

Damage Localization and Uncertainty Analysis of Weld Cracks in Portal Steel Frame Based on Vibration and Electromechanical Impedance Technique

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ABSTRACT

Steel structures widely used in modern infrastructure development due to their fast assembly and easy of repair abilities, often rely on welded connections. However, these connections are prone to damage due to corrosion and dynamic loads, leading to progressive cracks and sudden structural failure. Hence, these connections should be continuously monitored for damage to ensure structural safety and sustainable use. Structural health monitoring methodologies using electromechanical impedance (EMI) have been proven to be useful and reliable techniques for evaluating the state of a structure at early stages of damage. These investigations uses strain gauge for acquiring vibration data, and PZT sensor for getting impedance data through electromechanical coupling. The test frame is a two-story asymmetrical steel portal frame with welded connections at the joints. The connections are subsequently damaged using a manual saw cut to simulate the crack in the welded connection. At first, the strain data has been recorded for healthy and various damage conditions. Damage localization, along with uncertainty quantification, has been implemented using vibration time history obtained from strain sensors. Subsequently, the conductance signature for healthy and different damage states has been monitored. Different statistical damage parameters like modified root mean square deviation (mRMSD) and Average Canberra Distance (ACD), and Discrete wavelet transform based parameters like wavelet coefficient mean, skewness, and kurtosis are calculated. These damage parameters are then used to formulate an objective function which is optimized using particle swarm optimization (PSO) for damage severity estimation, considering the uncertainty in conductance signatures. The depth of weld damage has been estimated accurately using the proposed methodology, considering the effect of uncertainty. The devised methodology achieved more than 90% accuracy in the severity estimation of the saw cut damage and can be used as a low-cost continuous SHM solution for steel frame structures.

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INTRODUCTION

Connections in steel structures are essential for load transfer and overall structural stability. They are typically formed using bolts, rivets, or welds. Welded joints in portal steel frames are critical stress concentration zones and are highly vulnerable to crack initiation and propagation due to cyclic loading, fatigue, and environmental factors. Early detection and accurate localization of such damages are essential to prevent structural failure. In recent years, vibration-based damage identification techniques, such as those using strain gauges [1] and electromechanical impedance (EMI) methods [2, 3], have been employed to assess structural health and evaluate the presence and severity of damage [4]. However, more rigorous investigations have been required for accurate damage localization in structural connections.

The present study combines a conventional strain based damage assessment technique with a modern identification method, namely Electromechanical Impedance (EMI), to develop an integrated approach for enhanced damage identification in weld connection of steel portal frame. Strain measurements provide global structural information, making them effective for damage localization. This localized damage information is then used to estimate damage severity by analyzing the impedance spectra. The key novelties of this investigation are as follows:

1. A novel fusion of global and local techniques has been developed to quantify and characterize the damage associated with strain and EMI based measurements.
2. A new multi-sensing based twostep damage detection approach using regularization methods and particle swarm optimization for accurate localization and estimation of weld crack damage severity.

METHODOLOGY

This section describes the methodology employed for the determination of damage severity and localization of weld crack damage in an asymmetrical steel portal frame. In this investigation, a dual sensing approach involving strain-based damage localization methodology and electromechanical impedance (EMI) based severity estimation have been carried out to assess the extent of the damage. Initially, the asymmetrical frame is instrumented (Fig.1(left)) using strain gauges and PZT (Lead Zirconate Titanate) sensors (Fig.1(right)) placed near the weld connections. For the generation of strain data, the frame is excited using an impact hammer to apply the impact load at the outer nodes of the frame (node 10, 16, 20, and 24). Furthermore, E4980AL LCR meter have been used for generation of impedance data. The impedance spectra is acquired using a Python script for storing impedance data at a fixed interval of frequency 5Hz to 500kHz. The strain data and impedance data obtained from the pristine and damaged states are then used to formulate a combined dual sensing approach using damage detection methodology like L1 regularization and particle swarm optimization. The L1 regularization is used for the determination of damage localization based on the change of strain in healthy and damaged states. Additionally, the damage severity estimation is achieved using different statistical and wavelet-based damage parameters obtained from the impedance data.

