Structural Damage Detection Based on Static and Modal Analysis

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The present paper describes an approach for structural damage assessment that has its basis in methods of system identification. Response of a damaged structure differs from predictions obtained from an analytical model of the original structure, where the analytical model is typically a finite-element representation. The output error approach of system identification is employed to determine changes in the analytical model necessary to minimize differences between the measured and predicted response. Structural damage is represented by changes in element stiffness matrices resulting from variations in geometry or material properties of the structure during damage. Measurements of static deflections and vibration modes are used in the identification procedure. The identification methodology is implemented for representative structural systems. Principal shortcomings in the proposed approach and methods to circumvent these problems are also discussed.

Introduction

IN a typical load-bearing structure, degradation of structural properties because of damage manifests itself as a change in the static and dynamic structural response. A correlation of the measured response with that obtained from an analytical model of the undamaged structure allows for the possibility of determining a modified model that predicts the altered response. This process can be broadly categorized in the realm of system identification methods. This subject is not new and several studies pertinent to the field can be found in the literature (Refs. 1-5). A review of the principal exiting methods is available in Ref. 6.

The use of such techniques to detect damage in a structural assembly has been recently attempted[7,8] but with limited success. Chen and Garba[7] discuss the use of measured eigenmodes to determine the changes in the structure stiffness matrix, with the underlying assumption that the mass matrix does not change with damage. The minimum deviation approach is employed wherein the Euclidian norm of the matrix representing the perturbation of the analytical stiffness matrix due to the structural damage is minimized. The detection of damage is then attempted by examining the resultant entries of the perturbed matrix. This approach is only marginally successful, as it is difficult to identify damage from changes in the stiffness matrix. Entries in the stiffness matrix depend on the elastic and geometric properties of the structure as well as on the element connectivity. Hence, a given element of the matrix may have contributions from several members sharing the same node, making it difficult to identify the precise location of damage. Furthermore, the minimum deviation approach used by the authors results in small deviations from an a priori model. In this kind of a problem, the a priori model is the original stiffness matrix corresponding to the undamaged structure. In the event of severe damage, which may be located in different members of the structure, the changes in the stiffness matrix may be quite significant, increasing the possibility of obtaining poor results. These difficulties are clearly evidenced by the results obtained.

Smith and Hendricks[8] follow a similar approach using two different identification methods to identify the stiffness matrix based on the minimum deviation approach and using eigenmodes as experimental data. Similar difficulties are reported in their work. The entries of the stiffness matrix corresponding to the damaged members do show considerable variations. However, entries corresponding to undamaged members are also affected, thereby making the damage detection process more uncertain. The analysis of changes in the stiffness matrix is typically cumbersome, may not always yield correct answers, and does not permit the determination of the extent of damage.

This paper presents an approach that is designed to circumvent the problems just discussed. The output error method or structural identification[9] is used, wherein the analytical model is refined to minimize the difference between the predicted and measured response of the structure. Iterative nonlinear programming methods are employed to determine a solution to the unconstrained optimization problem. Damage is represented by reduction in the elastic extensional and shear moduli of the element, and those are designated as the design variables of the problem. The use of static structural displacements as the measured response is a departure from the standard practice of using eigenmodes alone for the identification problem. Numerical evidence clearly indicates that when eigenmodes alone are used for identification, the location and extent of damage predicted by the optimization approach is dependent on the number of modes used to match the measured and the predicted response. Higher modes are difficult to determine and measure, and the use of static displacements obtained by a loading that simulates higher modes is proposed as a solution to this problem.

The paper also presents an implementation of the proposed damage assessment strategies, with special focus on problems of practical significance. In this context, the use of incomplete modal or static displacement information in the identification problem is discussed. Further, the approach of treating the modulus of each structural element as an independent design variable results in a large dimensionality problem. This results in significant computational costs when using a gradient-based nonlinear programming algorithm for function minimization. The use of a reduced set of dominant design variables and the construction of equivalent reduced-order models for damage assessment are explored with some success.

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Structural Damage Assessment

In a finite-element formulation, the characteristics of the structure are defined in terms of the stiffness, damping, and mass matrices K, C, and M, respectively. Any variations in these matrices, such as may be introduced by damage, would affect the dynamic response characteristics of the structure. A change in the stiffness matrix alone would influence the static displacement response. In the present work, simulated measurements of structure eigenmodes and static deflections under prescribed loads were used for identification of structural damage.

