Bayesian Model Updating Approach for Systematic Damage Detection of Plate-Type Structures

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ABSTRACT

This paper presents a model-based monitoring framework for the detection of fatigue-related crack damages in plate-type structures commonly seen in aluminum ship hulls. The monitoring framework involves vibration-based damage detection methodologies and finite element modeling of continuum plate structures. A Bayesian-based damage detection approach is adopted for locating probable damage areas. Identifying potential damage locations by evaluating all possible combinations of finite elements in the model is computationally infeasible. To reduce the search space and computational efforts, initial knowledge of the probable damage zones and a heuristic-based branch-and-bound scheme are systematically included in the Bayesian damage detection framework. In addition to an overview of the model-based monitoring framework, preliminary results from numerical simulations and experimental tests for a plate specimen with a welded stiffener are presented to illustrate the Bayesian damage detection approach and to demonstrate the potential application of the approach to detect fatigue cracks in metallic plates.

1. INTRODUCTION

The adoption of aluminum alloy materials for ship structures presents many challenges to the naval engineering community. In addition to being light-weight, aluminum alloys have high corrosion resistance but often exhibit fatigue-related micro-cracks. High-speed aluminum hulls can remain in operation even after the initiation of micro-cracks because of the ductile mechanical characteristic of the material. Therefore, to enhance the maintenance of ships and to prevent catastrophic failure of ship's hull, one key component in monitoring aluminum ship structures is the early detection of fatigue-induced cracks.

This paper presents a preliminary investigation of a computationally efficient and practical framework for the monitoring and performance assessment of aluminum plate structures. Specifically, aluminum plate specimens have been designed and built with welded assemblies to facilitate the investigation of system identification and damage detection methods. The area of damage in the structure is estimated by a model-based damage detection methodology that compares the structural characteristics of the "true" structure (damaged or undamaged) to finite element "trial" models. The probability associated with a hypothesized damage state (*e.g.*, location and size) is evaluated through the calculation of an error between the "true" and "trial" models. Incorporating with prior knowledge and computational heuristics, the probable damage area (*i.e.*, fatigue crack path) is identified by repeatedly applying a Bayesian inference algorithm [1]. The Bayesian probabilistic model-updating framework is applied to validate its potential applicability for damage identification around critical weld zones in the plate specimens. Numerical simulations and experimental tests are conducted to examine the model-based approach to the testing of aluminum plates with crack damages.

2. METHODOLOGY

2.1. Model Updating for Damage Detection:

A general class of damage detection algorithms is based on model updating. Model parameters are varied until the model approximates the behavior of the true observed system. To identify an optimal model, the outputs from the observed system are used to evaluate a pre-defined objective (or error) function. An appropriate objective function is one that takes into account the fundamental behavior of the system in both its damaged and undamaged states, yet is compatible with experimental data available. Changes in the model parameters are then correlated to the condition (damage versus undamage) of the structure.

Consider a simple plate structure. The governing equation describing the dynamic behavior of a vibrating plate can be written in the following form [2]:

$$D\nabla^4 w + \rho h \frac{\partial^2 w}{\partial t^2} = q(x, y, t) \quad \text{Eq. 1}$$

where D is the flexural rigidity and is defined as:

$$D = \frac{Eh^3}{12(1-\nu^2)} \quad \text{Eq. 2}$$

Here, w denotes the vertical displacement of the plate, $q(x, y, t)$ is the normal load distribution function on the top of the plate, ρ is the plate density (mass per unit area), h is the plate thickness, E is the Young's (elastic) modulus and ν is the Poisson ratio.

For a finite element model (FEM) with *N* elements, the elastic moduli for the elements can be denoted as:

$$E = \{E_1, E_2, \cdots, E_i, E_{i+1}, \cdots, E_{i+n}, \cdots, E_{N-1}, E_N\} \quad \text{Eq. 3}$$

For modeling purposes, fatigue crack damage is represented by a change in the flexural rigidity or stiffness of the plate, which, in turn, is reflected by a reduction in the elastic modulus of the damaged elements. If the model contains *n* damaged elements, their elastic moduli $\{E_{i+1}, \cdots, E_{i+j}, \cdots, E_{i+n}\}$ are replaced by

$$E_d = \{k_{i+1}E_{i+1}, \cdots, k_{i+j}E_{i+j}, \cdots, k_{i+n}E_{i+n}\} \quad \text{Eq. 4}$$

where k_{i+j} (<1), $j=1,\ldots,n$, denotes the reduction factor for the $(i+j)^{th}$ damaged element.

