Vibration Based Damage Identification in Welded Asymmetrical Steel Frames Using Regularization Techniques

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ABSTRACT

The damage identification problem for a frame structure can be formulated in a linear equation in the form $A\theta = b$. In this formulation, matrix A represents the FE model parameters, vector θ represents the change in state variables or the mathematical parameters which are to be determined, and vector b represents the response to an external excitation. In the real test case, the matrix A can be rectangular, and the linear relation is an over-determined and ill-posed problem. The results of these ill-posed problems are non-continuous and thus require special solution techniques like regularization techniques for getting a solution. This study is aimed at damage identification based on the vibration analysis of asymmetrical multistory plane frame structures with welded joints. Time-domain response analysis assisted by various regularization techniques is used to identify the damage in the portal frame structures, which is caused due to loss of stiffness. Initially, the effectiveness of the regularization method is examined by considering a one-story steel frame with welded connection, which is then analyzed analytically with FE formulation by simulating single damage cases. The analysis has been extended for an instrumented multistory asymmetrical plane frame structures for single damage cases with static analysis. Various regularization techniques like L_2 regularization or Least absolute shrinkage and selection operator (LASSO), L_1 regularization, elastic net regularization, and linear regression are used to study their effectiveness in the damage identification without doing model updating of the numerical model. In the study, the L_2 regularization gives better results than other methods for a single damage case. The damage identification in asymmetrical steel frames needs to be better studied, and this study can be replicated for more complex steel structures for real-life damage scenarios. This can be developed as a real-time standalone early warning system for important steel frame structures, thus ensuring their timely maintenance and continuous sustainable use.

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INTRODUCTION

Steel-framed structures are preferred in the construction industry for faster fabrication and installation. These structures cater to the increasing infrastructure in demand but are susceptible to damage due to corrosion, fatigue, buckling, loosening of bolts [1] and welding defects. This demands continuous or periodic health monitoring of these structures for their sustainable use. This continuous assessment of structure for identification and localization of damage in a structure needs integration of sensors in the design to get information about the current status of the structure. Continuous health monitoring of civil structures has gained much interest in recent times to avoid capital and human lives loss due to the failure of the structure.

The real-time data from sensors can be assimilated into a governing equation and measurement equation with appropriate assumptions to get an estimate of the location and severity of the damage in the structure. However, the continuous incoming data make these inverse problems highly overdetermined and ill-posed [2]. These problems require specialized techniques [3] for their solution to get a stable and continuous solution.

The damage identification problem for a structure can be simplified as an overdetermined ill-posed linear problem. To solve such an equation, standard methods like generalized inverses [4] factorization do not give unique and continuous results. However, special methods like regression analysis and regularization are used to get an optimized result. Ill-posed problems [2] can be defined as problems, which do not have a unique solution, and a small perturbation in input data can cause a large perturbation in the output or solution. To limit non-unique, and non-continuous behavior, regularization technique is used in which a penalty term is introduced in addition to the least square method [3] to get an optimized solution. This method was then extensively used in literature [5] to get the damage identification results. However, the damage in a structure is generally confined to certain locations; thus, the damage identification method's solution has a sparse solution. The L_2 or Tikhonov regularization gives a smooth solution; however, a more feasible sparse solution can be achieved by exploiting the sparsity of the solution. In recent publications [6], authors have started to employ L_1 norm-based regularization term for getting a sparse solution. A comparison of Tikhonov regularization and L_1 regularization was extensively studied in [5], and the authors found that sparse or L_1 regularization is more effective in localizing and identifying damage than L_2 regularization.

In recent literature, model updating has been extensively used in damage identification algorithms [1, 5, 7]. However, in present study, the difference in the instrumentation value from the model and simulation is assumed as additive noise. Different regularization techniques' effectiveness in localizing and identifying the damage was studied. There are very few literatures on damage identification of asymmetrical frames [7]. In this regard, preliminary analysis for single damage identification for asymmetrical frames with comparative analysis of regularization techniques is conducted. This analysis has shown that the model updation is not a prerequisite for single damage analysis and can be achieved based on the difference in vibration data from healthy and damaged structures generated by multiple static excitation cases.

This investigation focuses on the applicability of different regularization techniques and their comparative analysis without doing any model updating of the analytical model. The stiffness reduction due to the change in cross-section is assumed as the damage.

Damage identification algorithms are applied on a single-story frame and an asymmetrical plane frame structure with single damage cases. Detailed discussion on methodology, results, and conclusion are given in subsequent sections.

