

# NON-BASELINE DAMAGE DETECTION FROM CHANGES IN STRAIN ENERGY MODE SHAPES. EXPERIMENTS ON ARMORED VEHICLE LAUNCHED BRIDGE

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**ABSTRACT.** There are several existing methods for damage detection based on identifying changes in strain energy mode shapes. Most of these methods require knowing strain energy mode shapes for a structure without damage in order to establish a baseline for damage detection. Usually, the mode shapes from the structure under test should be compared to the baseline mode shapes to identify and locate damage. However, these methods of damage detection are not very suitable for application on structures where baseline mode shapes cannot be readily obtained, for example, structures with preexisting damage. Conventional methods, like building a finite element model of a structure to be used as a baseline might be an expensive and time-consuming task that can be impossible for complex structures. A new (non-baseline) method for the extraction of localized changes (damage peaks) from strain energy mode shapes based on Fourier analysis of the strain energy mode shapes has been developed and analytically proved for the cases of a pinned-pinned and a free-free beam. The new method looks for characteristic changes in the power spectrum of the strain energy mode shapes in order to locate and identify damage. The analytical results have been confirmed both by the finite element model and impact testing experiments on a free-free aluminum beam, including single and multiple damage scenarios. This paper presents results of testing the non-baseline method on a complex structure – Armored Vehicle Launched Bridge, which consists of loosely coupled hinged beams with variable cross-section. The results of testing confirm applicability of the non-baseline method to damage detection in complex structures and highlight certain particularities of its use.

## INTRODUCTION

In the recent past, several methods for detecting and locating damage (usually cracks) from changes in Strain Energy Mode Shapes (SEMS) have been developed. All these methods attempt to detect and locate damage that produces localized changes in elastic modulus without significant changes in mass. Such damage can be observed as localized changes (damage peaks) on strain energy mode shapes.

The majority of these methods requires knowing strain energy distribution (mode shapes) for the structure without any damage or so-called baseline SEMS. The comparison to the baseline is used to enhance appearance of damage peaks that sometimes may not be

observed otherwise. The need for baseline SEMs is especially obvious for identifying small damages that produce very subtle changes in SEMs.

Unfortunately, such an approach often is not feasible for a class of structures where undamaged state is unknown and cannot be acquired experimentally. This class of structures primarily includes old structures where damage state is unknown but the need for non-destructive testing is usually greater. Conventional methods, such as building a Finite Element (FE) model of a structure may represent a tedious, expensive and time-consuming task. Besides, it is difficult or sometimes impossible to reach required accuracy of mode shape approximation by a FE model.

If applicability of non-destructive damage detection utilizing SEMs could be extended by eliminating the need for baseline mode shapes and employing a non-baseline approach, it would significantly increase the class of structures where non-destructive damage detection could be performed.

Consider some of the recent work in this area. Shi et.al. [1] suggested using changes in strain energy distribution to detect and localize damage. The recommended method monitors changes in modal strain energy in each structural element comparing the states before and after it was damaged. Farrar and Jauregui [2] conducted a comparative study of different damage identification algorithms on a bridge. The strain energy methods performed very well compared to other methods tested in the experiments, occupying the top two places by the accuracy of detection. The authors also noted the methods' high sensitivity to less severe damage cases. Osegueda, Carrasco and Meza [3] investigated strain energy method on aluminum cantilever beams and honeycomb composite plates. The authors received positive damage detection results in experiments with beams and negative results in experiments with composite plates. They also claimed that strain energy methods not only can identify damage but also quantify it by accounting the energy relations between damaged and undamaged states. Cornwell et. al. [4] performed a comparative study of two vibration-based damage identification algorithms, including strain energy method. The testing was conducted on a beam and a plate, comparing the damaged vs. undamaged strain energy distribution. Strain energy method successfully identified severe damage cases, but a masking effect was reported for lower level damages, i.e. when the two damage locations had different levels of damage, the algorithm tended to only conclusively identify the location with the largest amount of damage. Yoo, Kwak and Kim [5] used difference in strain energy mode shapes between damaged and undamaged cases to detect and locate damage in a plate. Yan and Deng [6] applied the strain energy algorithm to nondestructive damage detection in bridges. They conducted numerical experiments on a finite element model of a freely supported bridge T-beam. Pereyra et. al. [7] studied damage detection in an aluminum stiffened-plate panel resembling aircraft fuselage construction. As in most other studies, the damaged strain energy mode shapes were compared to the undamaged strain energy mode shapes. Statistical methods were employed to jointly analyze information from several mode shapes and to locate damage. Napolitano [8] investigated quality of damage detection using reduced measurements and the strain energy algorithm. The author concluded that the strain energy method performs better when many response points are measured. Cornwell, Doebling and Farrar [9] provided a detailed theoretical explanation on application of the strain energy method to plate-like structures. They reported that the method was effective enough to detect areas with 10% reduction in stiffness.