The model updating problem is posed as a combinatorial optimization problem that seeks to find the optimal set of elastic moduli that minimizes a defined objective function by comparing the FEM model output and the output derived from actual measurements taken from the structure. In other words, the inverse problem can be posed as a combinatorial optimization problem for finding the optimal set of *n* elements, whose effective elastic moduli represent the damage state of the real structure as denoted in Eq. 4.

2.2. A Flexibility-Based Objective Function:

Conceptually, damage detection methods seek to identify changes (damages) in a structure by using certain structural characteristics as the basis for evaluation. Vibration data are among the most common sensor information easily obtained from dynamic excitations. Vibration-based damage identification methods using mode-shape information have been proposed [3]. One approach is to detect damages directly based on the changes in structural characteristics between damaged and undamaged structures. Examples of structural characteristics include curvature mode shape [4], flexibility parameters [5, 6], strains and modal strain energy [7]. Although current research in damage detection has made substantial progress, the methods developed so far are primarily restricted to simple beam or frame structures with a limited number of degrees-of-freedom (DOFs). In contrast, continuum systems, such as plate-like structures, pose many challenges for current methods because of the large number of DOFs that are required to properly model the structure. Additionally, it is not realistic to place sensors to measure the system responses at all of the DOFs. An alternative approach is to construct a system model (such as a FEM model) of a target structure using measurement data. This "model-based" approach updates the system model by modifying the structural properties of the elements until the model resembles the dynamic characteristics estimated from sensor information. The objective is to define an objective (error) function and to compute the difference (error) between the trial FEM model and the target structure. Damages, if any, are identified and revealed through the changes in the model parameters during the model-updating process.

For the plate problem, our study indicates that the use of flexibility matrices constructed based on modal properties (modal frequencies and mode shapes), as opposed to the direct use of modal properties, is an appropriate choice for the objective function [8]. The inverse relationship between the flexibility matrix and the square of modal frequency renders the flexibility matrix as less sensitive to high frequency modes which are difficult to identify in vibration tests. This unique characteristic allows for the inclusion of lower order modes in a truncated flexibility matrix. This feature has attracted many researchers to explore flexibility as a core element in developing structural damage detection algorithms [5-7, 9]. In the "Flexibility-Based Approach" (FBA) described below, the objective (error) function is expressed in terms of the difference between the flexibility matrices that correspond to the true (measured) and trial (FEM) models.

When the mode shapes are mass-normalized (*i.e.*, $\bar{\phi}^T M \bar{\phi} = I$), the flexibility matrix F can be expressed in terms of the modal properties as follows:

$$F = \bar{\phi}\Omega^{-1}\bar{\phi}^T = \sum_{i=1}^{N} \frac{1}{\omega_i^2}\bar{\phi}_i\bar{\phi}_i^T \quad \text{Eq. 5}$$

where M is the mass matrix, $\bar{\phi} = \left[\bar{\phi}_1\bar{\phi}_2 \ldots \bar{\phi}_N\right]$ is the mode shape matrix, $\Omega = \text{diag}(\omega_i^2)$ is the spectral matrix consisting the square of the modal frequencies ω_i, and N is the number of DOFs in the system. The mass-normalized modal vector $\bar{\phi}_i$ is related to the arbitrarily scaled mode shape ϕ_i as:

$$\bar{\phi}_i = \phi_i d_i \quad \text{Eq. 6}$$

where $d_i = \dfrac{1}{\sqrt{\phi_i^T M \phi_i}}$ is a mass normalization constant for the i^{th} mode.

Suppose only a few (lower) modes are available (*e.g.*, from experimental tests), a truncated flexibility matrix is obtained as:

$$F_{trun} = \sum_{i=1}^{n} \left(\frac{d_i}{\omega_i^2}\right)^2 \bar{\phi}_i\bar{\phi}_i^T \quad \text{Eq. 7}$$

where n denotes the number of modes available.

Let's define the difference (ΔF_{trun}) between the flexibility matrices of the true (damaged) structure and the trial FEM model as:

$$\Delta F_{trun} = F_{trun}^{true} - F_{trun}^{trial} \quad \text{Eq. 8}$$

When a trial FEM model reasonably resembles the damaged structure with true damage, the difference in flexibility matrices is close to zero (exactly zero if there is no measurement noise nor modeling error). The scalar magnitude on the difference in the flexibility matrices can be measured by calculating the Frobenius norm of ΔF_{trun}:

$$\left\|\Delta F_{trun}\right\|_F = \sqrt{\sum_i \sum_j x_{ij}^2} \quad \text{Eq. 9}$$

which vanishes when all matrix elements x_{ij} in ΔF_{trun} are zero (*i.e.*, the FEM model perfectly matches the observed structure).