METHODOLOGY

The equation of motion for a simplified structure with applied load can be written as

$$KX = F \tag{1}$$

where, K is the frame's global stiffness matrix, F is a vector of nodal load values, and X is the system's response. The damage in the structure can be represented as the change in the stiffness of the individual local stiffness matrices, which will reflect in the global stiffness matrix and alter the structure's response. The structure's response can be found using sensors or instrumentation like strain gauges and LVDTs. These sensor values can be used in formulating the measurement equation. For this analysis, the change in stiffness can be represented as the change in the state variable. The healthy state variables can be represented as θ_0, and the damaged state variable can be represented as θ, where $\theta = \theta_0 + \Delta\theta$. The $\Delta\theta$ is the change in the state variable due to the introduction of damage in the structure. The measurement equation for the frame for the applied instrumentation can be written as

$$y = HX + \epsilon \tag{2}$$

where, y is the value obtained from sensors, H is a matrix relating the displacement and sensor data, and ϵ denotes the noise due to various sources. The measurement equation can be written for healthy and damaged states with θ as a state variable.

$$y(\theta_0) = H(\theta_0)X(\theta_0) + \epsilon(\theta_0) \tag{3}$$

$$y(\theta) = H(\theta)X(\theta) + \epsilon(\theta) \tag{4}$$

The equation 4 can be expanded using the Taylor series, by considering only first-order terms and substituting expression from equation 3 will yield the following expression:

$$\Delta y = \sum_{i=1}^{r} \left[\frac{\partial H}{\partial \theta} X(\theta_0) + H(\theta_0) \frac{\partial X}{\partial \theta} \right] \Delta\theta_i + [\epsilon] \tag{5}$$

The same equation can be written for p loading scenario in the form

$$\begin{bmatrix} \Delta y^1 \\ \Delta y^2 \\ \vdots \\ \Delta y^p \end{bmatrix}_{p.s\times 1} = \begin{bmatrix} A_1^1 & A_2^1 & \dots & A_r^1 \\ A_1^2 & A_2^2 & \dots & A_r^2 \\ \vdots & \vdots & \ddots & \vdots \\ A_1^p & A_2^p & \dots & A_r^p \end{bmatrix}_{p.s\times r} \begin{bmatrix} \Delta\theta_1 \\ \Delta\theta_2 \\ \vdots \\ \Delta\theta_r \end{bmatrix}_{r\times 1} + \begin{bmatrix} \epsilon^1 \\ \epsilon^2 \\ \vdots \\ \epsilon^p \end{bmatrix}_{p.s\times 1} \tag{6}$$

$$\big[\Delta y\big]_{p.s\times 1} = \big[A\big]_{p.s\times r} \big[\Delta\theta\big]_{r\times 1} + \big[\epsilon\big]_{p.s\times 1} \tag{7}$$

where, superscripts in equation 6 represent independent loading cases from p loading cases. Subscript s denotes the number of instrumentation, and r represents the number of damage parameters to be identified. Equation 6 can then be written in the form of a linear relation between instrumentation reading and structure parameters and noise terms in the form of equation 7.
These linear equations are ill-posed and overdetermined with rectangular matrices and thus cannot be solved by traditional methods like inverting a matrix. In this study, the regularization methods like Tikhonov regularization or L_2 regularization, L_1 regularization, and Elastic net regularization along with linear regression are used, and their results are compared for single damage scenarios.

NUMERICAL MODELLING AND ANSLYSIS

The numerical finite element models for the frame were made in MATLAB, and corresponding models were simulated in ANSYS 2020. For this analysis, a single-story steel frame with welded joints along with an asymmetric frame with welded connections is considered. In the single-story steel frames with welded joints, nine strain gauges are employed, whereas, in the asymmetric frame, a single strain gauge was present at the center of the members. The healthy state strains at predefined locations are computed for the same value of loads in MATLAB and ANSYS.

For the generation of the dataset in single-story steel frame, eight loading episode of mid-load in the beam and eight loading episodes of the side load is simulated using ANSYS. Similarly, five static loading episodes at different nodes are considered for the asymmetric frame. The damage is then introduced to the ANSYS models to get the strain values for predefined loading conditions in the damaged condition. In this method, no model updating was done, and the strain values from the ANSYS model were directly used as an input in the regularization technique to observe its effectiveness in localizing and quantifying the damage.

The schematic details of the single-story welded frame and the independent loading episodes location used in this model are shown in figure 1. The members of the single-story frames were assumed to be 20 $\times$ 5 mm, Column height = 406 mm, Beam length = 250 mm, and Young's modulus = 2.1 Gpa. The abovementioned sizes were chosen as the steel frames with those dimensions were available in the laboratory, which can be used for experimental validation.

For the damage identification study in single-story frame, two single damage scenarios are simulated, refer to table I.

