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Health Monitoring and Damage Assessment of Truss Structures from Static Responses

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Abstract:
A method for structural damage assessment of truss structure utilizing static displacement measurement is presented. Damage is defined as abrupt changes in some parameters of the considered structure. Abrupt change means that change of system parameter occurs either instantaneously or at least very fast with respect to the sampling rate of the measurements due to severe events such as earthquake, typhoon, crash and so on. This method preserves the structural connectivity and determines changes in cross-sectional properties at the element level, including large changes or element failures for stable structures. The identified cross-sectional element properties can be used for damage assessment and load rating of structures. Two numerical examples, including two-dimensional (2D) and three-dimensional (3D) truss structures are presented and the element stiffness's are successfully and accurately evaluated.

***Key words**: Structural health monitoring; Damage detection; Error elimination*

1. Introduction

Structural Health Monitoring (SHM) has become a vital component to structural engineering practices. Structural Health Monitoring aims to give, at every moment during the life of a structure, a diagnosis of the "state" of the constituent materials, of the different parts, and of the full assembly of these parts constituting the structure as a whole. The state of the structure must remain in the domain specified in the design, although this can be altered by normal aging due to usage, by the action of the environment, and by accidental events. An international workshop on structural health monitoring was held at Stanford University in September of 1999. The results of this workshop are summarized in a subjective manner herein. The Second International Workshop on Structural Health Monitoring was held on the campus of Stanford University in 8-10 September 1999. According to Professor F-K Chang (the Editor of Proceedings and the Organizer of both workshops), participation has grown tremendously compared with the First Workshop, also held at Stanford University in 18-20 September 1997, when approximately sixty papers were presented and discussed. Chang (1999) gave the five major components of the structural health monitoring systems as follows:

- Sensing technology
- Diagnostic signal generation
- Signal processing
- Identification and interpretation
- Integration

Structural parameter estimation is a powerful tool capable of updating an analytical model using a set of measured test data. An optimization-base method is proposed to adjust the parameters of the finite element model (FEM), minimizing the difference between the analytical response and nondestructive test (NDT) data. Parameters of the FEM can be any appropriate geometric or material property, including cross-sectional properties of the structural components. Using parameter estimation results, major differences between the estimated and expected parameters are classified as damage.

For parameter estimation the applied forces are chosen so that structural responses are linear-elastic despite some degree of damage that structural components may have experienced.

The need to monitor the health of our infrastructure and also maintain it has never been more necessary than now with most of the infrastructure being structurally deficient. In order to monitor the health of a structure a structural health monitoring system must

be implemented to fully understand how the structure in question is responding to various loading conditions and determine whether it is susceptible to failure.
The main objectives of the SHM are to monitor the loading conditions of a structure, to assess its performance under various service loads, to verify or update the rules used in its design stage, to detect its damage or deterioration, and to guide its inspection and maintenance.
It is very important to understand the effects of accelerations of a structure because it will govern the design of a structural health monitoring system. When structures are being designed, such as bridge structures, properties such as dead load can be calculated with a high level of confidence and accuracy. When it comes down to wind, seismic or temperature loads, the accuracy is not as good because they are based on design standards. This makes the design of a SHM very important to monitor these effects on a bridge structure, to insure adequate design.
When designing a SHM system it is also very important to understand the structure completely to insure proper design. Whether the structure in question is brand new or an existing structure, there are many things to consider when designing. These would include the environment the structure will be in, the traffic loads it will undergo on a consistent basis, how the structure was designed, whether or not the structure could with stand a natural disaster, and also the potential failures it could face.

2. Need for SHM

The potential failure of structures is a major concern for any society. The impact of structural failure can have large economic and public safety consequences. SHM systems can provide a sensible way to prevent failure. Another important need for SHM is to fully understand how a structure will respond or man-made disasters.
Natural disasters would include, tornados, earth quakes, and most importantly for bridge structures-flooding. Man-made disasters would include fires, and for bridge structures-large accidents such as a large ship colliding into the bridge. To know whether or not a bridge structure was safe moments after a disaster would play a pivotal role in the survival of the structure and the people who need to cross it.
Structural health monitoring can also be used to assess preexisting damage to a structure, and determine whether or not the structure is still safe. This also aides in the maintenance of a structure and gives key information on which part of the structure might need repair or inspection to prevent failures from occurring.
To be able to monitor potential failures or points of weakness in a structure is very advantages to society because it prevents the unnecessary shutdown of a bridge so that it can be inspected, and also limits the amount of human error during the inspection process. Both of which saving time and money, this is very important when dealing with very large structures such as a bridge.