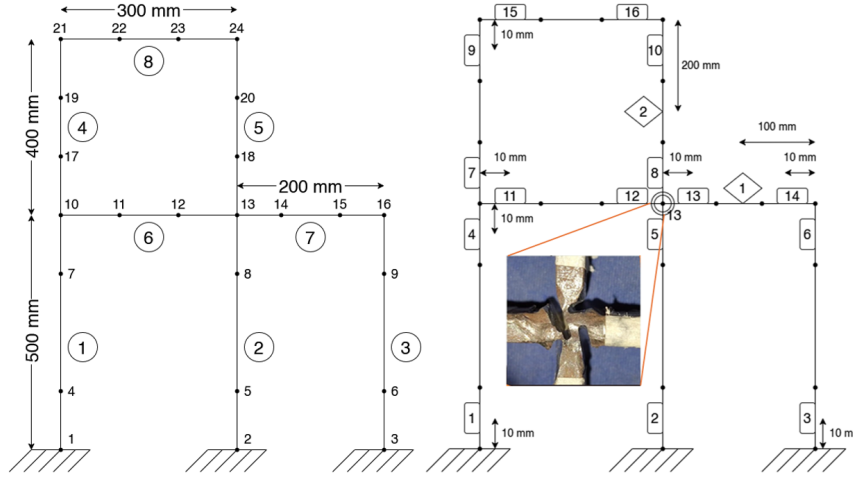


Figure 1. (left) Schematic diagram of the test frame (member numbers are given in circles), (right) weld connection damage and location of different sensors (strain gauges are denoted by rectangular boxes and PZT patches are shown by rhombus shaped boxes)

Analysis of dynamic strain

The response of a structure can be written in terms of its structural parameters in the following expression:

$$M\ddot{x}(t) + C\dot{x}(t) + Kx(t) = f(t) \quad (1)$$

where M is the mass matrix of the structure, C is the damping matrix, and K is the global stiffness matrix. Additionally, $\ddot{x}(t)$, $\dot{x}(t)$ and $x(t)$ represent the acceleration, velocity, and displacement responses of the structure due to the application of load $f(t)$. The strain response of the structure for a given loading condition can be linked with the displacement response as:

$$y = Hx + \epsilon \quad (2)$$

The experimental setup is given in 2, along with the employed strain gauge (near the weld connection at node 16) and PZT patch (PZT1, on member 7, between strain gauge 13 and 14).

Where y is the strain and H is the strain displacement relationship matrix. In this expression, noise is also included to account for perturbations arising due to environmental and man-made factors. Damage detection methodology as explained in [2] for formulating an inverse problem, which can be solved using the L1 regularization method for localization of the damage.

Regularization methods

These methods are generally used for finding an optimal solution to ill-posed problems. The inverse problems in the structural damage identification domain can be written in terms of a linear relation. These linear relations incorporate the Finite element variables and the instrumentation data in terms of large sparse matrices. These relations are generally over-determined and are ill-posed in nature. Specialized solution methodology



Figure 2. (left) Full experimental setup, (right) Enlarged image of employed strain gauge and PZT patch.

like regularization methods introduce additional constraints in the least squares solution for eliminating overfitting and instability of the solution. L1 regularization, or Least absolute shrinkage and selection operator (LASSO) introduces a one-norm penalty term in the least square solution, which encourages the algorithm to select the most important and influential variables and shrink the search space, thereby producing sparse results. The mathematical expression for L1 regularization can be written as

$$x = \arg \min_x (\| Ax - b \|_2^2 + \lambda \| x \|_1) \quad (3)$$

Where A and b are the matrices containing finite element variables and the strain vector, respectively. Theta is the variable containing the terms related to the percentage change in the stiffness of the members of the frame. The localization results obtained from this analysis are then used for damage severity estimation analysis using local sensing methods like EMI.