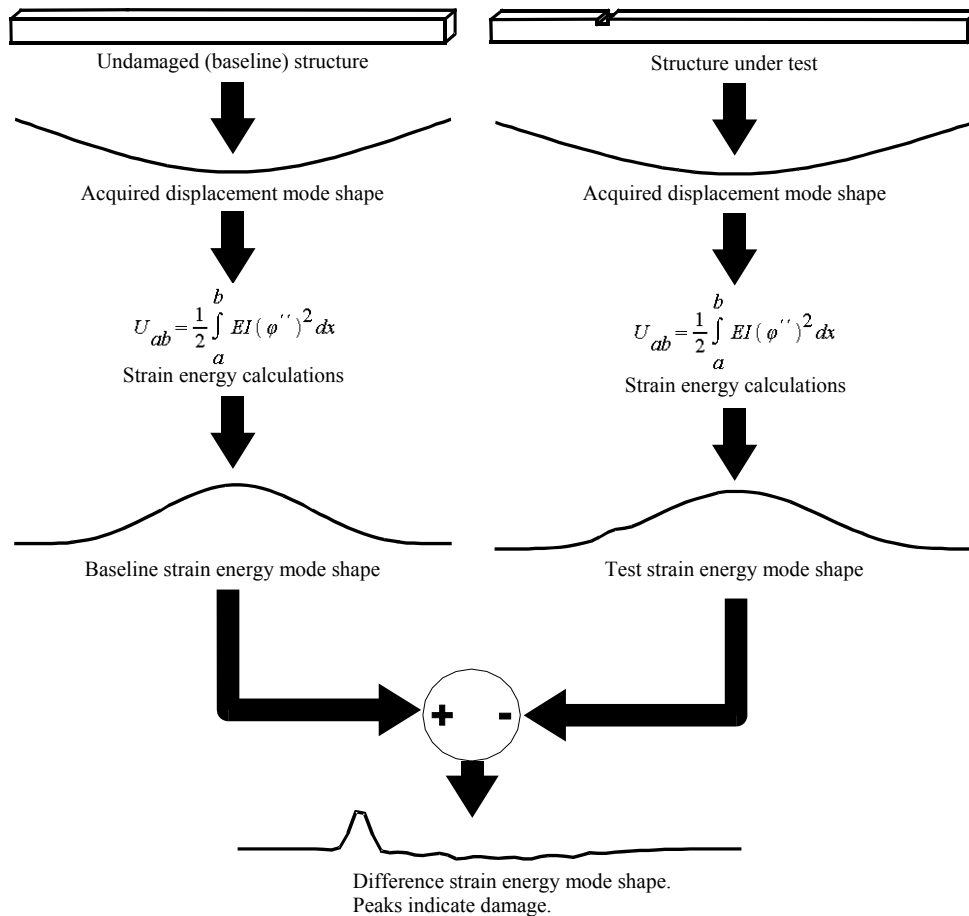
A method based on strain energy mode shapes was developed at West Virginia University (WVU) [10]. Strain energy for an interval  $[a,b]$  was computed using the following formula:

$$U_{[a,b]} = \frac{1}{2} \int_a^b EI (\Phi'')^2 dx, \quad (1)$$

where  $EI$  is the flexural stiffness of the cross-section;  $\Phi$  is the mode shape vector (displacement mode shape).

Subtracting the baseline SEMS from the SEMS acquired from the structure under test produces so-called Difference Strain Energy Mode Shapes (DSEMS) where crack locations are identified as damage peaks (FIGURE 1). Again, this method requires a baseline to extract and enhance appearance of damage peaks. An extension of the WVU method is described in [11]. The suggested procedure performs extraction and enhancement of damage peaks appearance through separation of damage information in frequency domain rather than traditional spatial domain. It was shown that the damage introduced into a beam creates additional harmonics in the amplitude spectrum of the strain energy mode shapes that have not been present in the undamaged beam. These additional harmonics can be extracted by filtering and restored to produce enhanced damage peaks.