The difference in the flexibility matrices can also be further decomposed into singular values by singular value decomposition (SVD):

$$\Delta F_{trun} = USV^T \quad \text{Eq. 10}$$

where V^T and U are matrices of singular vectors, S is the diagonal matrix whose elements are the singular values, s_i. Since the Frobenius norm is invariant under unitary transformation, the SVD of the ΔF_{trun} yields

$$\left\|\Delta F_{trun}\right\|_F = \left\|USV^T\right\|_F = \left\|S\right\|_F = \sqrt{s_1^2 + s_2^2 + \cdots + s_R^2} \quad \text{Eq. 11}$$

where R is the rank of ΔF_{trun}. Thus, the objective is to search for a trial model that minimizes the Frobenius norm shown in Eq. 11.

Since the mode shapes experimentally obtained are arbitrary scaled, the mass normalization constants (d_i) are required to properly compute the flexibility matrix of the real, true structure. One approach to extracting the mass normalization constants is based on testing the structure with a perturbed mass matrix (by adding a known mass at a certain location) and examining the sensitivity of the eigenvalues [10, 11]. In this study, mass normalization constants are estimated using the FEM model and applied to the experimentally obtained (*i.e.*, not mass normalized) mode shapes.

2.3. Bayesian Probabilistic Approach:

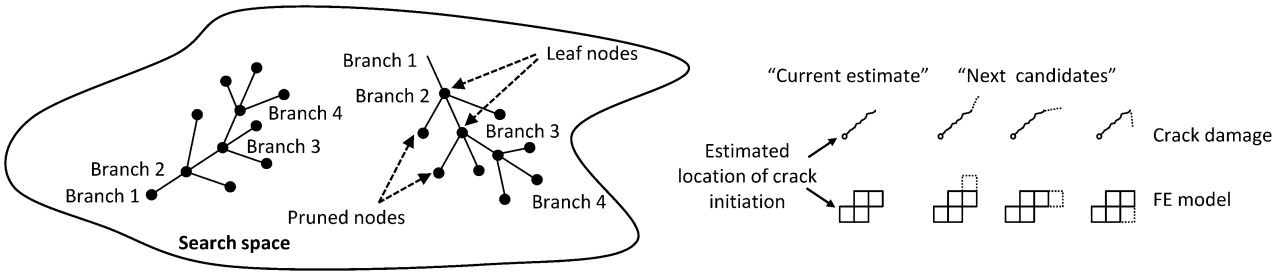
The model updating procedure adopted in this study is based on a Bayesian probabilistic approach which utilizes the parameters measured or estimated from a series of collected vibration signals or data. Unlike a deterministic optimization formulation, the state space search must reflect the relative degree of belief on the estimates of the optimal subset (*i.e.*, E_d , in this case). Let M denote the hypothesized damage states of the model. The calculation of the error that exists between the "true" structure and the FEM "trial" model is based on the measured or estimated structural parameters. The updated estimates on the damage of the structure are expressed as the posterior distribution based on Baye's rule as follows

$$p(M \mid s) = \frac{p(s \mid M)\, p(M)}{p(s)} \propto p(s \mid M)\, p(M) \qquad \text{Eq. 12}$$

where $p(M \mid s)$ is the posterior distribution function for a hypothesis M given the measured or estimated parameters, s. $p(s \mid M)$ is termed the likelihood function, $p(M)$ is the prior probability of the hypothesis and $p(s)$ is treated here as some normalization constant. By collecting the likelihood function, the posterior distribution $p(M \mid s)$ would progressively become a better estimate than the prior probability $p(M)$ as the process goes on. For instance, if the initial estimate of the probable area of damage is assumed to be uniformly distributed over the structure before the model updating procedure, the most likely damaged areas are revealed with relatively higher posterior estimates by the repeated applications of the Bayesian inference process.

The selection of the most probable events from all conceivable possibilities using the Bayesian probabilistic approach can be systematized using various "optimal" search methods; otherwise a random search in optimal subspace becomes a computationally intractable task. To sample the posterior parameter distribution, the Bayesian approaches implemented with the Markov Chain Monte Carlo (MCMC) method and genetic algorithms (GA) have been reported with successful performance in detecting structural damage [12-14]. However, these approaches are computationally expensive and they do not guarantee convergence to an optimal solution. To reduce the computational effort, the Bayesian damage detection algorithm proposed herein is enhanced with a branch-and-bound (BB) search technique where the search space is systematically narrowed through enumeration and pruning of candidate model solutions [1].

