# Vibration Based Damage Identification in a Composite T-Beam Utilising Low Cost Integrated Actuators and Sensors

T. H. OOIJEVAAR, L. L. WARNET, R. LOENDERSLOOT,
R. AKKERMAN and A. DE BOER

## ABSTRACT

The development of integrated measurement systems for composite structures is urged by the fact that a Structural Health Monitoring environment requires these systems to become an integral part of the structure. The feasibility of using low cost piezoelectric diaphragms for dynamic characterisation and vibration based damage identification in a composite T-beam structure is demonstrated. The dynamic behaviour is analysed by applying these basic electronic sound components for actuation and sensing. Impact induced damage at the skin-stiffener connection is detected and localized by applying the MSE-DI algorithm on the measured bending strain mode shapes.

## INTRODUCTION

The development of Structural Health Monitoring (SHM) technologies for composite materials involves multidisciplinary research challenges. Failure mechanisms, like delaminations, should be uniquely identified by robust and reliable methodologies operating on realistic measured data from an integrated sensing system.

A wide range of technologies is employed for health monitoring purposes [1, 2]. A SHM environment requires these technologies to become an integral part of the structure. This urges the development of integrated measurement systems. An enormous amount of researches showed the successful application of piezoelectric ceramic actuators and sensors for structural dynamic measurements and health monitoring [2, 3]. Piezoelectric unimorph diaphragms, consisting of a circular piezoelectric element with a metal backing plate, are a low cost implementation of piezoelectric ceramic material.

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T.H. Ooijevaar*, L.L. Warnet, R. Loendersloot, R. Akkerman and A. de Boer
University of Twente, Faculty of Engineering
Technology, P.O. Box 217, 7500AE, Enschede, The
Netherlands

*E-mail: t.h.ooijevaar@utwente.nl

These diaphragms are mass produced and are frequently applied as a basic electronic sound component ("buzzers") in mobile devices. They are designed and optimized for this purpose and are therefore not calibrated for strain monitoring. Their stability and variability are unknown parameters. Moreover, a practical limitation is the inability to conform to curved surfaces. The number of applications of these low cost piezoelectric diaphragms to vibration based health monitoring methods is limited.

This paper focuses on an experimental investigation of the feasibility of using low cost piezoelectric diaphragms for dynamic characterisation and damage identification by a vibration based damage identification method. Earlier performed research [4–6] showed that the Modal Strain Energy Damage Index (MSE-DI) algorithm is a suitable method to identify impact damage in skin-stiffened composite structures using laser vibrometer measurements and a shaker. This research is extended by employing piezoelectric diaphragms for the actuation and measurement of the global dynamic response. This approach is demonstrated of a composite T-beam structure with a length of 1m. The dynamic response of an intact and a (by impact) damaged structure is analysed by applying the MSE-DI algorithm.

The improvement aimed for in this paper is the fact that piezoelectric diaphragms are an integrable and low cost alternative for the dynamic measurements employing a laser vibrometer and shaker. To authors' best knowledge, low cost piezoelectric diaphragms have not been used in combination with modal domain damage features. Lesari [7] and Qiao [8] were the only one who used the MSE-DI algorithm in combination with PVDF film sensors on simple specimen.

## COMPOSITE SKIN-STIFFENER STRUCTURE WITH INTEGRATED ACTUATORS AND SENSORS

The multi-functional composite skin-stiffener structure used in this study is presented in figure 1. This typical aerospace structure combines specific structural performance with two actuators and 2×12 sensors for health monitoring.