This paper attempts to test the suggested non-baseline procedure on a complex structure, such as the AVL B. The goal of testing is to verify applicability of the suggested methodology on hinged beams with variable cross-section.



**FIGURE 1.** Traditional strain energy method.

## METHODS

### The Non-Baseline Strain Energy Procedure for Simple Beams

Consider an undamaged pinned-pinned beam of length  $L$  and a uniform cross-section with the flexural stiffness of  $EI$ . The bending mode shapes of the beam for a variety of the boundary conditions can be found in [12]. For a pinned-pinned beam, displacement mode shapes for mode  $k$  are given by the following equation:

$$\Phi_k(x) = Q_k \sin\left(\frac{\pi k}{L}x\right) = Q_k \sin\left(\frac{\omega_k}{2}x\right) \quad (2)$$

where  $Q_k$  is the amplitude of mode  $k$ ,  $\omega_k = \frac{2\pi k}{L}$  is the angular frequency for mode shape  $k$ .

It can be shown [11] that the frequency spectrum of the strain energy mode shapes  $U_k(x)$  for a pinned-pinned beam is limited to two terms ( $A_0^k$  and  $B_k^k$ ) in the corresponding Fourier series of the general form:

$$f(x) = A_0 + \sum_{n=1}^{\infty} A_n \sin \omega_n x + \sum_{n=1}^{\infty} B_n \cos \omega_n x \quad (3)$$

The Fourier series for  $U_k(x)$  of a pinned-pinned beam is given by the following equation:

$$U_k(x) = \frac{C_k \Delta}{2} - \frac{C_k \Delta}{2} \cos \omega_k x = \frac{C_k \Delta}{2} (1 - \cos \omega_k x), \quad (4)$$

where  $C_k = \frac{EI Q_k^2 \omega_k^4}{32}$ , and, thus, the bandwidth of the  $k^{\text{th}}$  strain energy mode shape is limited by the  $k^{\text{th}}$  harmonic.

Displacement mode shapes for mode  $k$  of a free-free beam are given by the following equation [12]:

$$\Phi_k(x) = \cosh\left(\frac{\lambda_k x}{L}\right) + \cos\left(\frac{\lambda_k x}{L}\right) - \sigma_k \left(\sinh\left(\frac{\lambda_k x}{L}\right) + \sin\left(\frac{\lambda_k x}{L}\right)\right) \quad (5)$$

where  $L$  is the length of the beam,  $\lambda_k$  and  $\sigma_k$  are the mode shape coefficients dependent on  $k$ :  $\lambda_k = \{ 4.730040739999998, 7.853204619999998, 10.9956078, 14.1371655, 7.278759699999999, (2k+1)\pi/2 \text{ for } k > 5 \}$  and  $\sigma_k = \frac{\cosh \lambda_k - \cos \lambda_k}{\sinh \lambda_k - \sin \lambda_k}$ .

For the case of a free-free beam it can be shown [11] that the cut-off frequency that limits the energy of strain energy mode shapes at 95% of the total energy has a well-defined dependency on  $k$ :

$$n_{\text{Cut-off}} = k + 1. \quad (6)$$

Thus, the amplitude spectrum of SEMS for a beam with free-free boundary conditions is band-limited by the  $k+1$  harmonics.