The analytical model describing the eigenvalue problem for an undamped system can be stated in terms of the preceding system matrices, the ith eigenvalue ω_i^2, and the corresponding eigenmode ξ_i as follows.

$$(K-\omega_i^2 M)\{\xi_i\}=\{0\} \tag{1}$$

Matrices K and M may be adjusted to minimize the differences between the experimentally observed eigenmodes and values obtained from the analytical model just described. In using static deflections for identification purposes, the analytical model is even simpler, involving only the system stiffness matrix K as follows.

$$Kx=P \tag{2}$$

Here x is a vector of displacements under applied static loads P. Although it is very clear from the previous equations that a variation in the system matrices results in a changed response, it is more important from a damage assessment standpoint to relate these differences to changes in specific elements of the system matrices. Since internal structural damage typically does not result in a loss of material, one can assume the mass matrix to be a constant. Typically, the stiffness matrix can be expressed in terms of the sectional properties of the various elements such as the cross-sectional area A, and the bending and polar moments of inertia I and J. There is also a dependence on element dimensions denoted by t and L, and on the extensional and shear moduli E and G, respectively. These dependencies may be stated in a functional form as follows.

$$K_{ij}=[K(A,I,J,L,t,E,G)]_{ij} \tag{3}$$

In the present work, the net changes in these quantities due to damage are lumped into a single coefficient d_i for each element, which is used to multiply the extensional modulus E_i for that particular element. These d_i constitute the design variables for the optimization problem. If the measured and analytically determined static displacements or eigenmodes are denoted by Y_m and Y_a, respectively, the optimization problem can be formulated as determining the vector of design variables d_i (and hence the analytical stiffness matrix) that minimize the solar objective representing the difference between the analytical and experimental response and stated as follows:

$$\sum_i \sum_j (Y_m^{ij}-Y_a^{ij})^2 \tag{4}$$

Here i represents the degree of freedom and j denotes a static loading condition or a particular eigenmode. This minimization requires that Y_a be obtained from the eigenvalue problem or the load deflection equations, using the K matrix that must be identified. Lower and upper bounds of 0 and 1 were established for the design variables d_i.

One important advantage of this approach is that the complete set of modes or displacements is not needed since the objective function involves only the difference between components of those vectors. Some of the components may be neglected according to their importance in the behavior of the structure. As an example, consider the 15-bar truss of Fig. 1.

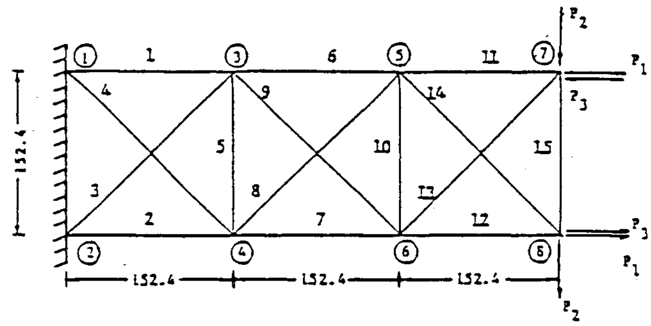

Fig. 1 A 15-bar planar truss structure ($P_1=P_2=40$ kN and $P_3=400$ kN represent three loading cases); dimensions in centimeters.

This structure is subjected to extensional forces applied at the free end. For damage assessment purposes, only the displacements in the direction of the applied forces can be used. They are dominant and easy to measure. The other components are relatively small, and neglecting them in the objective function does not prejudice the process of damage detection. The approach still works, and the solution becomes more realistic, since, in a large structure, only few dominant displacements can be obtained accurately.

The present approach also allows the use of a combination of static displacements and eigenmodes. It is obvious that a static load distribution affects some structural components more significantly than others. If the damaged member of the structure was one that does not play an important role in the load-bearing process for the set of applied loads, the use of static displacements in damage detection would yield erroneous results. The same is true of displacements for any given eigenmode. A combination of static displacements and eigenmodes is used in the present work with some degree of success. Subsequent sections of the paper describe an implementation of the proposed strategy.