The BB technique is a general search method originally developed for discrete optimization problems and is a powerful technique for controlling the size of a search space used in model updating [15]. As illustrated in Figure 1, the BB algorithm initially starts its search from some random subspaces (*i.e.*, leaf nodes associated with Branch 1 in Figure 1(a)). At each step, the algorithm takes an additional sample (*i.e.*, an additional element in the hypothesized subset) at each leaf node and aims to improve its estimates (this process is called branching). As the search proceeds, the branches associated with large "errors" are pruned and the search is bounded by evaluating the remaining branches (this process is called pruning). Figure 1(b) schematically shows the application of BB technique in FEM updating of a plate-type structure. Here, the crack is assumed to damage the entire section of the plate in the thickness direction and represented in the model by a set of finite elements with substantially reduced elastic modulus for simplicity. The collection of survived leaf nodes (or "trial" model with small error) is mapped to reveal a potential damage area at every branching process. Therefore, the probable damage area in a system can be systematically updated by implementing the BB technique in the Bayesian formulation. The computational effort and accuracy of the estimates for the optimal subset (*i.e.*, E_d) can be controlled by pruning the less likely candidates during the branching process.



(a) Concept of the branch-and-bound search scheme (b) Candidates for probable damage state

Figure 1. Application of the Branch and Bound (BB) technique for model-updating.

2.4. Summary of the Model Based Bayesian Damage Detection Framework

In summary, the model-based structural monitoring framework consists of three phases. The first phase is the construction of the FEM model with structural properties and boundary conditions close to that of a target structure. In the second phase, the monitoring system acquires information about the status of the target structure through a network of sensors deployed to the structure. Once the variation in the modal properties exceeds a pre-defined threshold value, the third phase involving the Bayesian-based damage detection algorithm proceeds to compute the error associated with an initial set of hypotheses using the flexibility-based objective function. Engineering judgment based on knowledge about common damage patterns can be very useful to account for the selection of the initial set of hypotheses; for instance, heat affected zones around welds or notches along edges are good initial candidates for hypothetical probable damaged areas. The branching process adds one more damaged element to each hypothesis following the branching rule shown in Figure 1(b). Hypotheses with relatively large error are pruned before the next branching process. The branching, error computing and pruning processes make a finite loop until the damage identification algorithm terminates. At the end of each loop, the elements survived in the current and previous pruning processes are classified and stored in bins based on their error. The histogram-like plot of survived elements serves as a damage map showing the probable area(s) of damage. The search process is terminated when the deviation between the current and last damage areas converges within a predefined tolerance.

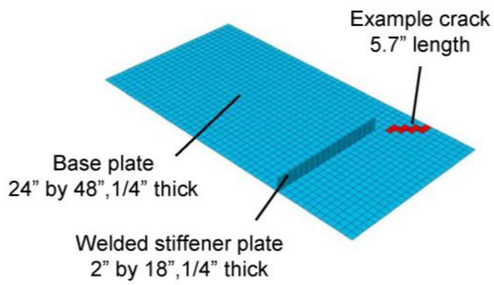
3. NUMERICAL SIMULATION AND EXPERIMENTAL VALIDATIONS

The Bayesian model-updating procedure is applied to the problem of damage detection on a stiffened aluminum plate as shown in Figure 2(a). The design of the structural plate is intended to include the geometric complexity that is commonly found in aluminum ship hull structures. The aluminum plate includes an area with high stress concentration due to the presence of a welded stiffener. Such areas are the likely location for fatigue-related damage (*i.e.*, fatigue cracking). Knowledge of this fact allows one to customize the model updating algorithm to prioritize the search of this area. The aluminum plate is 24 in by 48 in and is ¼ in thick. In addition, the plate has a 2 in by 18 in by ¼ in stiffener plate; the base plate and the stiffener plate are rigidly welded together. Crack paths in the main plate initiating from the heat affected zone (HAZ) around the welded stiffener plate are considered as example damage scenario cases.