Electromechanical impedance

This method relies on the evaluation of the electrical impedance of the PZT patches. In this method, a single PZT patch works as both an actuator and receiver. As explained in the recent investigation [4], the electrical impedance of the sensor is affected by the change in the mechanical impedance of the structure by the following expression:

$$Z_e(j\omega) = \left[j\omega \frac{w_p l_p}{h_p} \left(\epsilon_{33}^T - \frac{Z_s}{Z_s + Z_p} d_{31} Y_{11}^E \right) \right] \quad (4)$$

The mechanical impedance of the structure is a function of the structural properties in terms of mass, damping, and stiffness. Relative changes in these quantities due to damage can be estimated using the relative change in the impedance spectra in healthy and damaged structures. In this investigation, different damage parameters like modified root mean square deviation (mRMSD), Average canberra distance (ACD) [6], Wavelet mean,

Kurtosis, and Skewness are considered for assessing the damage severity. An objective function is formulated between these damage parameters and damage severity, which has been optimized using particle swarm optimization [5].

EXPERIMENTAL SETUP AND ANALYSIS

The instrumented experimental setup, along with the sensors employed, is shown in Fig.2. The members of the frame are 20mm wide and 5mm deep. The test frame is a two-storey asymmetrical steel portal frame with eight members, has a total height of 900 mm and a total width of 500 mm. The Young's modulus of the steel member is 200 GPa with weight density as 7850 Kg/m³. In this instrumented structure, sixteen 5mm gauge TML strain gauge and two 10mm diameter PZT patches are placed near the weld connections for recording vibration and impedance data. Every strain gauge is placed 10 mm away from the nearest weld connections. Additionally, PZT1 is placed 100mm away, and PZT2 is placed 200 mm away from node 13 on members 7 and 5, respectively. The frame has been damaged by a manual saw cut of 1 mm, 2 mm, and 3mm depth at the weld connection at node 13.

The strain in healthy and damaged states is recorded and is used for formulating an inverse problem (equation 5), whose solution has been found using L1 regularization (equation 6).

$$\Delta y = A\Delta\theta + \epsilon \quad (5)$$

$$x = \arg \min_x (\| Ax - b \|_2^2 + \lambda \| x \|_1) \quad (6)$$

Furthermore, EMI spectra of the PZT patches are recorded for a frequency range of 5 Hz to 500 kHz with a frequency step of 100 Hz. This impedance data is given in terms of the real part or conductance and the imaginary part as susceptance. Different statistical parameters based on the conductance signal like mRMSD, ACD [6], and wavelet parameters like mean, kurtosis, and skewness are calculated. Mathematical expressions of these damage parameters are given below:

$$mRMSD = \sum \sqrt{\frac{(Re(Z_{ed}) - Re(Z_{eh}))^2}{Re(Z_{eh})^2}} \quad (7)$$

$$ACD = \frac{1}{N} \sum \left(\frac{|Re(Z_{ed}) - Re(Z_{eh})|}{|Re(Z_{ed})| + |Re(Z_{eh})|} \right) \quad (8)$$

$$\mu = \frac{1}{N} \sum_{i=1}^N w_i \quad (9)$$

$$k = \frac{E(x - \mu)^4}{\sigma^4} \quad (10)$$

$$s = \frac{E(x - \mu)^3}{\sigma^3} \quad (11)$$

These damage parameters are used for formulating a linear relationship (equation 12) between damage severity in terms of weld crack size, damage parameters, and relative

