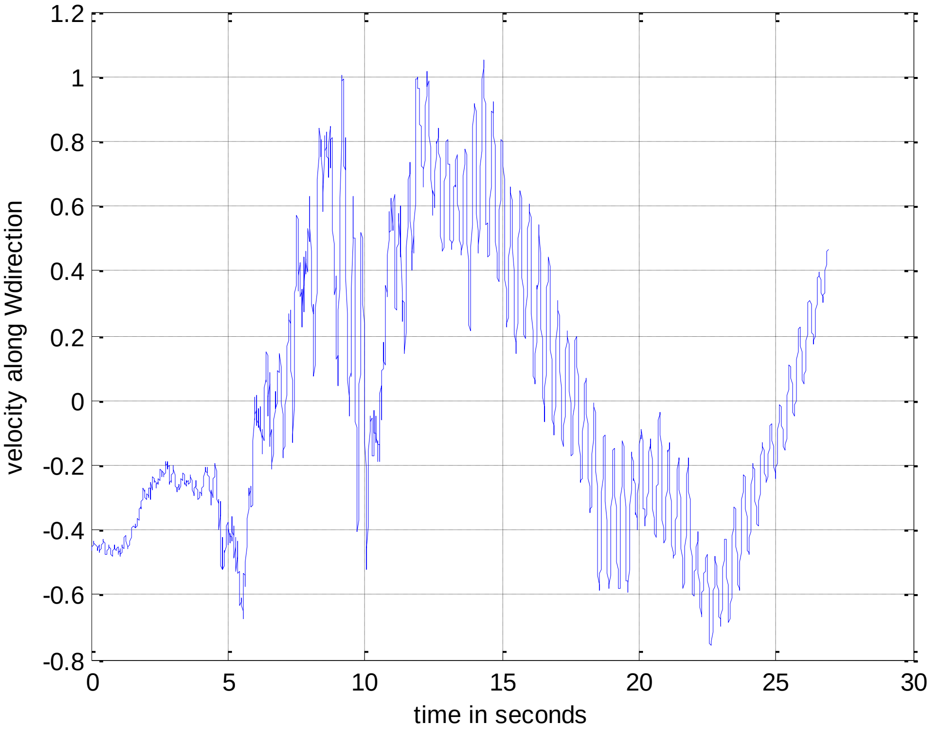
For the east and west towers' bases of the sign support structure:

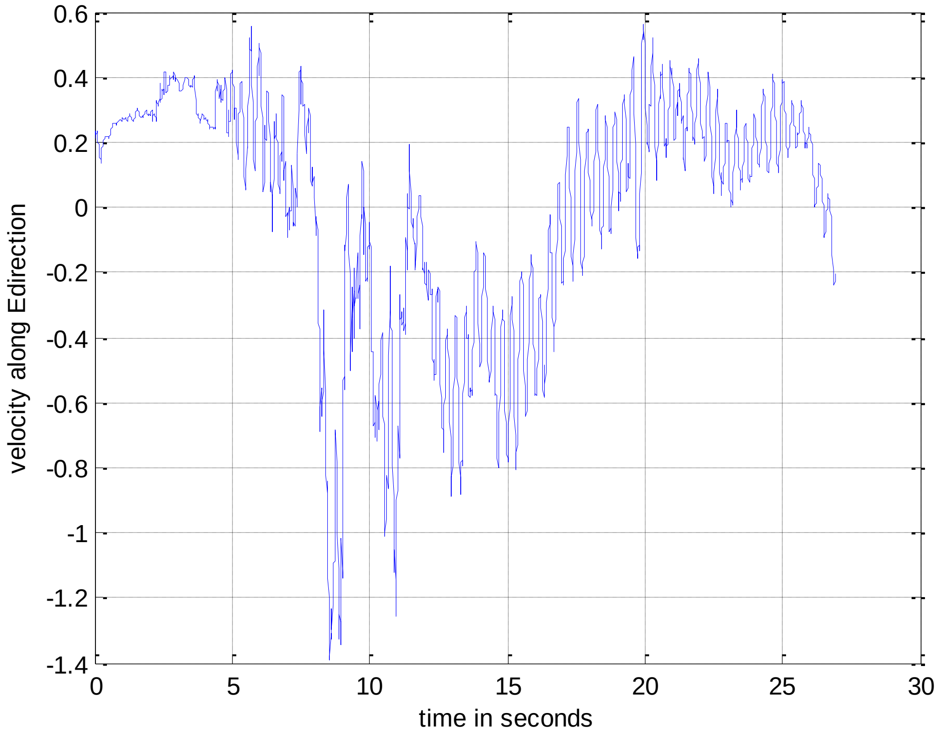




Calculated Velocity

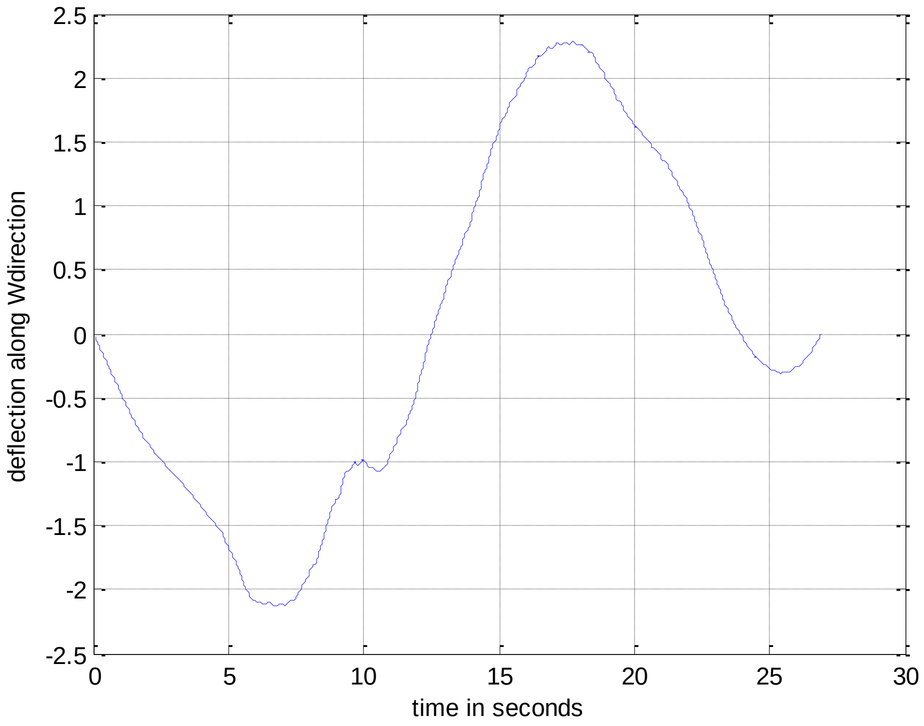
Through integration for the east and west towers' bases of the sign support