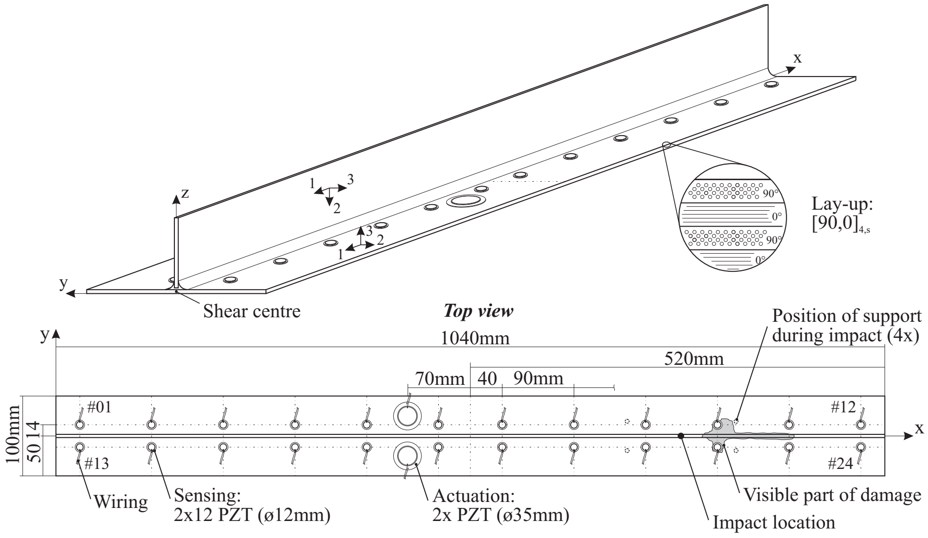


Figure 1: An overview of the composite structure including the positions of the actuators and sensors.

Two large piezoelectric diaphragms (∅35mm), positioned at the skin on both sides of the stiffener, are used to provide sufficient energy to excite the structure in its global dynamic behaviour. These actuators are used simultaneously to control the structure to vibrate in either bending or torsion. The type of mode affects the sensitivity of the approach to identify specific damage scenarios, as was shown in [4]. Small piezoelectric diaphragms (∅12mm) are used for sensing. The sensors are equally distributed over the length and are positioned close to the most susceptible region for damage, the connection between skin and stiffener. The diaphragms are glued to the surface with two component fast curing X60 glue (HBM).

## Composite Skin-stiffener structure and impact induced damage

The composite T-shaped stiffener section investigated consists of a new type of skin-stiffener connection, referred as butt joint, developed by Fokker Aerostructures [9]. A PEKK injection moulded filler containing 20% short fibres is used as a connection. The laminate is build from 16 individual plies of uni-directional co-consolidated carbon AS4D reinforced PEKK. A $[90/0]_{4,\mathrm{s}}$ lay-up is used. The dimensions of the specimen are indicated in figure 1.

The location with the highest risk of failure of the structure under impact is the connection between skin and stiffener. A typical damage occurring to composite structures is delamination. The aim of this research is to identify such damage. Naturally originated defects are obtained by applying a local impact with the help of a Dynatup 8250 Falling Weight Impact Machine and a repeated impact up to maximum 9.2J. Visual inspection showed that the damage can be characterised as Barely Visible Impact Damage (BVID) and consists of first-ply failure and interface failure between the filler and skin. The damaged region is indicated in figure 1.

## Piezoelectric unimorph diaphragms

The piezoelectric unimorph diaphragms are mass produced and therefore commercially available at extremely low cost. Typical prices are currently a few tens of eurocents. A diaphragm consist of a circular piece of piezoelectric ceramic P-7 material (Lead Zirconate Titanate / PZT) covered by an electrode at both sides and deposed on a brass backing plate. Characteristic properties are presented in table 1 and figure 2. The piezoelectric ceramic material properties are specified in [10].

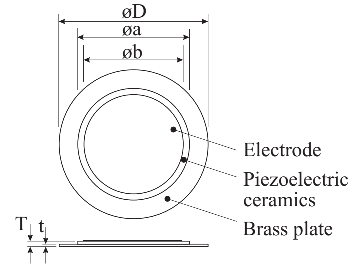


Figure 2: Schematic presentation of a piezoelectric diaphragm

Table 1: Properties of piezoelectric diaphragm

| Property | PZT ∅12mm | PZT ∅35mm |
|---|---|---|
| Resonant frequency [kHz] | 9.0 | 2.8 |
| Resonant impedance [Ohm] | $\leq 1000$ | $\leq 200$ |
| Capacitance (1 kHz) [nF] | $8.0 \pm 30\%$ | $30.0 \pm 30\%$ |
| $D$ [mm] | 12.0 | 35.0 |
| $a$ [mm] | 9.0 | 25.0 |
| $b$ [mm] | 8.0 | 23.0 |
| $T$ [mm] | 0.22 | 0.53 |
| $t$ [mm] | 0.10 | 0.30 |
| Mass $m$ [g] | $0.143 \pm 0.5\%$ | $3.281 \pm 0.1\%$ |

## DAMAGE FEATURES FOR DAMAGE IDENTIFICATION

A 1D formulation of the MSE-DI algorithm was introduced by Stubbs [11]. The basics of this formulation are shortly explained in this section. A more elaborate derivation and explanation of the assumptions made can be found in [4, 12, 13].