Approximation Strategies

The nonlinear programming problem that must be solved in the damage detection strategy just proposed can become computationally demanding, especially in the presence of a large number of design variables. Approximation methods were adopted to circumvent this problem and are discussed here. These methods have been used successfully in the context of structural optimization problems.[10]

The first approach was one in which, at any given stage of the optimization problem, a select number of dominant variables were allowed to vary keeping other inactive members fixed at their current values. A meaningful measure of design variable dominance was discussed in Ref. 10, involving gradients of both the objective function and constraints. The present problem deals with unconstrained minimization, rendering the objective function gradient as the most obvious measure of design variable dominance. In the present work, the Broydon-Fletcher-Goldfarb-Shanno variable metric method was used for function minimization, and design variable dominance was assessed on the basis of the computed search direction given as

$$S^q=-H\,\nabla F(X^q) \tag{5}$$

where $\nabla F(X^q)$ is the gradient of the objective function at a particular iteration q, and H is a matrix initialized as the identity matrix and updated according to the Broydon-Fletcher-Goldfarb-Shanno formula.[11] This set of dominant variables was used for a prescribed number of optimization cycles with imposed lower and upper bounds on the variables. The set of variables was then revised with a new assessment of dominance.

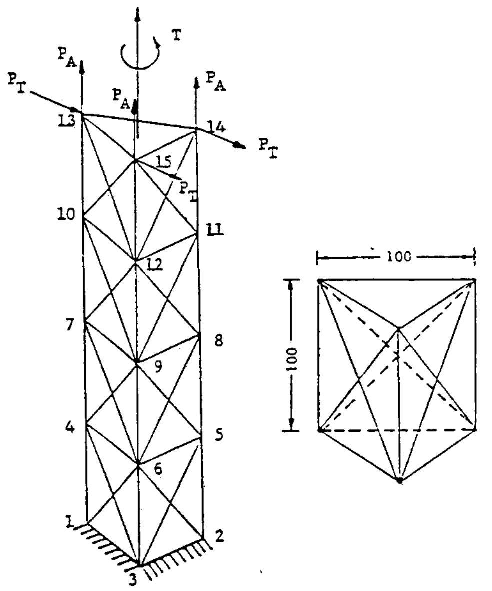

Fig. 2a A 48-bar space truss structure ($P_A = 10$ kN, $P_T = 1$ kN and $T = 1$ kN.m represent three loading cases); dimensions in centimeters.

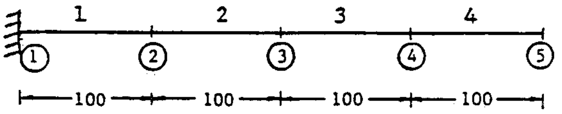

Fig. 2b Equivalent beam model for the 48-bar space truss; dimensions in centimeters.

A second approach implemented in the current work was one in which equivalent reduced-order models of the actual structure were constructed. Consider the truss shown in Fig. 2a, subjected to tensile, bending, and torsional loads. An equivalent beam model (Fig. 2b), with an independent axial, bending, and torsional stiffness for each section, was obtained to simulate the deflection characteristics of the truss structure. Each section of beam corresponds to a bay in the truss. The reduced-order beam model with only four design variables is first used to determine the approximate location of damage. The model of the truss structure has a total of 48 design variables. The identification problem is then solved for the beam model, using interpolated displacements obtained from the damaged truss. These interpolations are necessary because of the difference in the number of degrees of freedom for the two models. The beam section that corresponds to the bay of the truss containing the damaged members will show appreciable variation in the value of the parameter d_i in comparison to an undamaged value initialized as unity. Once the region of damage is identified, the actual structure is then solved, considering as design variables only the parameters d_i corresponding to the members of the damaged bay(s). If only one member is damaged as in the example of Fig. 2a, the problem reduces to one with 15 design variables.

A third approach to enhance efficiency for large-order systems, and used in conjunction with reduced-order models, involves techniques of substructuring. In the event that damage is located in more than one bay, the substructure of each bay can be solved separately with appropriate force and displacement conditions to detect its damaged member(s). A related approach using static displacements is one in which the

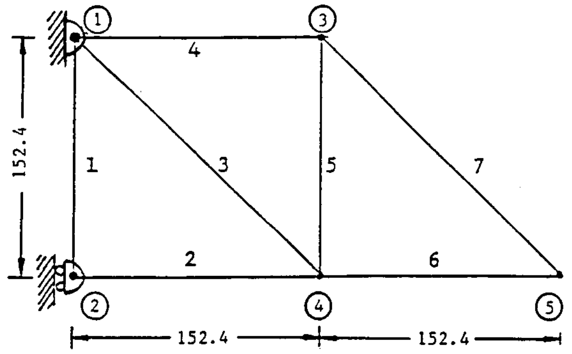

Fig. 3 A seven-bar planar truss; dimensions in centimeters.