TABLE I. DAMAGE SCENARIOS FOR SINGLE-STORY STEEL FRAME

Damage case	Element (Nodes)	Damage description
Damage 1	1 (1-2)	10 mm wide, 1 mm deep damage at mid
Damage 2	6 (6-7)	12.5 mm wide, 1 mm deep damage at 68 mm away from node 6

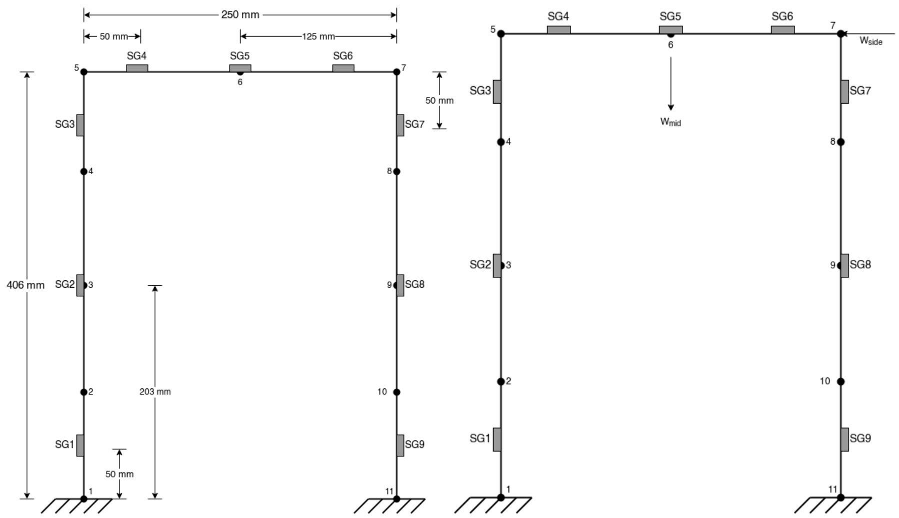

Figure 1. (left) Schematic diagram for single-story welded frame, instrumented with 9 strain gauges (grey boxes on members); nodes are denoted as black dots at the ends of the members, (right) Location of application of loads for different independent loading episodes, mid loads are applied on node 6, whereas the side loads are applied on node 7.

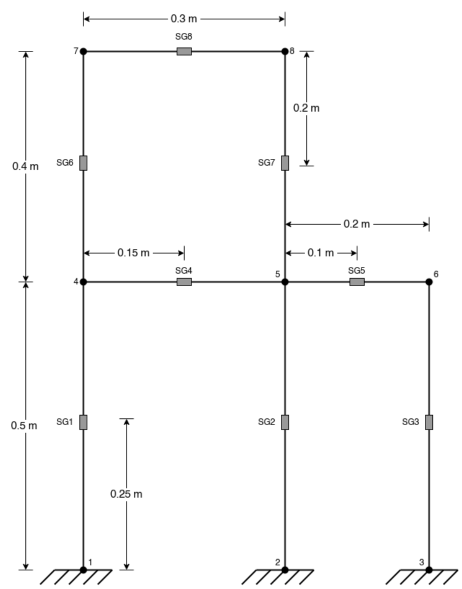

Figure 2. Schematic diagram for asymmetrical steel frame with welded connection, instrumented with 8 strain gauges (denoted by grey rectangles) at the mid of members; nodes are denoted as black dots at the ends of the members.

The schematic details of the asymmetrical frame with welded connections used in this analytical study are shown in figure 2. The members of the single-story frames were assumed to be of the cross-section 20×5 mm, and Young's modulus = 2.1 Gpa.

For the damage identification study in asymmetrical frame, two single damage scenarios were simulated, refer to table II.

TABLE II. DAMAGE SCENARIOS FOR ASYMMETRICAL STEEL FRAME

Damage case	Element (Nodes)	Damage description
Damage 1	2 (2-5)	1mm depth reduction for entire column
Damage 2	5 (4-5)	0.5mm depth reduction for entire beam

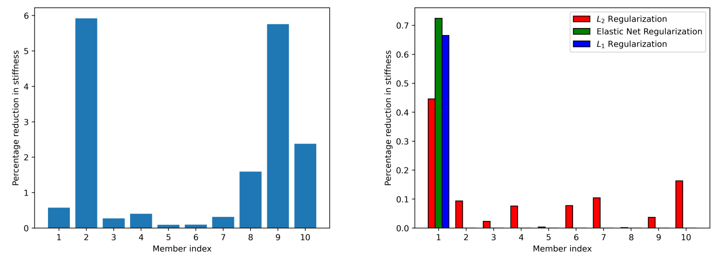

Figure 3. Damage identification result for single-story frame; 1 mm reduction in depth of 10 mm width for member 1 (Node 1-2) (left) Linear regression, (right) L_2, Elastic net, and L_1 regularization