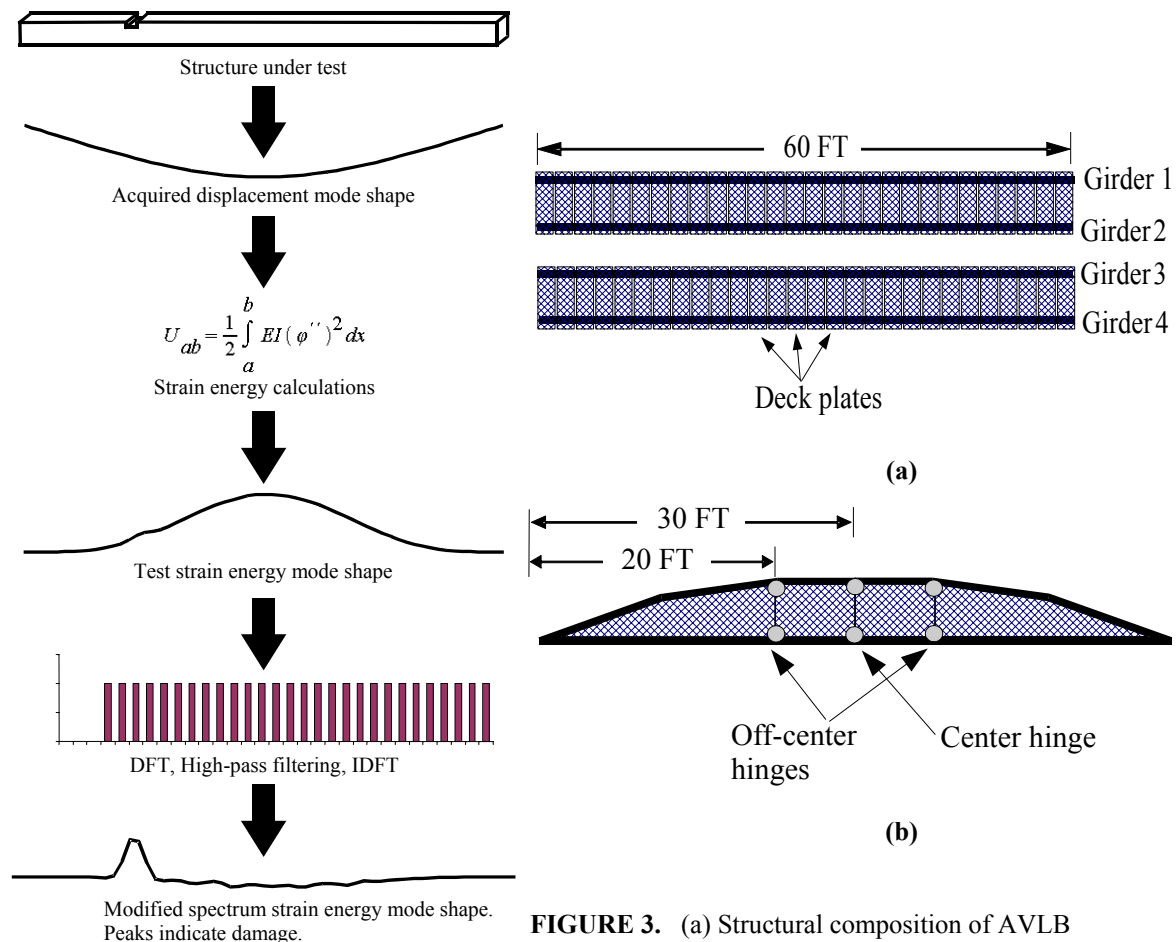
Therefore, the amplitude spectrum of strain energy mode shapes for pinned-pinned and free-free boundary conditions of a beam is limited to the first  $k+1$  harmonics (as the most general case) in the Fourier series representation.

It can also be shown [11] that the amplitude spectrum of a damage peak on the strain energy mode shapes is significantly wider than the amplitude spectrum of an undamaged strain energy mode shape. Additionally, all damage peaks of the same shape and amplitude have the same amplitude spectrum but different phase spectrum. Therefore,

it is possible to separate mode shape information from damage information in the frequency domain and avoid using a baseline by removing the first  $k+1$  harmonics in the frequency spectrum of a strain energy mode shape. The procedure is illustrated in FIGURE 2. The non-baseline method has been successfully tested both on finite element models of a free-free beam and experimental data.

### Acquisition of Modal Parameters on the AVLB

AVLB is a folding scissors-type lightweight aluminum-steel combination bridge with the maximum span of 60ft. (18.3m) [13]. Structurally the bridge consists of the 4 hinged girders (FIGURE 3) with the deck plates attached on top of each girder pair. Each girder has 6 hinges: one top and bottom hinge pair located at the center of the bridge span, and two off-center hinge pairs. The acquisition of the displacement mode shapes and other model parameters from the AVLB was performed by an automated damage detection system designed specifically for AVLB [14]. The system utilizes a non-contact laser vibrometer mounted on a computer-controlled robotic gantry as the measurement sensor. Acquired data is automatically processed to obtain strain energy mode shapes, which are used as the damage indicator. The analysis of the strain energy mode shapes is performed by a fuzzy expert system. This system was successfully tested on a full-scale AVLB with different damage scenarios.