Consider a beam-like structure to be discretised in $N_x$ elements in $x$-direction. The strain energy $U$, based on bending deformation in $z$-direction, of each of the individual modes $n$ and element $i$ is represented by:

$$U_{B,i}^{(n)} = \frac{1}{2}\int_{x_{i-1}}^{x_i} (EI)_i \left(\frac{\partial^2 u_z^{(n)}(x)}{\partial x^2}\right)^2 \mathrm{d}x \tag{1}$$

with $u_z^{(n)}(x)$ the displacement amplitude of the $n^{\text{th}}$ participating mode shapes, $EI$ the bending rigidity of the beam, $x_i$ and $x_{i-1}$ the limits of element $i$ of the discretised structure in $x$ direction. The total modal strain energy is approximated by the sum of equation 1 over a limited set of $N_{freq}$ modes.

The numerical errors induced by the computation of the second derivative of the displacement can be omitted by directly relating the modal strain energy to strains instead of displacements. The displacement curvature, represented by $\kappa$, is proportionally related to strain $\varepsilon_x$ for a beam in bending ($\kappa \propto \varepsilon_x$):

$$\kappa^{(n)}(x) = \frac{\partial^2 u_z^{(n)}(x)}{\partial x^2} = -\frac{\varepsilon_x^{(n)}(x)}{z} \tag{2}$$

with $z$ being the distance from the neutral axis.

Following the definition proposed in [12], the ratio of fractional element stiffnesses of the damaged structure over the reference structure provides the base of the damage index:

$$\frac{\tilde{\gamma}_i^{(n)} \Big/ \tilde{\gamma}^{(n)}}{\gamma_i^{(n)} \Big/ \gamma^{(n)}} = \frac{\int_{x_{i-1}}^{x_i} \tilde{w}^{(n)}\mathrm{d}x \Big/ \int_0^l \tilde{w}^{(n)}\mathrm{d}x}{\int_{x_{i-1}}^{x_i} w^{(n)}\mathrm{d}x \Big/ \int_0^l w^{(n)}\mathrm{d}x} \tag{3}$$

where $w^{(n)}(x)$ represents the second term in the integrand of equation 1, $\gamma_i^{(n)}$ the integral of $w^{(n)}(x)$ over element $i$ and $\gamma^{(n)}$ the integral $w^{(n)}(x)$ over the entire length $l$. The damaged case is represented by the tilde sign on top of the variable. The information in each of the mode shapes is combined in a damage index $\beta$, according to the definition proposed by Cornwell et al. [12]:

$$\beta_i = \sum_{n=1}^{N_{\text{freq}}}\left[\tilde{\gamma}_i^{(n)} \Big/ \tilde{\gamma}^{(n)}\right] \Bigg/ \sum_{n=1}^{N_{\text{freq}}}\left[\gamma_i^{(n)} \Big/ \gamma^{(n)}\right] \tag{4}$$

An overview of most common alternative formulations is presented in [6]. The damage index $\beta_i$ is generally normalised using the standard deviation $\sigma$ and the mean $\mu$ of the damage index over all elements. This results in the value Z, defined in each element $i$:

$$Z_i = \frac{\beta_i - \mu}{\sigma} \tag{5}$$

## EXPERIMENTAL ANALYSIS

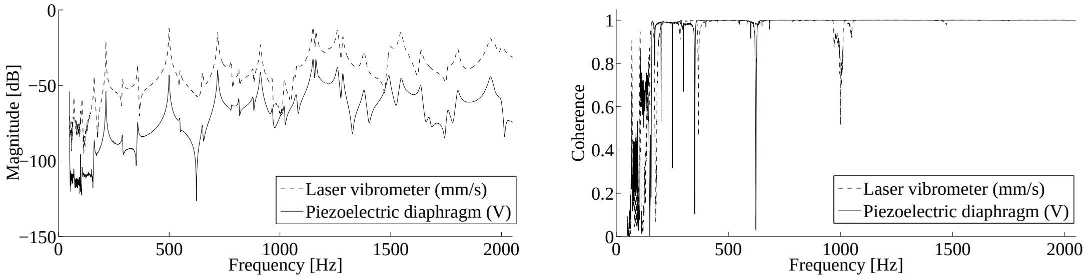
Vibration measurements are performed on the instrumented T-beam specimen before and after the impact damage was applied. The T-beam was supported by two foam blocks, representing a free-free boundary condition. A chirp excitation signal and a power amplifier were utilized to excite the two ∅35mm piezoelectric diaphragms in phase, causing the structure to dominantly vibrate in its bending modes. The frequency response functions (FRFs) between the excitation signal of the fixed actuators and the voltage generated by the 2×12 ∅12mm piezoelectric sensors are recorded by a Siglab system. A frequency range of 50-2050 Hz (resolution: 0.6250 Hz) was selected. Each measurement consists of 30 windowed averages. The modal parameters (natural frequency, mode shapes and damping values) are obtained from the FRFs by using Experimental Modal Analysis [4]. The strain mode shapes are linearly interpolated and are the input for damage diagnosis by the MSE-DI algorithm.

## RESULTS AND DISCUSSION

The damage identification procedure consists of two steps, the dynamic characterisation and the application of the MSE-DI algorithm. The feasibility of using low cost piezoelectric diaphragms for both steps is investigated in this section.

### Performance of piezoelectric diaphragms for dynamic measurements

The performance of a piezoelectric diaphragm to measure dynamic responses is evaluated by comparing its response with the response measured by a laser vibrometer. Figure 3(a) shows a FRF measured at grid point #9. Despite a difference in the magnitude level, the signature and frequencies of the vibration modes matches accurately. A 90° phase difference is obtained between the two FRFs. This shift is caused by the fact that the measured variables, velocity and deformation, deviate one order in the time derivative. Coherence values close to one are presented in figure 3(b). This indicates a good linear dependency between the input and output signal for both cases. The coherence drops at lower frequencies (below 170Hz) due to insufficient excitation energy provided by the actuators. Despite the fact that the sensors are not designed



(a) Magnitude response.

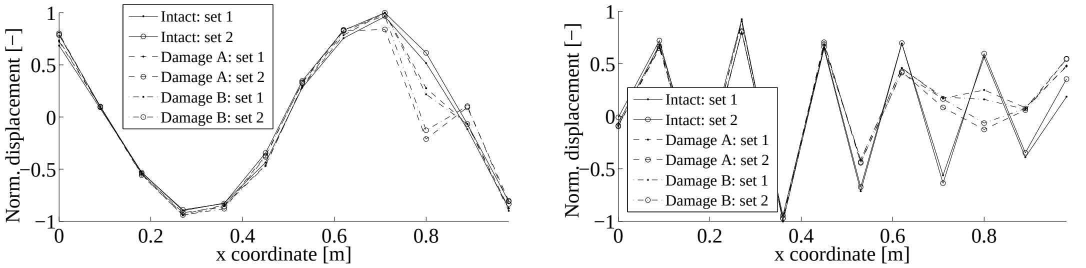
(b) Coherence function.

Figure 3: FRFs obtained by a laser vibrometer and piezoelectric diaphragm at measurement point #9.

and calibrated for strain monitoring, the quality of the response is equivalent to obtained by the laser vibrometer. The piezoelectric diaphragms are considered to be an appropriate alternative to measure the dynamic behaviour of the composite structure.

## Damage identification utilizing low cost piezoelectric diaphragms

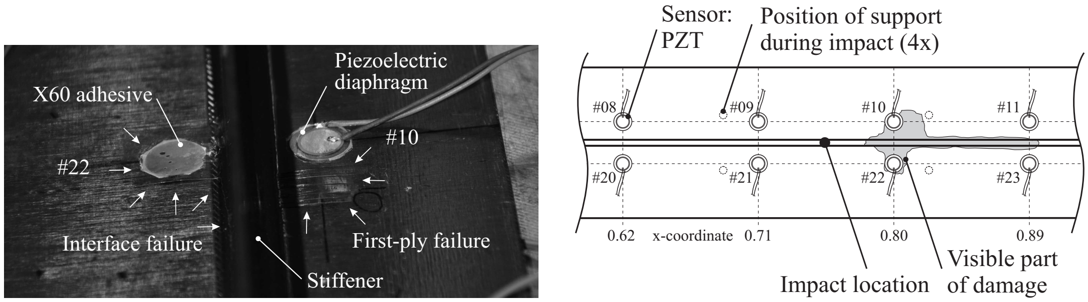
The bending strain mode shapes are extracted from the FRFs before and after the impact. Figure 4 shows the $2^{\text{nd}}$ and $9^{\text{th}}$ mode shape of the structure measured by the piezoelectric diaphragms. Both mode shapes show a clear reduction in amplitude at the damaged region, when the intact and damaged (“A”) situation are compared. Subsequently, the four piezoelectric diaphragms at the damaged region (#09, #10, #21, #22, figure 5) were replaced to verify whether the local reduction is purely caused by the structural change and not by internal failure of the diaphragms. A reduction of the same order of magnitude is obtained for this situation (“B”), indicating that the change measured was purely caused by the structural damage.