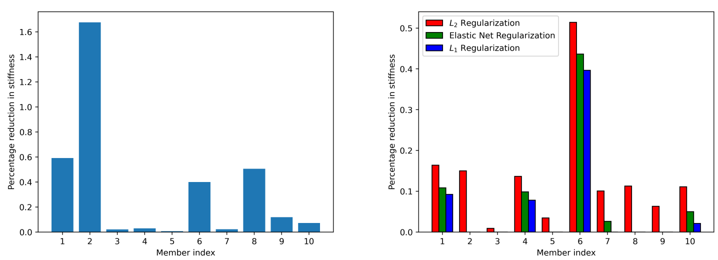

Figure 4. Damage identification result for single-story frame; 1 mm reduction in depth of 12.5 mm width for member 6 (Node 6-7) (left) Linear regression, (right) L_2, Elastic net, and L_1 regularization

DAMAGE IDENTIFICATION RESULTS AND DISCUSSION

This analysis was conducted for various locations of different kinds of damages (refer table I and II) in the example problems of single-story steel welded frame (figure 1) and asymmetrical steel frame with welded connection (figure 2).

The performance of considered algorithms for the first damage case (refer table II) for single-story welded steel frame are combined in figure 3. Similarly, the results are combined in figure 4 for the second single damage case. In both the damage identification analysis, it can be observed that linear regression can not be used for localization and identifying the damage.

The performance of considered algorithms for the first damage case (refer table II) for asymmetrical steel frame are combined in figure 5. Similarly, the results are combined in figure 6 for the second single damage case. The results show that the number of false positives in L_2 regularization is more than L_1 and Elastic net regularization. As L_1 regularization imparts sparsity behavior in the model; it can identify damage more clearly

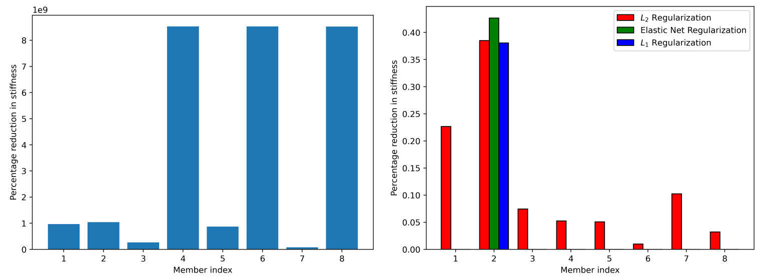

Figure 5. Damage identification result for asymmetrical frame; 1 mm reduction in depth for member 2 (Node 2-5) (left) Linear regression, (right) L_2, Elastic net, and L_1 regularization

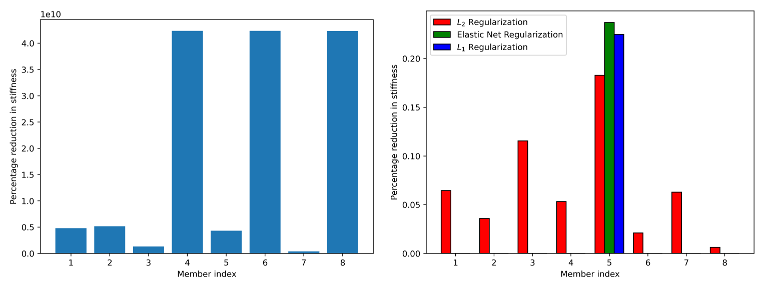

Figure 6. Damage identification result for asymmetrical frame; 0.5 mm reduction in depth for member 5 (Node 4-5) (left) Linear regression, (right) L_2, Elastic net, and L_1 regularization

than other methods. The effect of introducing sparsity in the algorithm is also evident in elastic net regularization, which incorporates both L_2 and L_1 regularization. The L_2 regularization tries to give a smooth solution, whereas L_1 regularization tends to remove less impactful variables and gives a sparse solution.

CONCLUDING REMARKS

Model updating is an important step for many damage identification algorithms. This enables numerical model to incorporate the behaviour of original test setup, which gives a good identification of damage. However, this analysis have shown that for single damage case in asymmetric steel welded frames, model updating can be skipped, and regularization techniques alone can identify the damage. From this comparative analysis of different regularization and regression algorithm following remarks can be made

1. For a single damage identification case, model updating is not a prerequisite.
2. Sparse and Elastic net regularization identified the damage with lesser false positives.
3. Tikhonov regularization yielded many false positives for asymmetrical structure compared to sparse and elastic net regularization results.

4. Linear regression should not be used for damage identification for complex structures and should be replaced with specialized methods like regularization for better damage identification. The effect of sparsity and the ill-posed nature of the problem on damage identification can be seen in the results.

5. For the damage identification for asymmetrical frame structure, L_1 and elastic net regularization may be used for further analysis with multiple damage cases.

FUTURE SCOPE

This study can be extended to more complex asymmetrical frame geometries, with validation study on actual lab and field tests. The ability of the above algorithms on multiple damage cases can also be analyzed.

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