**FIGURE 2.** Non-baseline damage detection procedure.

**FIGURE 3.** (a) Structural composition of AVLB (b) hinges of a girder.

## TESTING

The mode shapes for the first three bending modes of AVLB were acquired by the automated damage detection system (FIGURE 4). Next, the strain energy computations were computed from the bending mode shapes. The strain energy mode shapes from the undamaged AVLB were stored as the baseline.

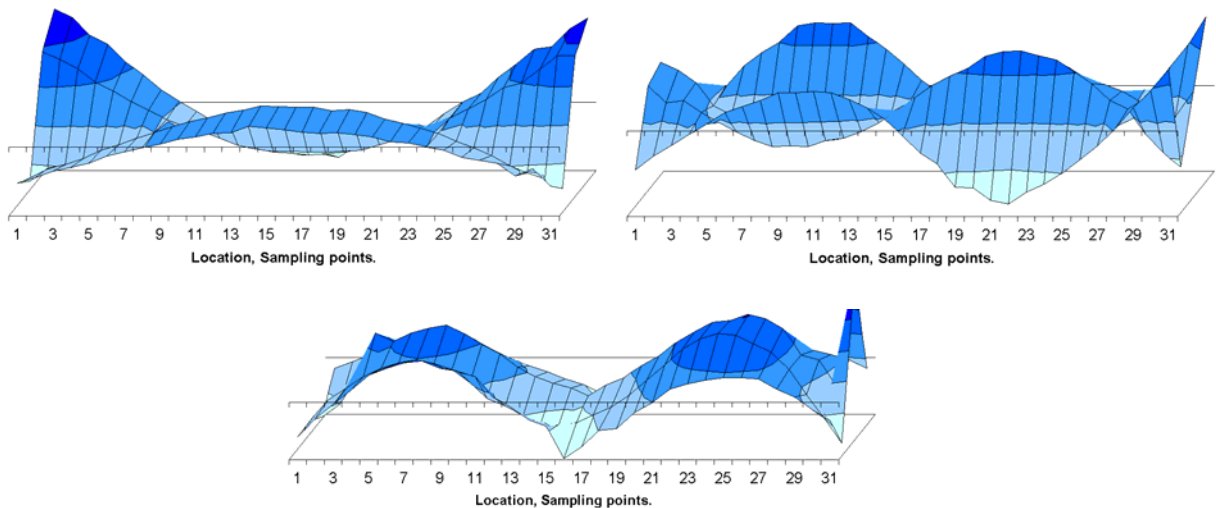
Three damage cases were simulated by removing the central bottom hinge pin and either of the off-center bottom hinge pins. These three simulated cases of damage represent different degrees of damage severity. According to the AVLB manual, if the bottom central pin is missing or cracked (regardless of length), or damaged, or even missing retainer clips/ hinge pins, the AVLB is considered Not Mission Capable. If an off-center bottom hinge pin is removed, the AVLB is still considered Mission Capable. The strain energy mode shapes from the three damaged cases were also stored for further processing.

A side-by-side comparison of the difference strain energy mode shapes obtained by the subtracting the baseline strain energy mode shapes from the test strain energy mode shapes (traditional strain energy method) and the modified spectrum strain energy mode shapes obtained by removing first  $k+1$  harmonics in the frequency spectrum of the test strain energy mode shapes (non-baseline strain energy method) was conducted to compare the quality of damage peak expression.