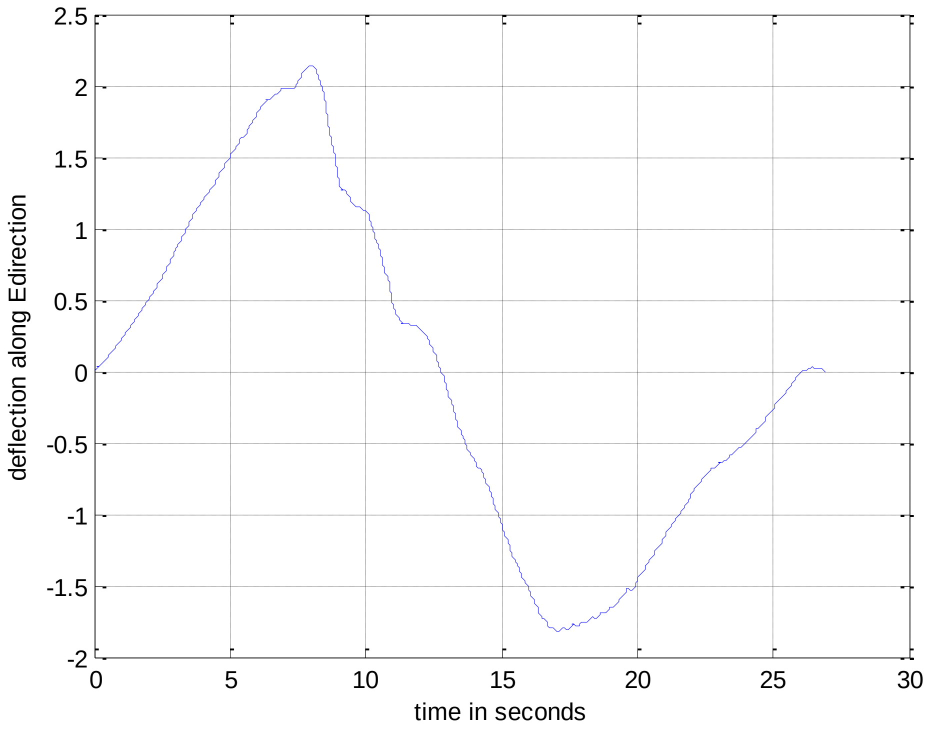




Calculated Displacement

Through integration for the east and west towers' bases of the sign support





Displacement on Towers in Fourteen Tests

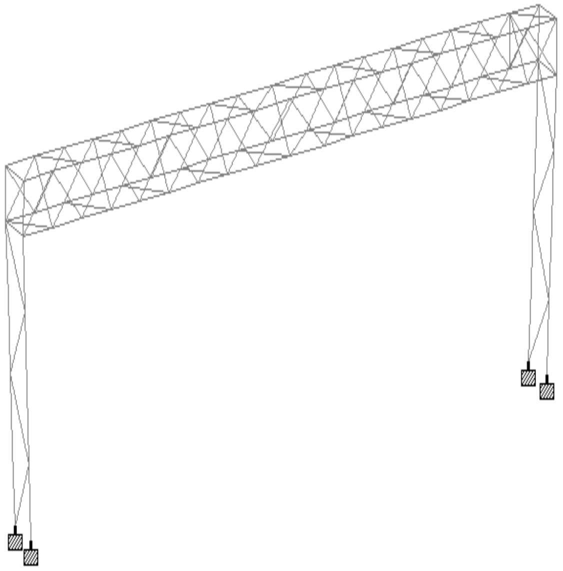
Test	WEST TOWER Deflection(in)		EAST TOWER Deflection(in)	
	Minimum	Maximum	Minimum	Maximum
1	-0.269	0.4036	-0.1025	0.1766
2	-0.4236	0.6631	-0.2468	0.1283
3	-0.0844	0.1533	-0.0632	0.0649
4	-0.6992	0.9815	-0.4269	0.4506
5	-0.2273	0.1211	-0.5182	0.561
6	-0.375	1.1282	-0.4872	0.4811
7	-0.9154	1.4212	-0.9759	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

Data Processing

- For each set of experiment data, maximum and minimum base deflections in the towers are determined.
- The results of fourteen experiments are combined using interval variables. For towers, deflection intervals, to be used in the IFEM are:

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

Interval Finite Element Analysis



- The calculated interval deflections for towers' bases were applied and interval finite element analysis is performed.
- The maximum induced stresses for each member are determined.

Interval Finite Element Analysis

- The interval finite element analysis is performed using MATLAB.
- The developed procedure is conducted and the structure is modeled using three-dimensional elements
- The structure model has 92 nodes and 197 elements and 552 DOFs.

Interval Finite Element Analysis (Cont.)

- Define the properties:
  - Structure’s mechanical and geometric properties .
  - Element stiffness matrices, $[K]_i$
  - Element rotation matrices, $[R]_i$

- Transform element stiffness matrices from local to global coordinate system

$$\left[K_g\right]_i = [R]_i [K_l]_i [R]_i{}^T$$

Interval Finite Element Analysis (Cont.)

- Structure Assemblage
  - Define the Boolean connectivity matrices,
  - Obtain global stiffness matrix

$$[K_G] = \sum_{i=1}^{n} [L]_i \left[K_g\right]_i [L]_i^T$$

Interval Finite Element Analysis (Cont.)

- Construct the equilibrium equation,

$$\begin{pmatrix} P_f \\ P_s \end{pmatrix} = \begin{bmatrix} K_{ff} & K_{fs} \\ K_{sf} & K_{ss} \end{bmatrix} \begin{pmatrix} U_f \\ \widetilde{U_s} \end{pmatrix}$$

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

Interval Finite Element Analysis (Cont.)

- Obtain the unknown interval displacement,

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

- Perform analysis and determine internal axial forces.

$$\{\tilde{f}\}_i = [K]_i [R]_i{}^T [L]_i{}^T \begin{pmatrix} \widetilde{U}_f \\ \widetilde{U}_s \end{pmatrix}$$

- Determine the interval stress in each element

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

Identification of Damaged Member

The maximum induced interval stress in the girder is

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

The upper bound of maximum normal stress in the girder:

$$\sigma_{max} = \max\left(|\widetilde{\sigma}_{max}\,|\right) = 536.2\,psi$$

This maximum induced stress occurs in the chord member of the girder adjacent to the tower which is the actual failed member.

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.

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

- 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.

Sign Support Truss Lifetime Analysis (Cont.)

- For the truss aluminum weld detail ET, C_f =1,870,000.
- Stress range of the critical member, $S_R = 1.0675\ ksi$
- Substituting the values to the equation $\mathrm{N_f} = 1{,}537{,}226$ cycles

Sign Support Truss Lifetime Analysis (Cont.)

The fatigue analysis for lifetime of the failed member in terms of truck passage is calculated using Miner's rule as:

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

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).

Sign Support Truss Lifetime Analysis (Cont.)

The lifetime of the failed member is:

$$Lifetime = 29\ years$$

Verification of Failure

This analysis indicates that the largest axial stress in the chord members occur at the ends of the truss, which is the locations of the observed fracture failure.

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

Decision-Making

The correlation between the analysis and the actual failure time suggests that the new sign support structure must be replaced after around 30 years of service in order to prevent any catastrophic failure and/or fatalities.

Summary and Conclusions

- This work develops a new methodology for condition assessment management and engineering decision-making for infrastructures using a combination of experimental health monitoring and theoretical structural uncertainty analyses.

- The developed method is versatile and computationally efficient due to its set theoretic approach.

- The results of this work suggests that establishing a relationship between structural health monitoring and engineering uncertainty analysis will provide an increased confidence in the results of condition assessment program for infrastructure management.

Questions