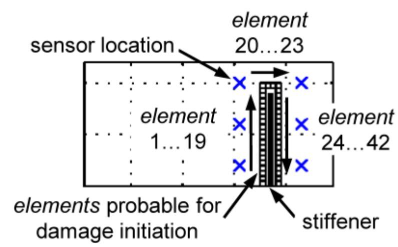
The plate structure is modeled using ABAQUS, a general-purpose FEM analysis program. The base plate and stiffener plate are modeled with 4-node reduced integration, doubly curved shell elements with hourglass control (*S4RSW*). These plates are assumed to be rigidly connected. The mesh size of the plate elements are 1 in × 1 in. The elastic modulus E of the undamaged elements is 10300 ksi while for the cracked elements, the elastic modulus is reduced 10^{-6} times the original modulus ($E_d = E \times 10^{-6}$). The mass density of the aluminum is assumed to be 2.489×10^{-7} slug/in^3. The *Lanczos* frequency analysis method in ABAQUS is employed to compute the modal properties (*i.e.*, modal frequency and mode shape) of the base structure as well as the structures with different damage scenarios. Only the first five modes are considered in both the numerical and experimental simulations. Additionally, sensors are placed (or assumed to be placed for numerical simulations) at strategic locations as shown in Figure 2(b).

3.1 Numerical Simulations

For the numerical simulation study, the test-bed plate structure as shown in Figure 2(a) is employed for evaluating the model-based damage detection algorithm. Two separate cases are considered. First, damage detection of the plate with a single stiffener having individual cracks around the stiffener is investigated. Second, the plate is assumed to have an additional welded stiffener and the initial probable damage zone is expanded to include areas around both stiffeners and



(a) Schematics of the test-bed plate structure



(b) Sensor locations and probable damage zone

Figure 2. A testbed plate structure.

along the edges of the plate.

Damage Detection of Individual Crack Path with A Single Stiffener: Numerical simulations of the plate with a single stiffener are studied first. The three crack paths (*i.e.* the targeted area) considered in the numerical studies are shown in Figure 3. The modal properties of the undamaged plate structure and of the hypothetical damaged plate are obtained first. Table 1 summarizes the modal frequencies obtained for the undamaged and damaged plates. Using the computed modal frequencies and mode shapes, the flexibility matrices of the damaged models are constructed using Eq. 7.

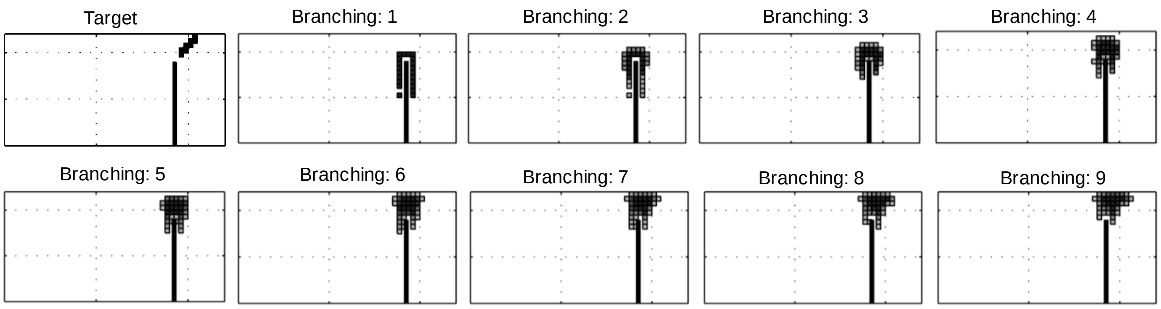
The Bayesian-based damage detection procedure, as described in phase 3 of the model-based monitoring framework, is employed to identify the individual cracks. Figure 3(a) illustrates the basic process of locating crack path 1 (the "Target") as shown. Starting from the probable damaged elements in the vicinity of the weld as shown in Figure 2(b), at each branching step, the probabilistic branch-and-bound scheme proceeds to search for the most likely set of damaged elements based on the objective function shown in Eq. 11, which evaluates the difference between the trial FE model and the true damaged FE model. The results shown in the figure is based on a pruning rate of 50% (*i.e.*, only 50% of the hypotheses which have smaller error are retained in the next branching process). In the damage maps, the elements marked with darker color have the higher probabilities of being damaged. As shown in Figure 3(a), the procedure progressively converges to the crack region and is terminated when the variation between 8^{th} and 9^{th} branching results becomes negligible.

The probabilistic model-based updating procedure is also applied for the detections of crack paths 2 and 3 as shown in Figures 3(b) and (c), respectively. These two cracks are slightly shorter than crack 1 and they are located internally inside the plate boundaries. The detection of these two cracks is more challenging because of the relatively small changes in the modal properties between the undamaged and damaged plates as shown in Table 1. As shown in Figure 3(b), the model-updating algorithm is able to identify accurately the location of crack path 2. It can be seen from the damage map that the search for probable damaged elements converges quickly with only a modest number of branching steps. Crack path 3 is a particularly challenging case because the crack is oriented in the longitudinal direction (*i.e.*, along the longer side of the plate). It may also be interesting to point out that the finite elements are uniformly and regularly distributed in the mesh. As shown in Table 1, there are very little changes in the modal properties between the damaged and the undamaged plates. Nonetheless, as shown in Figure 3(b), the model-updating procedure is able to locate the probable damage area that includes the crack but the area is distributed in the transverse direction (*i.e.* along the shorter side of the plate). Again, the probable damage area converges very quickly with very few branching steps.