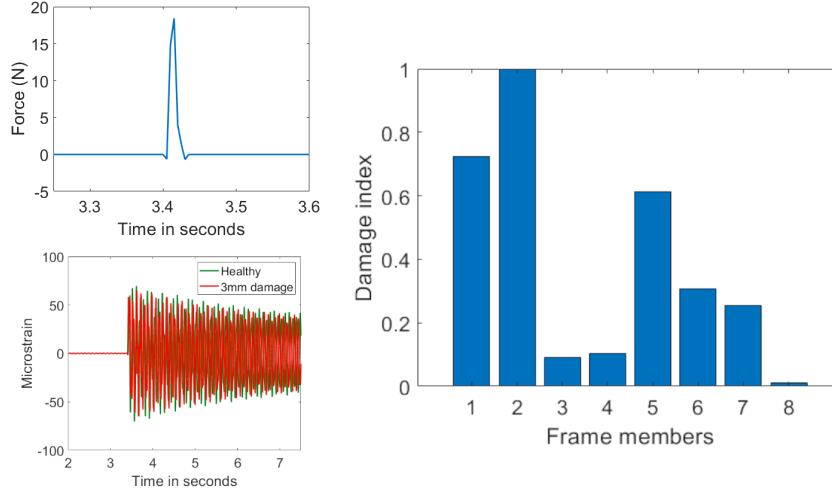


Figure 3. (left) Sample impact hammer loading applied at node 10 and its strain values reading for strain gauge sensor 1, (right) Damage localization results of L1 regularization.

location of the sensors with the weld connections.

$$DS = \alpha_1 DP + \alpha_2 DL + \alpha_3 DA + c \quad (12)$$

Where DS, DL, and DA are damage size, damage location, and damage angle with respect to the sensor, respectively. C is the linear relationship constant. The linear relations are written for each sensor and are combined to form an L2 norm objective function (equation 13), which has been solved using particle swarm optimization.

$$OF = \min \| abs(\alpha_1 DP + \alpha_2 DL + \alpha_3 DA + c)_1 + abs(\alpha_1 DP + \alpha_2 DL + \alpha_3 DA + c)_2 \|_2^2 \quad (13)$$

RESULTS AND DISCUSSION

In this investigation, the steel portal frame is excited using an impact hammer loading. A sample impact hammer loading with the corresponding time history of strain in healthy and 3mm damaged state has been presented in Fig. 3(left). The change in the strain values of healthy and damaged states is used for the localization of damage using L1 regularization. The result of the damage localization using regularization for 3mm damage case is given in Fig. 3(right). The regularization-based identification identified damage in members 1, 2, 5, 6, and 7. From Fig. 1, we can see that members 2, 5, 6, and 7 meet at node 13, thus, this approach correctly identifies the weld damage location with a false positive at member 1. This localization result is then used in the impedance-based damage severity estimation detection algorithm.

Initially, the impedance spectra for healthy and damaged states are collected, and the conductance signal (Fig.4 (left)) is extracted for further damage assessment analysis. The conductance plot for PZT1 with the enlarged plot for the frequencies between 206 kHz to 212 kHz is shown in Fig. 4 (right). These conductance signals are used to find

