Parameter Estimation of a Frame Structure Based on Static Displacement Measurements

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***Abstract*—An analytical method is investigated to identify the damage of a frame structure from static displacement measurements. This method is to adjust the parameters of the frame structure to match the analytical and measured displacements. Based on a set of applied static forces and static displacement measurements of the frame structure, the damage condition of the frame structure can be obtained by optimizing the objective function. In addition, the effect of the number of displacement sensors on the parameter identification was studied using parameter identification of a two-story steel frame structure. This method can accurately identify the damage of the frame structure using limited displacement measurements.**

***Index Terms*—frame structure, parameter identification, displacement measurement**

I. Introduction

Detecting the health of and identifying the damage to a structure in a timely manner is critical for structural safety. With the development in sensor manufacturing technology, many new techniques for structural-damage identification using different types of structural response have been developed. These identified damages to the structure using these techniques can be divided into two methods based on the dynamic [1] and static [2] responses.

According to the static-response data, Sanayei et al. [3] proposed a method for detecting the damage condition of truss and frame structural elements. Hajela et al. studied the structural damage detection method based on static responses and modal Analysis [4]. Chou et al. presented a structural damage technique to identify the changes in the characteristic properties of structural members using static measurements of displacements [5]. Bakhtiari-Nejad et al. presented a structural damage detection algorithm based on static test data, that relate the changes in the static response to the location and severity of the damage [6]. Kesavan et al. analyzed the damage criticality assessment method in complex geometric structures using static strain response-based signal processing techniques [7]. Chen et al. proposed a new structural damage identification technique using limited test static displacement based on grey system theory, that is used to locate damage in the structure and identify the damage magnitude [8]. Kaushik et al. introduced the details of the numerical studies carried out on the application of the damage locating vector method for damage localization using deflection data from the static analysis [9]. Li et al. presented a static-based method for damage identification in the simply supported beam structure based on the incomplete measured static displacement parameters [10]. Colombo et al. proposed a methodology to perform structural health monitoring leveraging the inverse finite element method and numerically demonstrated using a structure subjected to fatigues crack damages [11]. Tian et al. proposed a damage identification method based on static strain responses using Fiber Bragg Grating in a wind turbine blade and verified the accuracy and effectiveness of the proposed method [12]. Xiao et al. investigated the optimal placement of static strain sensors for structural-damage identification and analyzed the identification effects of different optimization methods [13, 14]. Lozano-Galant et al. presented an observability technique to identify structural parameters in cable-stayed bridges by using static monitoring information [15]. Adbo [16] analyzed the relationship between damage characteristics and changes in displacement curvatures and applied it to the damage identification of beams. Using static test data, Yang et al. [17] proposed a parameter identification method to identify the location and extent of structural damage. Sohail et al. presented an approach to identify the change in structural parameters of flexural rigidity of a frame model using few response measurements [18]. Liao et al. [19] presented a method for finite element model updating based on the quasi-static generalized influence line of the structure. These studies have obtained the damage condition of structural elements using static test data and enriched the damage identification studies based on static measurements.

To obtain the overall damage condition of a structure, Seyed et al. proposed a two-stage approach for damage identification of two-dimensional frame structures based on the dynamic response [20]. Yang et al. investigated structural-damage identification methods using static and dynamic data [21]. Jamalkia et al. proposed a fuzzy-based damage identification method based on the dynamic response of the floating wind turbine structure [22]. Lee et al. presented a damage detection method based on the second derivative of flexibility estimated from

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incomplete mode shape data [23]. Lofrano et al. studied optimal sensors placement method in dynamic damage identification of beams based on a statistical approach and verified the capability and reliability of the method [24]. Cheng et al. proposed an innovative two-level damage identification technique applicable to real-world online structural health monitoring systems for in-service large steel arch bridges [25]. Meixedo et al. presented an unsupervised automatic data-driven methodology to detecting damage in railway bridges based on traffic-induced dynamic responses [26]. Pooya et al. proposed an efficient and novel method for parameter identification in beam-like structures solely based on damaged structure data and using mode shape curvature estimation [27]. Khosravan et al. developed a novel method called the improved modal strain energy decomposition method to detect structural damage of jacket-type offshore platforms using a limited number of sensors just above the water [28].

For the parameter identification based on static responses, these methods were designed to provide comprehensive structural information and optimization methods. In the damage-identification process, the number of sensors are also important factors that affect the efficiency of the parameter identification and need further research.

The present study analyzed a parameter-identification method for frame structures based on static-response data. The effect of the number of displacement sensors and their arrangements on the damage identification was analyzed using parameter identification of a two-story steel frame structure.

II. Objective Function for Parameter Identification

Constructing the objective function is a key factor in structural parameter identification. In this study, applied static forces were used to excite the frame structure, and the measured displacements were calculated based on the "as-is" condition. Then, the analytical displacements were obtained using the stiffness method, which contained unknown parameter p that required to be updated [13, 29]. Objective function $f(p)$ is defined based on the analytical and measured displacements.

$$f\left(p\right) = \sum_{i=1}^{n} (\mathrm{D}_a{}^i - \mathrm{D}_m{}^i)^2 \tag{1}$$

where p (including the cross-sectional area A and moment of inertia I, which reflect the axial and bending rigidity that represent the deformation resistance of the frame structure) represents the unknown parameters of the damaged frame structure. D_a is the analytical displacement, and D_m is the measured displacement. n is the total number of measured displacements used to identify the structural damage. Unknown parameters A and I can be obtained when the objective function approaches zero.