Table 1 Results for the seven-bar planar truss

Element no.	Design variables (d_i) using four eigenmodes Value	Exact sol
1	0.98518	1.00000
2	0.86645	1.00000
3	0.36214	0.40000
4	0.87894	1.00000
5	0.35088	0.40000
6	0.96098	1.00000
7	0.87421	1.00000

stiffness matrix of the structure is expressed in a partitioned form as follows:

$$\begin{bmatrix} K_{11} & K_{12} \\ K_{l2}^T & K_{12} \end{bmatrix} \begin{Bmatrix} U_1 \\ U_2 \end{Bmatrix} = \begin{Bmatrix} F_1 \\ F_2 \end{Bmatrix} \tag{6}$$

Here, the submatrix K_{11} contains those members of the structure where damage may be present. The first row of this partitioned system may be expanded in the following form:

$$K_{11}U_1 + K_{12}U_2 = F_1 \tag{7}$$

The identification problem then reduces to determining the design variables d_i for the submatrix K_{11} that satisfy Eq. (7). This strategy is more amenable to the equation error approach of system identification and is reported in another publication.[12]

Numerical Implementation

The procedure described in the preceding sections was implemented on a VAX 11-750 computer. The Broydon-Fletcher-Goldfarb-Shanno variable metric method was used for function minimization. A finite-element analysis program, EAL,[13] was used for response analysis. The simulated measured data was the finite-element solution obtained for the damaged structure, corrupted by a random noise signal. The flow between the various processors was controlled in the Command language feature of DEC systems.

Discussion of Results

The method for damage detection was applied to a series of representative truss and semimonocoque structures. For the seven-bar truss shown in Fig. 3, damage was introduced in elements 3 and 5 by reducing their Young's moduli to 40% of the original value. The first four measured and analytically predicted eigenmodes were used to detect the extent and location of damage in the structure. Table 1 shows the results obtained in this exercise from which the location of the damaged elements can be easily identified. Furthermore, the extent of that damage is also assessed with reasonable accuracy. The same structure was damaged in element 5 by reducing the Young's modulus to 10% of its original value. Table 2 shows the effect of including a progressively larger number of modes on the results for damage detection.

The 15-bar planar truss of Fig. 1 was damaged in members 1 and 13, and both eigenmodes and static displacements were used for damage detection. The results for this example are summarized in Table 3. Damage in member 1 is clearly critical to the structural integrity and is identified easily. However, the nonconvex nature of the design space makes the detection of damage in member 13 more difficult. This can be partly attributed to the fact that this member has a stronger influence on the higher modes, which are not included in the damage detection process. The effect of adding a static displacement corresponding to a simple extensional load to the set of the first four modes shows a distinct improvement in locating the global damage. It is also quite evident from the results that when the static displacements are used for identification by themselves, the definition of the loading becomes critical. The stiffness of the diagonal member 13 is brought into play by load case 3, which, when excluded from consideration, results in an incomplete detection of damage. This is analogous to results produced when excluding higher vibration modes.

A more rational approach to avoiding problems such as incomplete damage detection due to a poorly defined load set is to choose a load condition that results in an equal stress distribution in each of the members. Even though this kind of loading is difficult to apply in a real structure, it still has some useful features. The displacement field obtained from the application of such a load can be expanded in a series of measured eigenmodes. These eigenmodes constitute a convenient set of orthogonal vectors, can be obtained from the actual structure, and can be combined to represent that displacement field. This approach is summarized in Ref. 12.

Another representative example is that of a semimonocoque wing box structure (Fig. 4) consisting of axial rod elements

Table 2 Results obtained for the seven-bar planar truss using an increasing number of eigenmodes

	Design variables (d_i) using eigenmode response			
Element no.	4 modes	6 modes	7 modes	Exact sol
1	1.0000	0.6790	0.8706	1.0000
2	0.4205	0.8882	0.8690	1.0000
3	0.9251	0.8944	0.8892	1.0000
4	0.8614	0.9022	0.8677	1.0000
5	0.7650	0.0890	0.0860	0.1000
6	1.0000	0.7862	0.8714	1.0000
7	0.4629	0.8085	0.8780	1.0000