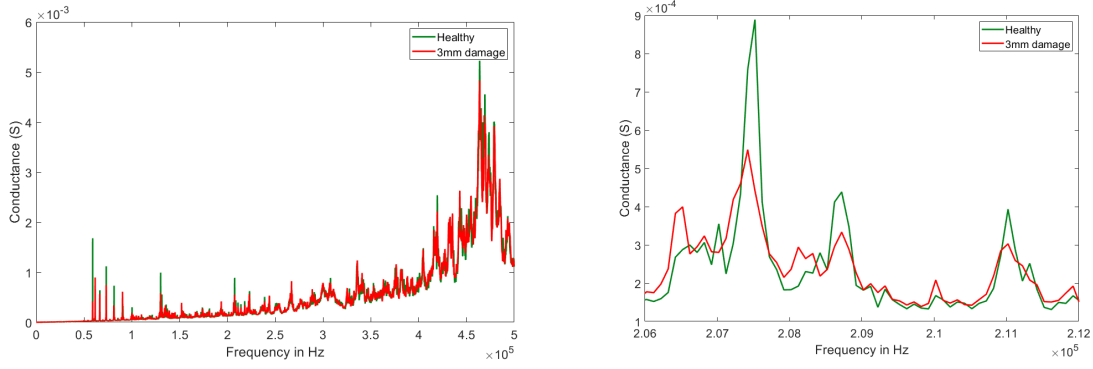


Figure 4. (left) Conductance frequency plot of PZT1 for 5 Hz to 500 kHz, (right) enlarged conductance frequency plot for 206 kHz to 212 kHz

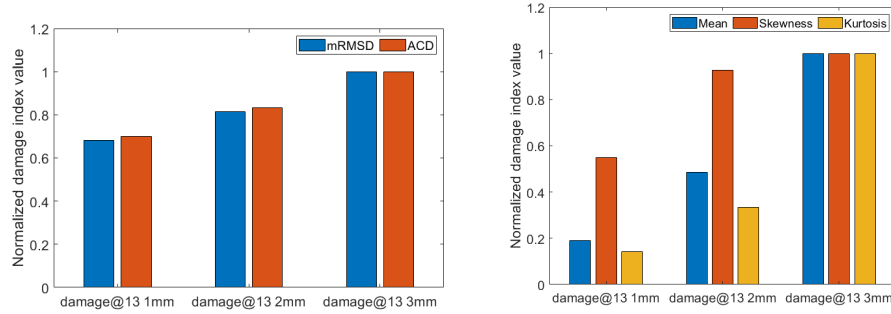


Figure 5. (left) Normalized statistical damage indices plot for different damage cases, (right) Normalized wavelet based damage parameter plots for different damage cases

different statistical and wavelet-based damage parameters. The normalized damage parameters plot for the healthy and the different damaged states is given in Fig. 5. Here normalized values of different damage parameters are shown as the individual values of different parameters have different scales of values, which might hide the trend in the damage parameter whose values are smaller. The damage parameters are showing a monotonically increasing trend as the damage increases in the frame. The change in the damage parameters is then used for optimization investigation. The damage location as obtained from the regularization, along with the respective damage parameter obtained from the related impedance spectra, is then used to find out the damage severity. A random white Gaussian noise is also added to the impedance data to check the effectiveness of the devised methodology. The result of the damage severity estimation using particle swarm optimization is given in Table I along with the relative error with the actual damage (3mm).

CONCLUDING REMARKS

The study demonstrated the ability of a dual-sensing approach to detect and localize weld damage in steel structures. The damaged weld location can be deduced by looking at Fig. 1 and finding the node where all the identified members are connected. The major conclusion drawn from this investigation can be stated as follows:

TABLE I. DAMAGE SEVERITY ESTIMATION RESULTS FROM PARTICLE SWARM OPTIMIZATION

Damage parameter	Identified damage severity (% error)
mRMSD	2.7997 mm (6.6753 %)
ACD	3.2866 mm (9.5540%)
Wavelet mean	2.7473 mm (8.4223%)
Kurtosis	2.6883 mm (10.3896%)
Skewness	2.6637 mm (11.2091%)

1. The normalized EMI-based mRMSD and ACD, wavelet mean, kurtosis, and Skewness damage indicators are growing as the damage level increases.
2. The regularization-based localization approach reliably identified the damage at node 13 by detecting damage in members 2, 5, 6, and 7.
3. All the damage parameters provide good results in identifying the damage severity. The statistical parameters performed well and achieved more than 90% accuracy in estimating the damage severity. Similarly, the wavelet mean achieved 92% accuracy and performed better than other wavelet-based damage parameters.

The investigation can be further extended to multiple damage locations to evaluate the methodology's effectiveness in detecting distributed damage within the structure.

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