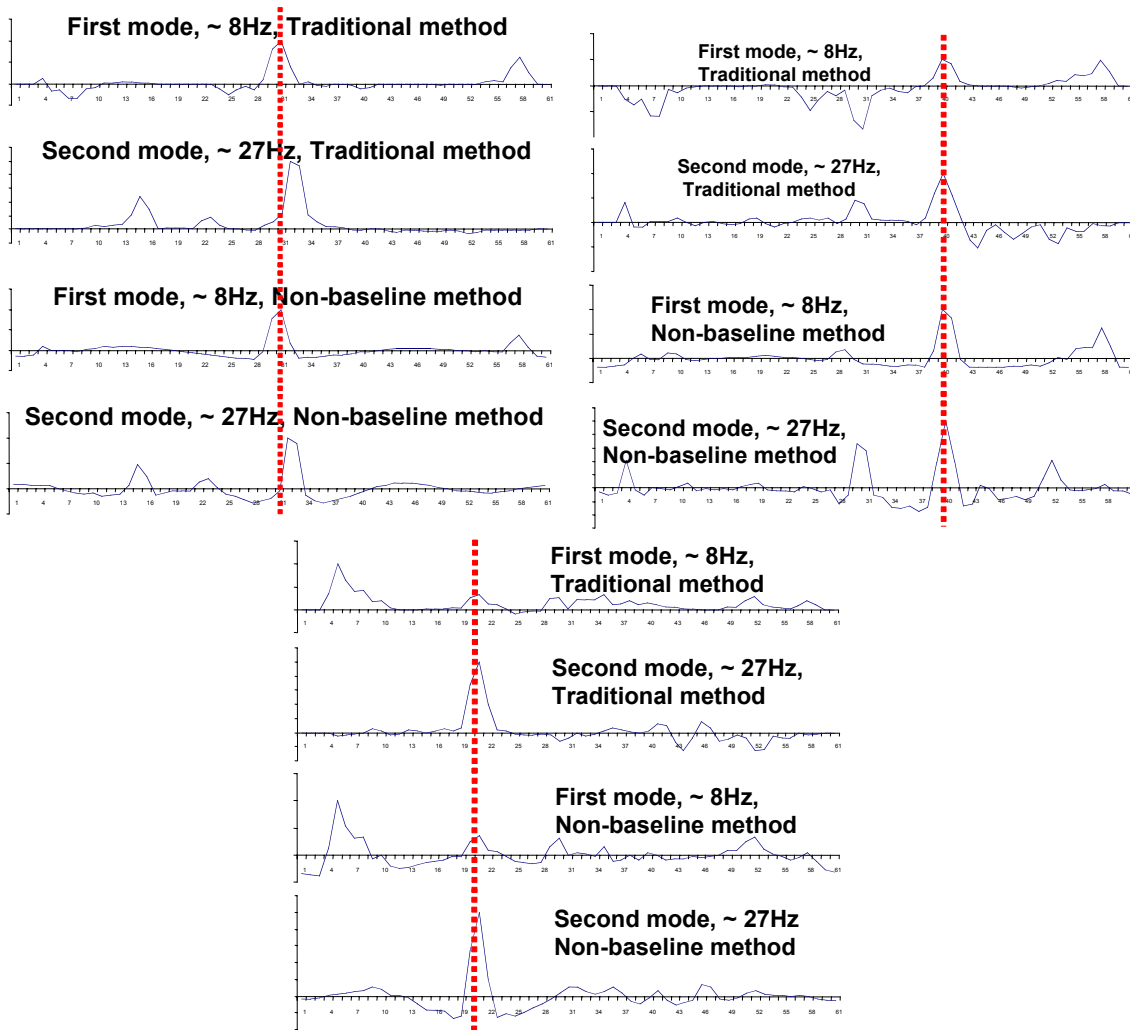
As FIGURE 5 shows, expression of the damage peaks is approximately equal for both the traditional and the non-baseline strain energy methods. The dissimilarities in the resulting difference strain energy mode shapes and modified strain energy mode shapes are minor and cannot drastically change the results of the damage detection.

## CONCLUSIONS

The experiments on the AVLB have shown that the damage indicators extracted either by the traditional or by the non-baseline strain energy methods have the approximately the same degree of expression and provide essentially the same amount of information for detecting damage. These results practically justify the applicability of the non-baseline method to complex structures, thus significantly expanding the class of structures where the damage detection by strain energy mode shapes can be applied.



**FIGURE 4.** First three mode shapes acquired on the AVLB.



**FIGURE 5.** Damage indicators of the first two bending modes of the AVL B extracted by traditional and non-baseline strain energy methods.

At the present time, the analytical proof of the non-baseline procedure exists only for a limited number of boundary conditions of a simple beam. The results obtained on the AVL B show that it may be possible to extend the analytical coverage to more complex beams, such as hinged beams of variable cross-section. Such analytical work should establish the proper procedure and interpretation of the results obtained on the complex structures. Indeed, a special case may exist when a structure has an abrupt change in cross-section that can be falsely identified as a damage peak. Baseline methods would provide relatively good, although not complete, cancellation of such peaks, while the proposed non-baseline approach does not have such capability. A possible solution to this problem might be in matching of the modified strain energy mode shapes to the geometric configuration of the structure and discarding the false peaks.

## ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support provided by the U.S. Army (contract # DAAE07-96-C-X226).

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