3. Estimation of Parameter

An optimization-based parameter estimation method is presented to adjust the parameters of a finite element model with simulated static strain measurements. Forces are applied at a subset of DOFs and strains are measured on a limited number of structural elements.
A method for the parameter estimation of structures was developed in a companion paper. It used subsets of static applied forces and strain measurements and successfully identified structural element stiffness.
Elemental strain vector,

$$\{\varepsilon\} = [M]\{V\}$$

Where, $\{V\}$ = global displacement vector,

$[M]$ = element mapping vector.

The definition of axial strain in terms of the DOFs is

$$\varepsilon_n = \frac{\bar{u}_j - \bar{u}_i}{L_n}$$

Where $\bar{u}_i$ and $\bar{u}_j$ = displacements at nodes *i* and *j* in the local element coordinate system; and L_n = length of element *ij*.

Then it arranged into matrix from as

$$\varepsilon_n = \frac{1}{L_n}\{-1 \quad 1\}\begin{Bmatrix}\bar{u}_i \\ \bar{u}_j\end{Bmatrix}_n$$

The mapping vector $\{\bar{M}_n\}$ for the axial deformation of a truss element *n* in the local coordinates

$$\{\bar{M}_n\} = \frac{1}{L_n}\{-1 \quad 1\}$$

To transform the mapping matrix from the local coordinates $\bar{x}$ to the global coordinates in a 2D or 3D space, direction cosines are defined mathematically, they are

$$l_{\bar{x}x} = \cos(\alpha_x);\, l_{\bar{x}y} = \cos(\alpha_y);\, l_{\bar{x}z} = \cos(\alpha_z)$$

Where $l_{\bar{x}y}$ = cosine of the angle between the local $\bar{X}$ -axis and the global *Y*-axis.

The mapping vector for the axial deformation of a truss element *n* in 2D global coordinates

$$\left\{M_n\right\} = \frac{1}{L_n}\left\{-l_{\bar{x}x} \quad -l_{\bar{x}y} \quad l_{\bar{x}x} \quad l_{\bar{x}y}\right\}_n$$

This is extended to third dimensions by including the third direction cosine as

$$\left\{M_n\right\} = \frac{1}{L_n}\left\{-l_{\bar{x}x} \quad -l_{\bar{x}y} \quad -l_{\bar{x}z} \quad l_{\bar{x}x} \quad l_{\bar{x}y} \quad l_{\bar{x}z}\right\}_n$$

Strain Error Function: To measure the difference between the analytical strains and measured strains, an error function is formed. The "output strain error function" is defined as

$$\left[e(p)\right] = \left[\varepsilon_a(p)\right]^a - \left[\varepsilon_a\right]^m$$

The a superscript = analytical values; and m = measured values.
Then,

$$\left[e(p)\right] = \left[B_a\right]\left[K(p)\right]^{-1}\left[F\right] - \left[\varepsilon_a\right]^m$$

Then $\left\{e(p)\right\}$ is linearized using a first-order Taylor series expansion as

$$\left\{e\left(p+\Delta p\right)\right\} \cong \left\{e\left(p\right)\right\} + \left[\frac{\partial\left\{e\left(p\right)\right\}}{\partial\left\{p\right\}}\right]\left\{\Delta p\right\}$$

This sets up the definition of the sensitivity matrix $\left[S\left(p\right)\right]$ of size $NM \times NUP$ as

$$\left[S\left(p\right)\right] = \left[\frac{\partial\left\{e\left(p\right)\right\}}{\partial\left\{p\right\}}\right]$$

An iterative technique is used, whereby, for each iteration k

$$\left\{p\right\}_{k+1} = \left\{p\right\}_k + \left\{\Delta p\right\}_k$$

Where $\left\{\Delta p\right\}$ = change in parameters and is of size $NUP \times 1$.

4. Two-Dimensional Truss Example

The first example structure is a two-dimensional 25 member truss element, as seen in figure, members carrying axial loads only and pinned at the ends. This also means that the only applicable parameter is the cross-sectional area A of the members.