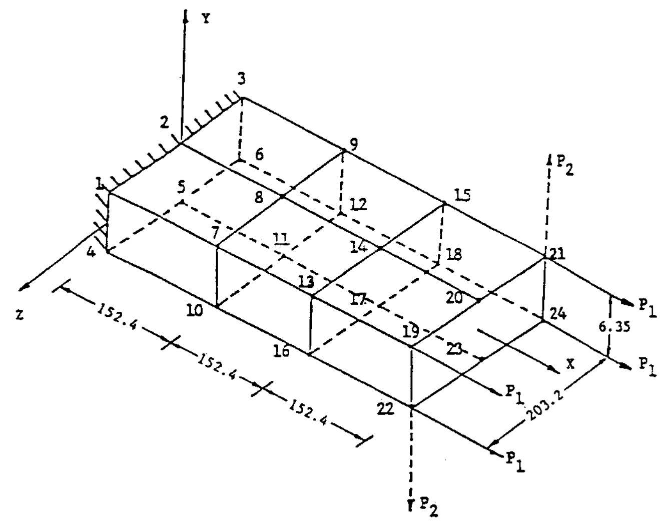

Fig. 4 Semimonocoque wing box structure ($P_1 = P_2 = 40$ kN represent two loading cases); dimensions in centimeters.

Table 4 Results for the semimonocoque wing box structure

		Design variables (d_i) using static response		
Element no. (panel)	Connectivity (nodes)	Load 1 only	Loads 1 & 2	Exact sol
1	1-7-8-2	1.0000	1.0000	1.0000
2	2-8-9-3	0.1240	0.1020	0.1000
3	7-13-14-8	0.9601	1.0000	1.0000
4	8-14-15-9	0.7720	1.0000	1.0000
5	13-19-20-14	0.9585	1.0000	1.0000
6	14-20-21-15	0.9837	0.9999	1.0000
7	4-10-11-5	0.9736	1.0000	1.0000
8	5-11-12-6	1.0000	1.0000	1.0000
9	10-16-17-11	0.9954	1.0000	1.0000
10	11-17-18-12	0.8713	1.0000	1.0000
11	16-22-23-17	0.9979	1.0000	1.0000
12	17-23-24-18	0.8984	1.0000	1.0000
13	1-4-10-7	0.9999	1.0000	1.0000
14	7-10-16-13	0.9998	1.0000	1.0000
15	13-16-22-19	0.9981	1.0000	1.0000
16	3-6-12-9	0.9926	0.9702	1.0000
17	9-12-18-15	1.0000	1.0000	1.0000
18	15-18-24-21	0.9855	0.9999	1.0000

Table 3 Results for the 15-bar planar truss

	Design variables (d_i) using both static and modal response					
Element no. (truss member)	First four eigenmodes (case 1)	Case 1 + load 1 (case 2)	Load 1 only (case 3)	Loads 1&2 (case 4)	Loads 1, 2 & 3 (case 5)	Exact sol
1	0.0000	0.0069	0.0266	0.0257	0.0218	0.0000
2	0.7461	1.0000	1.0000	0.9999	0.9999	1.0000
3	0.7571	0.9761	1.0000	1.0000	1.0000	1.0000
4	0.7748	0.9503	0.7560	0.8366	0.8540	1.0000
5	0.9934	1.0000	1.0000	0.9999	0.9730	1.0000
6	0.8107	0.7515	0.7230	0.7823	0.7817	1.0000
7	0.7517	0.9216	0.7358	0.9847	0.9999	1.0000
8	0.9825	1.0000	1.0000	1.0000	1.0000	1.0000
9	0.6603	0.8977	0.8841	0.9015	0.8962	1.0000
10	0.7640	1.0000	1.0000	1.0000	0.9698	1.0000
11	0.8116	0.9930	0.9686	0.8235	0.7849	1.0000
12	0.7763	1.0000	0.8668	0.9933	0.9930	1.0000
13	0.0006	0.0000	1.0000	1.0000	0.0868	0.0000
14	0.7557	0.9433	1.0000	1.0000	0.7566	1.0000
15	0.7623	1.0000	1.0000	1.0000	0.9396	1.0000