(a) $2^{\text{nd}}$ bending strain mode shape ($F_n = 524.96$ Hz, $\tilde{F}_n^A = 520.99$ Hz, $\tilde{F}_n^B = 520.95$ Hz).

(b) $9^{\text{th}}$ bending strain mode shape ($F_n = 1210$ Hz, $\tilde{F}_n^A = 1195.2$ Hz, $\tilde{F}_n^B = 1194.6$ Hz).

Figure 4: Mode shapes of the composite T-beam measured by low cost piezoelectric diaphragms.

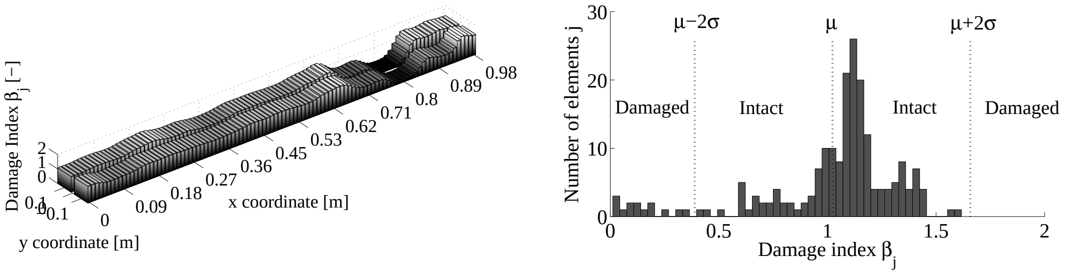


(a) Failure and debonded sensor at point #22.

(b) Top view indicating damaged region.

Figure 5: First-ply and interface failure in the connection between skin and stiffener of the T-beam.

The strain mode shapes are directly used in the 1D formulation of the MSE-DI algorithm, according to equation 2. The bending strain mode shapes result in a local decrease of the damage index $\beta_j$ as shown in figure 6(a). Figure 6(b) depict that damage index $\beta_j$ tend to show a normal distribution and approaches 1 for the undamaged regions. Elements with a $\beta_j$ value deviating more than $2\sigma$ from the mean value $\mu$ are classified as damaged. According to this criteria, the predicted location of the damage



(a) Damage index $\beta_j$ distribution.

(b) Normal distribution of damage index $\beta_j$.

Figure 6: MSE-DI results for impact induced damage by incorporating the first nine bending strain mode shapes measured by low cost piezoelectric diaphragms.

in figure 6(a) matches with the real damaged region indicated in figure 5(b). The normalized damage index $Z_j$, described by equation 5, provides a statistical measure for outliers. This index becomes negative at the damaged region, as shown in figure 7.

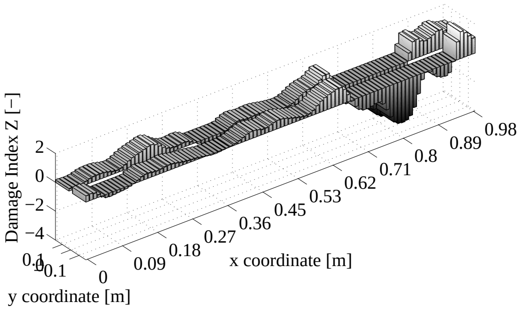


Figure 7: Normalized damage index $Z_j$ for impact induced damage by incorporating the first nine bending strain mode shapes measured by low cost piezoelectric diaphragms.