- Modulus of elasticity E for all elements is 210 GPa,
- Initial iteration value of parameters is 35.25 cm^2,
- True value of parameters is 25.25 cm^2.

For this experiment, a 600 N load applied to every *FDOF*. Using Matlab programing we can identify the most effected member of the truss. And the results are bellow to tabulated format in TABLE I.

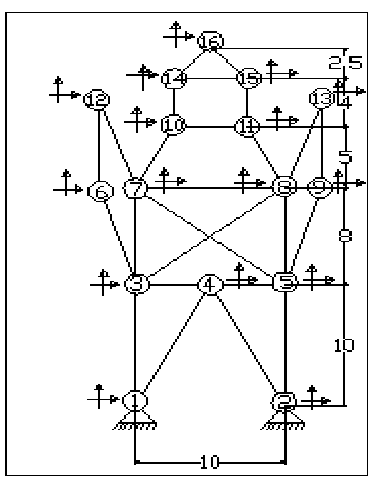

Figure 1: 25 member truss element

Compare between area found, true area and absolute percentage cross sectional error in 2D Truss members using Matlab programing are bellow-

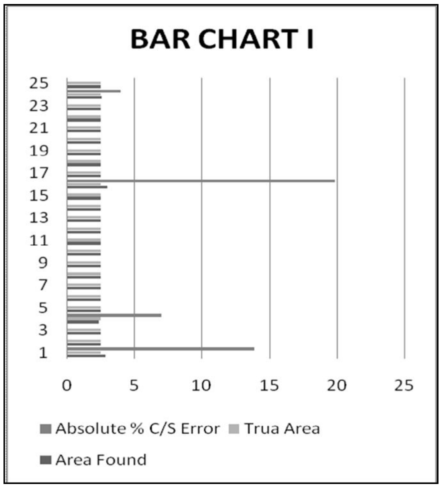

Figure 2

CASE				
Mem. No.	**Area found**	**True Area**	**% Error in C/S Area**	**Absolute % C/S Error**
	*1.0e+003 **	*1.0e+003 **		
1	2.875	2.525	13.86	13.86
2	2.525	2.525	0.00	0.00
3	2.525	2.525	0.00	0.00
4	2.3485	2.525	-6.99	6.99
5	2.525	2.525	0.00	0.00
6	2.525	2.525	0.00	0.00
7	2.525	2.525	0.00	0.00
8	2.525	2.525	0.00	0.00
9	2.525	2.525	0.00	0.00
10	2.525	2.525	0.00	0.00
11	2.525	2.525	0.00	0.00
12	2.525	2.525	0.00	0.00
13	2.525	2.525	0.00	0.00
14	2.525	2.525	0.00	0.00
15	2.525	2.525	0.00	0.00
16	3.025	2.525	19.80	19.80
17	2.525	2.525	0.00	0.00
18	2.525	2.525	0.00	0.00
19	2.525	2.525	0.00	0.00
20	2.525	2.525	0.00	0.00
21	2.525	2.525	0.00	0.00
22	2.525	2.525	0.00	0.00
23	2.525	2.525	0.00	0.00
24	2.625	2.525	3.96	3.96
25	2.525	2.525	0.00	0.00

Table 1: Specification of Areas in 2D

5. Three-Dimensional Truss Example

The second example structure is a three-dimensional 44 member truss element, as seen in figure, members carrying axial loads only and pinned at the ends. This also means that the only applicable parameter is the cross-sectional area *A* of the members.

- Modulus of elasticity *E* for all elements is 210 GPa,
- Initial iteration value of parameters is 35.25 cm^2,
- True value of parameters is 32.26 cm^2.

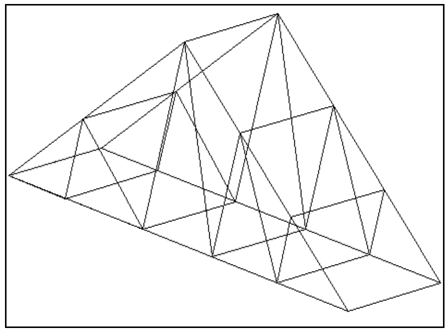

Figure 3: 44 member truss element in 3D members

For this experiment, a 445 N load applied to every *FDOF*. Using Matlab programing we can identify the most effected member of the truss. And the results are bellow to tabulated format in TABLE II.