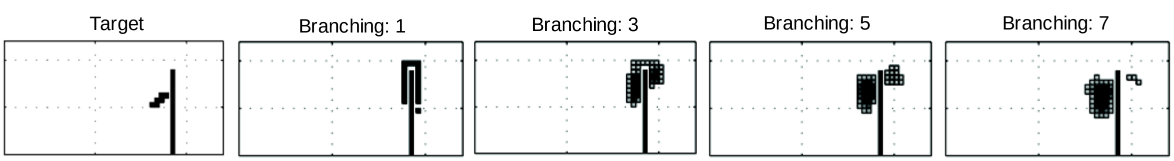
Damage Detection of Individual Cracks with Multiple Stiffeners: The model-updating procedure is applied to detect damages in a plate with two welded stiffeners as shown in Figure 4(a). Similar to the previous cases, the three crack paths as shown in Figure 3 are considered individually. However, the initial probable damage zone is expanded to include the weld toes around the two stiffeners and along the longitudinal edges of the plate. Figure 4(b) shows the probable damage areas identified. For the damage detection for crack path 1, areas around the longer stiffener and along the top edge are suspected for possible damage very early in the process. The hypothetical branches grow both from the weld toe and edges and later formed the most probable damage area around the vicinity of crack 1. For the detection of crack 2, the model-updating algorithm is not able to pin-point the damage area with high probability. Instead, the detection result suggests two damage prone areas as shown in Figure 4(b). Nevertheless, the area around crack 2 is included in one of the probable damage areas. For detecting crack path 3, the model-updating procedure identifies the damage area successfully with high probability, as noted with darker color elements shown in Figure 4(b). All in all, the damage detection results show the ability of the probabilistic model-updating algorithm in detecting cracks on a plate

Table 1. Modal frequencies of the damaged and undamaged plates.

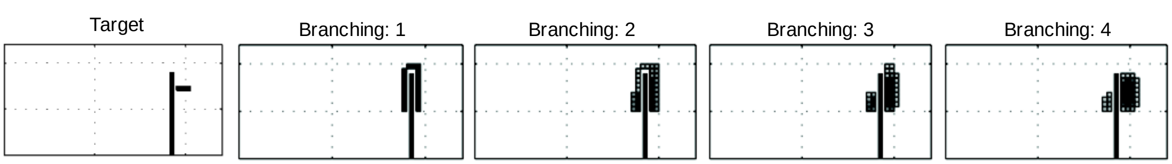
Mode	No crack	Crack 1		Crack 2		Crack 3	
	(Hz)	(Hz)	Diff (%)	(Hz)	Diff (%)	(Hz)	Diff (%)
1	26.88	26.52	-1.34	26.82	-0.22	26.86	-0.05
2	41.76	39.89	-4.48	41.60	-0.39	41.69	-0.18
3	72.87	70.89	-2.72	72.02	-0.18	72.82	-0.08
4	94.93	89.49	-5.73	94.88	-0.05	94.85	-0.09
5	128.95	126.93	-1.57	128.64	-0.24	128.93	-0.02



(a) Damage detection for crack path 1

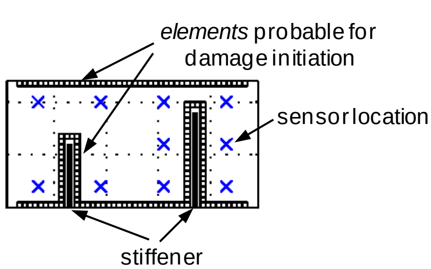


(b) Damage detection for crack path 2

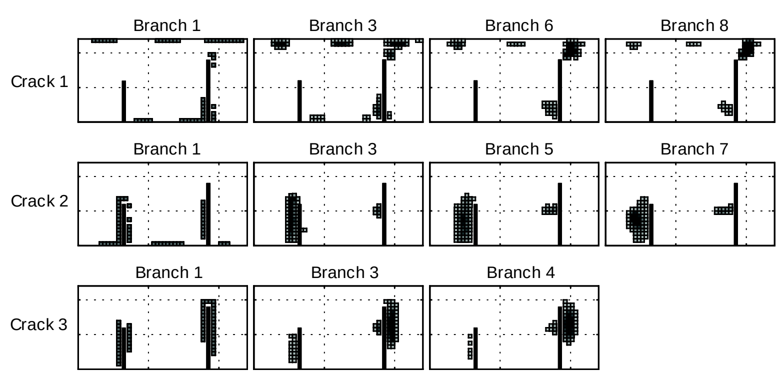


(c) Damage detection for crack path 3

Figure 3. Histogram-like damage map showing the basic process for locating probable damage region.