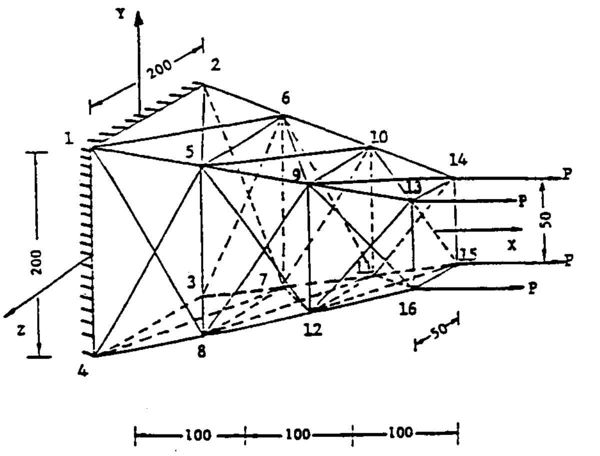

Fig. 5 Skeleton strucure idealization of a helicopter tail ($P = 100$ N); dimensions in centimeters.

and membrane elements. Membrane element 2 was damaged, and the identification of damage was conducted with the use of static displacements. Table 4 summarizes the results for this example. It is quite evident from these results that the application of a torque that forces the membranes to participate more equitably in the load-bearing process improves the results for damage assessment.

In a large structure, it is often difficult to obtain the displacements for all degrees of freedom. Typically, only a few dominant ones are measured, and, as described in a preceding section, these dominant displacements can be used effectively for damage detection. As an example, a model of a helicopter fuselage skeleton (Fig. 5) with 48 degrees of freedom was used. Damage was identified on the basis of measurements of 12 horizontal displacement components. Member 1 was damaged by reducing its Young's modulus to 10% of its original value. Table 5 summarizes the results for this example. In this problem, a full set of design variables was used. The damaged member was clearly detected, as was the extent of damage.

To demonstrate the use of an equivalent reduced-order model, a three-dimensional statically indeterminate truss was selected (Fig. 2a). It has 4 bays and a total of 48 members with 36 degrees of freedom and is subjected to extensional, bending, and torsional loads. The first step was to calculate the re-

Table 5 Results for the idealized helicopter fuselage model

Element no.	Nodes	Design Variables (d_i) Value	Exact sol
1	1-5	0.10498	0.10000
2	1-6	1.00000	1.00000
3	1-8	1.00000	1.00000
4	2-5	0.93199	1.00000
5	2-6	1.00000	1.00000
6	2-7	1.00000	1.00000
7	3-6	0.99781	1.00000
8	3-7	1.00000	1.00000
9	3-8	0.99781	1.00000
10	4-5	0.93199	1.00000
11	4-7	1.00000	1.00000
12	4-8	1.00000	1.00000
13	5-6	1.00000	1.00000
14	5-8	1.00000	1.00000
15	5-9	0.97783	1.00000
16	5-10	0.99372	1.00000
17	5-12	0.99368	1.00000
18	6-7	1.00000	1.00000
19	6-9	0.98869	1.00000
20	6-10	0.99906	1.00000
21	6-11	1.00000	1.00000
22	7-8	1.00000	1.00000
23	7-10	0.99157	1.00000
24	7-11	1.00000	1.00000
25	7-12	0.99157	1.00000
26	8-9	0.98858	1.00000
27	8-11	1.00000	1.00000
28	8-12	0.99991	1.00000
29	9-10	0.99995	1.00000
30	9-12	0.99995	1.00000
31	9-13	1.00000	1.00000
32	9-14	0.98484	1.00000
33	9-14	0.98484	1.00000
34	10-11	1.00000	1.00000
35	10-13	1.00000	1.00000
36	10-14	0.96628	1.00000
37	10-15	1.00000	1.00000
38	11-12	1.00000	1.00000
39	11-14	0.98508	1.00000
40	11-15	1.00000	1.00000
41	11-16	0.98506	1.00000
42	12-13	1.00000	1.00000
43	12-15	1.00000	1.00000
44	12-16	0.96631	1.00000
45	13-14	0.99994	1.00000
46	13-16	0.99992	1.00000
47	14-15	0.99996	1.00000
48	15-16	0.99992	1.00000

Table 6 Damage detection as seen in the equivalent beam model

Element no.	Design variables (d_i) Lower bound	Value	Upper bound
1	0.0000	0.9021	1.0000
2	0.0000	0.5849	1.0000
3	0.0000	0.9537	1.0000
4	0.0000	0.5890	1.0000

Table 7 Results for the 48-bar space truss (only members in the second and fourth bays are treated as design variables)