Compare between area found, true area and absolute percentage cross sectional error in 3D Truss members are bellow-

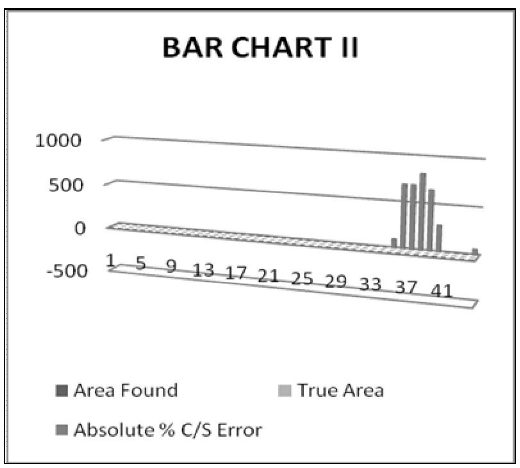

Figure 4

CASE				
Mem. No.	**Area found**	**True Area**	**% Error in C/S Area**	**Absolute % C/S Error**
	1.0e+04 *	**1.0e+004 ***		
1	0.3226	0.3226	0.00	0.00
2	0.3226	0.3226	0.00	0.00
3	0.3226	0.3226	0.00	0.00
4	0.3226	0.3226	0.00	0.00
5	0.3226	0.3226	0.00	0.00
6	0.3226	0.3226	0.00	0.00
7	0.3226	0.3226	0.00	0.00
8	0.3226	0.3226	0.00	0.00
9	0.3226	0.3226	0.00	0.00
10	0.3226	0.3226	0.00	0.00
11	0.3226	0.3226	0.00	0.00
12	0.3226	0.3226	0.00	0.00
13	0.3226	0.3226	0.00	0.00
14	0.3226	0.3226	0.00	0.00
15	0.3226	0.3226	0.00	0.00
16	0.3226	0.3226	0.00	0.00
17	0.3226	0.3226	0.00	0.00
18	0.3226	0.3226	0.00	0.00
19	0.2892	0.3226	-10.35	10.35
20	0.2956	0.3226	-8.37	8.37
21	0.309	0.3226	-4.22	4.22
22	0.3226	0.3226	0.00	0.00
23	0.3226	0.3226	0.00	0.00
24	0.3226	0.3226	0.00	0.00
25	0.3226	0.3226	0.00	0.00
26	0.3226	0.3226	0.00	0.00
27	0.3226	0.3226	0.00	0.00
28	0.3226	0.3226	0.00	0.00
29	0.3226	0.3226	0.00	0.00
30	0.3226	0.3226	0.00	0.00
31	0.3226	0.3226	0.00	0.00
32	0.3226	0.3226	0.00	0.00
33	0.3226	0.3226	0.00	0.00
34	0.3226	0.3226	0.00	0.00
35	-0.007	0.3226	-102.17	102.17
36	2.5799	0.3226	699.72	699.72
37	2.5804	0.3226	699.88	699.88
38	2.9802	0.3226	823.81	823.81
39	2.4494	0.3226	659.27	659.27
40	1.2559	0.3226	289.31	289.31
41	0.3226	0.3226	0.00	0.00
42	0.2916	0.3226	-9.61	9.61
43	0.318	0.3226	-1.43	1.43
44	0.1088	0.3226	-66.27	66.27

Table 2: Specification of Areas in 3D

6. Conclusion

A structural damage measurement method has proposed for locating and quantifying damage within structural systems. An example of truss structure is presented in this paper. The proposed damage detection method has demonstrated to be a reliable for identifying multiple damages within structural systems. A new method was proposed and successfully verified for parameter identification at the element level using static applied forces at a subset of DOFs and strain measurements at selective locations for linear-elastic structures. These strains represent both axial and bending deformations. This method is capable of identification of all or a selective subset of parameters of structures, including parameters with zero values in case of failures.

Two numerical examples were examined to validate the proposed method. However, this is just the necessary condition and not the sufficient condition for successful parameter identification. If linear dependencies exist in the sensitivity matrix, they reduce the capability to identify all parameters simultaneously.

7. References

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