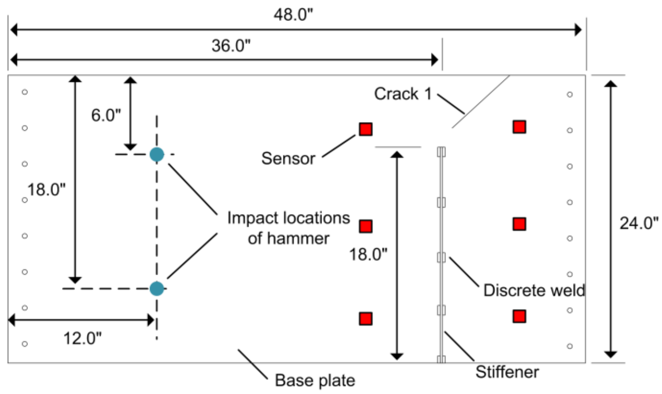


(a) A baseline structure with two stiffeners

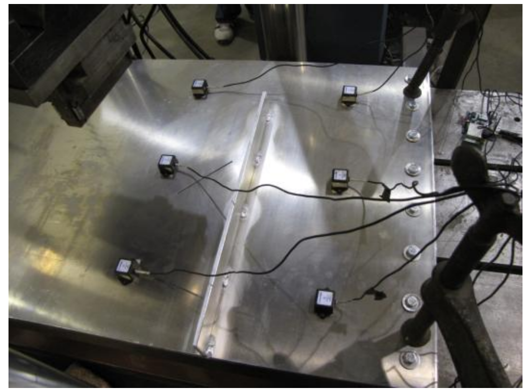


(b) Damage detection results with individual cracks and two stiffeners

Figure 4. Damage detection of cracks on a plate with multiple welded stiffeners.



(a) Schematics of the experimental plate specimens



(b) Specimen with crack and accelerometers

Figure 5. Setup for experimental tests on plate specimens with stiffener and crack.

with multiple stiffeners and the rapid convergence of the method on identifying the damage areas even when the initial probable damage areas includes relatively widespread regions around the stiffeners and along the edges of the plate.

3.2 Experimental Simulation

A number of plate specimens have been fabricated in full-scale (according to the schematic of the testbed structure shown in Figure 2(a)) to test the applicability of the probabilistic model-updating procedure for crack damage detection. The experimental setup is shown in Figure 5. The specimens are made of marine grade aluminum alloy (alloy 5086). As shown in Figure 5(a), an 18 in long stiffener plate has been welded to each of the tested plates with 0.625 in long discrete tungsten inert gas (TIG) welds at 5 locations (with a spacing of 4.5 in) to avoid excessive distortions that might result from weld heat. The base plates have been pre-heated using a gas torch to expedite the welding process. As shown in Figure 5(b), the base plates are fixed along the shorter edges using 8-3/8 in stainless screws with round aluminum washers; furthermore, the assemblage is rigidly connected to a large steel beam post-tensioned to the concrete strong floor. Figure 5(b) shows a diagonally cut (resembling crack path 2 as shown in Figure 3(b)) adjacent to the stiffener. As shown in the figure, MEMS-based accelerometers (Crossbow CXL02LF1Z) are used to measure the vibration of the specimen during the tests. Furthermore, the Narada wireless system developed at the University of Michigan, which has been successfully implemented for the monitoring of civil infrastructures, is deployed as the primary data acquisition system for collecting the acceleration data [16].

Modal Properties Extraction and Calibration: Both impact hammer tests and hand tapping tests were applied on each plate specimen. For each plate specimen, albeit the undamaged plate or the plates with crack, the hammer test is applied 6 times with impact locations away from the weld and crack damage areas as shown in Figure 5(a). Additionally, each plate specimen is hand tapped 5 times at random locations to simulate broad-band ambient excitation. The frequency domain decomposition (FDD) technique is employed to extract the modal properties of the plate specimens using the measured acceleration data. The FDD technique is widely used for modal parameter estimation and is based on the classical complex mode identification function [17].