Element no.	Nodes	Design variables (d_i) Value	Exact sol
Second bay			
10	4-5	1.00000	1.00000
11	4-6	1.00000	1.00000
12	4-7	0.10589	0.10000
13	4-8	0.99999	1.00000
14	4-9	0.99999	1.00000
15	5-6	1.00000	1.00000
16	5-7	0.89710	1.00000
17	5-8	1.00000	1.00000
18	5-9	1.00000	1.00000
19	6-7	0.89694	1.00000
20	6-8	1.00000	1.00000
21	6-9	1.00000	1.00000
22	7-8	1.00000	1.00000
23	7-9	1.00000	1.00000
27	8-9	1.00000	1.00000
Fourth bay			
34	10-11	1.00000	1.00000
35	10-12	0.96474	1.00000
36	10-13	1.00000	1.00000
37	10-14	0.99816	1.00000
38	10-15	1.00000	1.00000
39	11-12	0.97694	1.00000
40	11-13	0.11129	0.10000
41	11-14	1.00000	1.00000
42	11-15	0.93723	1.00000
43	12-13	0.93341	1.00000
44	12-14	1.00000	1.00000
45	12-15	1.00000	1.00000
46	13-14	1.00000	1.00000
47	13-15	0.98714	1.00000
48	14-15	0.99159	1.00000

Table 8 Properties of the studied structures

Structure	Young's modulus, GPa	Cross-sectional area, mm^2	Membrane thickness, mm	Moment of inertia, mm^4
15-bar truss (Fig. 1)	69.0	1400	—	—
48-bar truss (Fig. 2a)	69.0	1047	—	—
Equivalent beam (Fig. 2b)	69.0	1523	—	1.73E08
Seven-bar truss (Fig. 3)	69.0	1400	—	—
Wing box structure (Fig. 4)	69.0	1400	1.27	—
Helicopter tail (Fig. 5)	69.0	314	—	—

sponse of the undamaged structure to the applied loads. This information determines the geometric characteristics of the equivalent beam (Fig. 2b). The second step involved a solution of the damage detection problem for the equivalent beam with only four design variables. Damage was introduced in members 12 (second bay) and 40 (fourth bay) by reducing the respective Young's moduli to 10% of the original values. The results (Table 6) show considerable change in the final values of the design variables corresponding to the second and fourth bays. The actual structure was then solved considering as design variables the parameters d_i pertaining to the members of the damaged bays as detected from the equivalent beam model. This last step can also be done for each bay separately using substructuring techniques. The final results for the actual structure are shown in Table 7. The material and geometric properties for each of the structures examined in this study are shown in Table 8.

Two distinct strategies for reducing the number of design variables were studied in the present work. The approach using equivalent reduced-order models has proved to be more robust. The second approach was one in which only a dominant subset of the design variables was considered at any stage of the error minimization problem. This dominance was assessed on the basis of the gradients of the error with respect to each design variable. A switching in the dominant variables made the method unreliable in locating the global optimum. More frequent assessment of the dominance of the design variables adds to the computational requirements. The iterative optimization methods used in this study are also susceptible to convergence to local optimum and the use of different approaches to circumvent the problem of nonconvexities in the design space, such as the equation error approach and nongradient methods,[14] will be attempted in future work.

Conclusion

This paper presents an approach to damage detection in structures based on iterative methods of optimization. Both eigenmodes and static displacements are used in the identification procedure, with the static displacements providing the advantage of lower computational cost and providing more physical insight into the damage assessment process. There is a large class of structural systems for which static test data can be used directly in the damage detection process. At the surface, the applicability of this approach in space structures where static displacements cannot be obtained may appear to be limited. However an extension of the approach is proposed in Ref. 12, where measured eigenmodes are combined to represent a known static displacement field. The underlying concept behind this method is to identify a static loading condition, which is shown to be optimal in determining the location and extent of damage. The deflections under such a load can be sorted as reference data for use in damage detection during operation. Measured eigenmodes of the structure can be combined to reproduce this displacement field and are shown to be quite effective in accurately locating the damaged components.

Approximation concepts have been introduced to lower the computational costs, characteristic of iterative methods of optimization. The method has been implemented for a series of trial problems with extremely encouraging results. It has proved to be very flexible, allowing for the use of a reduced set of measurements, equivalent reduced-order models, and combination of modes and static displacements to determine the best condition necessary to detect global damage. Both the location and extent of damage can be clearly identified. Extension of this work to include the study of damage detection in composite materials that are used extensively in aerospace structures and laboratory experiments to verify the viability of the proposed procedure are currently in progress.

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