The reason for the notable local decrease in damage index $\beta_j$ is related to the orientation of the failure mechanism with respect to the position of the sensors. This orientation is defined by the laminate lay-up of the skin. Since the top-ply is a 90° layer, first-ply failure in the skin occurs perpendicular to the stiffener (figure 5). Piezoelectric diaphragms #9 and #22 are partially positioned on top of this delaminated top-ply. As a result, these diaphragms experience a reduced strain and do not capture the deformation of the major part of the skin. These results endorse the observation that the damage identification results are a function of the failure mechanism, partially defined by the laminate lay-up, and the position of the sensors.

## CONCLUSIONS AND RECOMMENDATIONS

The feasibility of using low cost piezoelectric diaphragms for dynamic characterisation and vibration based damage identification in a composite skin-stiffener structure is demonstrated. The dynamic behaviour is analysed by applying these basic electronic sound components for actuation and sensing. Impact induced damage at the skin-stiffener connection is detected and localized by applying the MSE-DI algorithm on the measured bending strain mode shapes.

The failure consists of interface and first-ply failure, where the latter is defined by the laminate lay-up of the skin. The origin of the local reduction in the damage index distribution showed that the MSE-DI results are directly related to the orientation of the first-ply failure with respect to the position of the sensors. This supports the conclusion that the development of a Structural Health Monitoring system is made-to-measure work.

The MSE-DI algorithm requires the computation of the second derivative of the displacement mode shapes. Measured strain mode shapes are potentially advantageous with respect to the numerical errors induced by the computation of second derivatives and will be investigated in future work. Moreover, a T-beam specimen with a $[0/90]_{4,s}$ lay-up will be investigated to verify the failure mechanism dependency of the damage identification results.

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## REFERENCES

[1] D. Montalvao, N. Maia, and A. Ribeiro. A review of vibration-based structural health monitoring with special emphasis on composite materials. *Shock and Vibration*, 38(4):295–326, 2006.

[2] A. Raghavan and C. Cesnik. Review of Guided-wave Structural Health Monitoring. *Shock and Vibration*, 39(2):91–114, 2007.

[3] V. Giurgiutiu. Damage Detection in Thin Plates and Aerospace Structures with the Electro-Mechanical Impedance Method. *Structural Health Monitoring*, 4(2):99–118, 2005.

[4] T.H. Ooijevaar, R. Loendersloot, L.L. Warnet, A. de Boer, and R. Akkerman. Vibration based Structural Health Monitoring of a composite T-beam. *Composite Structures*, 92(9), 2010.

[5] T.H. Ooijevaar, R. Loendersloot, L.L. Warnet, R. Akkerman, and A. De Boer. Structural Health Monitoring of an Advanced Composite Aircraft Structure Using a Modal Approach. In *Proceedings of the 8th International Workshop on Structural Health Monitoring 2011*, 2011.

[6] R. Loendersloot, T.H. Ooijevaar, A. De Boer, and R. Akkerman. Development of a Damage Quantification Model for Composite Skin-Stiffener Structures. In *SMART11 Conference*, 2011.

[7] W Lestari, P Qiao, and S Hanagud. Curvature mode shape-based damage assessment of carbon/epoxy composite beams. *Journal of intelligent material*, 18(3):189–208, 2007.

[8] P. Qiao, W. Lestari, M. Shah, and J. Wang. Dynamics-based Damage Detection of Composite Laminated Beams using Contact and Noncontact Measurement Systems. *Journal of Composite Materials*, 41(10), 2007.

[9] A. Offringa, J. List, J. Teunissen, and H. Wiersma. Fiber reinforced thermoplastic butt joint development. In *Proceedings of the International SAMPE*, 2008.

[10] Murata Manufacturing Co. Piezoelectric Ceramic Sensors. Technical report.

[11] N Stubbs and C.R. Farrar. Field Verification of a Nondestructive Damage Localization and Severity Estimation Algorithm. *Proceedings 13th International Modal Analysis Conference*, 1995.

[12] P.J. Cornwell, S.W. Doebling, and C.R. Farrar. Application of the Strain Energy Damage Detection Method To Plate-Like Structures. *Journal of Sound and Vibration*, 224(2):359–374, 1999.

[13] A. Alvandi and C. Cremona. Assessment of vibration-based damage identification techniques. *Journal of Sound and Vibration*, 292(1-2):179–202, 2006.