For the calibration of the finite element model, the modal properties of the undamaged plate specimen (without cracks) are extracted from the vibration tests. Slight differences in modal frequency between the experimental results and the original FEM model (used in the numerical simulation) has been observed. Such a difference is expected because of the variation in the idealized finite element model, the material properties in the plate specimens, and boundary conditions in the experimental setup. To better calibrate between the numerical model and the experimental specimens, the elastic (Young's) modulus used in the finite element model is reduced to 90% of the nominal values (10,300 ksi) so that the first mode frequencies of the undamaged plate from both the finite element model and the experimental tests are closely matched. Table 2 summarizes the modal frequencies of the plate structure with crack path 1 obtained from the experimental hammer and hand tapping tests as well as from the updated finite element model. It can be seen that the results match very well with the values of modal assurance criteria (MAC) well above 90%.

Damage Identification Results: The model-updating procedure is applied to identify the damage area (cracks) based on the modal properties extracted from the plate specimens. Figure 6 shows the damage identification results for the three crack paths from both impact hammer and hand tapping tests. It can be seen that the model-updating procedure

Table 2. Summary of modal properties extracted for specimen with crack path 1.

Mode	Impact hammer test			Hand-tapping test		
	Modal frequency		Mode shape	Modal frequency		Mode shape
	Test (Hz)	Updated FEM (Hz)	MAC	Test (Hz)	Updated FEM (Hz)	MAC
1	24.22	25.17	0.998	24.22	25.17	0.999
2	35.89	37.89	0.983	35.94	37.89	0.996
3	65.43	67.36	0.992	65.43	67.36	0.985
4	85.57	85.14	0.982	85.64	85.14	0.976
5	122.07	120.43	0.932	121.97	120.43	0.935

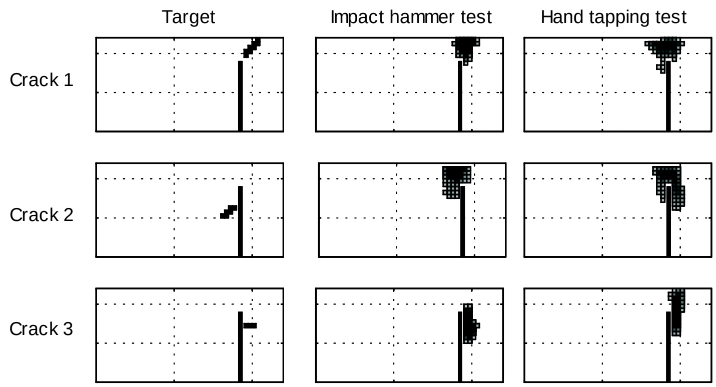


Figure 6. Damage identification results from experimental test specimens.

successfully detects crack paths 1 and 3. However, for crack path 2, although the most probable damage area is identified near the damage area, the procedure fails to pin-point the actual crack location. It can also be observed that, in general, the damage identification results based on impact hammer tests are more precise, as illustrated from the darker colors shown in the damage maps. It should be cautioned that, as in any experimental tests, the fabrication qualities of the plate specimens and the welds do vary. The modal frequencies could vary up to 5-7%. Further study on the impact of modeling uncertainties is needed. Preliminary investigation into the factors of noise to the probabilistic model-updating procedure is currently underway.

4. SUMMARY AND DISCUSSION

In this paper, a model-based monitoring framework for the detection of fatigue-related crack damage in plate-type structures commonly seen in aluminum ship hulls is presented. The monitoring framework involves vibration-based damage detection methodologies and finite element modeling of continuum plate structures. Modal properties derived from sensor information are employed to update the finite element models. A Bayesian-based approach is adopted for model updating. Inherent to the finite element modeling of a continuum structure is the large number of elements and degrees-of-freedom that are required to properly model the structure. To examine all possible combinations of elements to identify potential damage locations is computationally infeasible. To reduce the computational efforts involved in searching for possible damage locations, initial knowledge of probable damage areas and a heuristic-based branch-and-bound scheme are included in the Bayesian-based model-updating framework. Numerical simulations and experimental tests have been conducted to illustrate the model-based monitoring framework and to validate the potential application of the probabilistic-based damage detection approach. Preliminary numerical and experimental results for the plate specimens studied indicate that the proposed procedure is able to successfully identify crack damage areas, especially when the size of the crack is relatively large. However, further study is needed to enhance the damage detection algorithm for accurately locating the exact location of small cracks. Furthermore, modeling uncertainties, sensor noise, variations in loading excitations, and their effects on the proposed damage detection method are interesting subjects of future research.

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