III. Parameter Identification for a Frame Sample

To more clearly illustrate the parameter-identification method of the frame using the static measured displacements, the frame structure shown in Fig. 1 is analyzed. All frame "as-built" conditions have cross-sectional areas of A = 2.56 × 10^{-2} m^2 and a moment of inertia of I = 5.46133 × 10^{-5} m^4. The modulus of elasticity is 206 GPa. Let us assume that damage exists in Member 2. The "as-is" cross-sectional areas and moment of inertia of Member 2 are unknown and required to determined. The "as-is" cross-sectional areas and moment of inertia are shown as dotted lines in Fig. 2, Fig. 3, and Fig. 4.

This study uses applied forces of 100 and -150 kN along 4 and 11 degrees of freedom to excite the structure. Three cases are selected in the measured displacement combinations for parameter identification in this study. The measured displacement combinations for Case 1 are along the 1 and 4 degrees of freedom; those for Case 2 are along the 1, 4, 10, and 11 degrees of freedom; and those for Case 3 are along the 1, 4, 7, 8, 10, 11, 13, and 16 degrees of freedom.

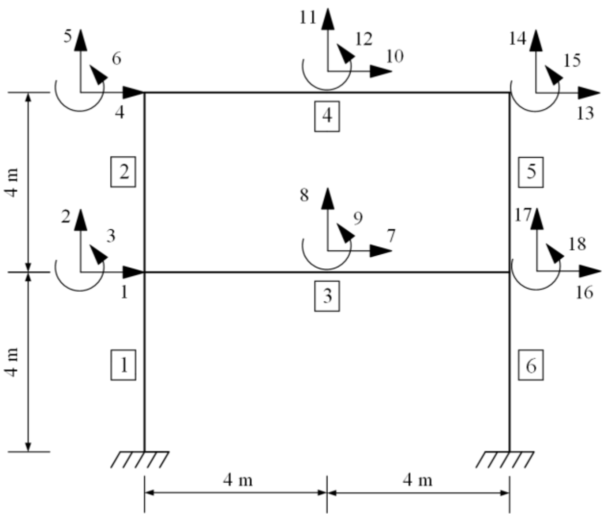
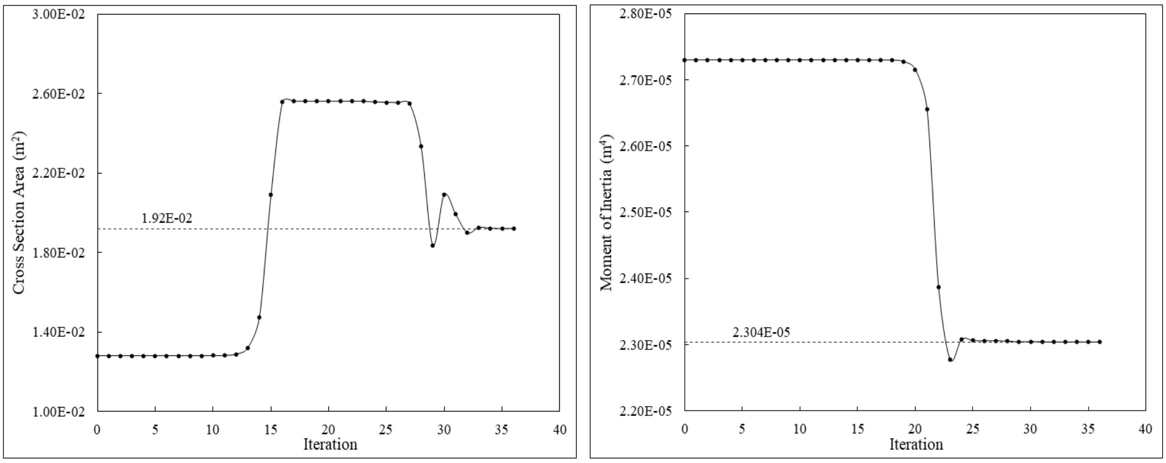


Figure 1. Frame sample for parameter identification

The objective function for the parameter identification can be obtained from Equation (1), and the interior-point method is used to optimize the objective function to obtain the damage condition of the frame. In this study, the starting points of cross-sectional variable A and moment of inertia variable I are 1.28 × 10^{-2} and 2.73 × 10^{-5}, respectively. The constraints on A are set between 0 and 2.56 × 10^{-2}, and those on I are set between 0 and 5.46133 × 10^{-5} according to the "as-built" condition and optimization method.

Fig. 2 shows the changes in A_2 and I_2 during the optimization process for Case 1. The horizontal axis represents the iteration steps, while the vertical axis represents the values of A_2 and I_2. Figure. 2(a) and Figure. 2(b) reflect that the process of searching the cross-sectional area and moment of inertia of the frame's damaged member using the interior point method, respectively.

The final results for the identification of the cross-sectional area and moment of inertia of the frame's damaged member are 1.28×10^{-2} m^2 and 2.304×10^{-5} m^4, respectively. The results show that the final optimal value of A and I are identified and consistent with the "as-is" condition.



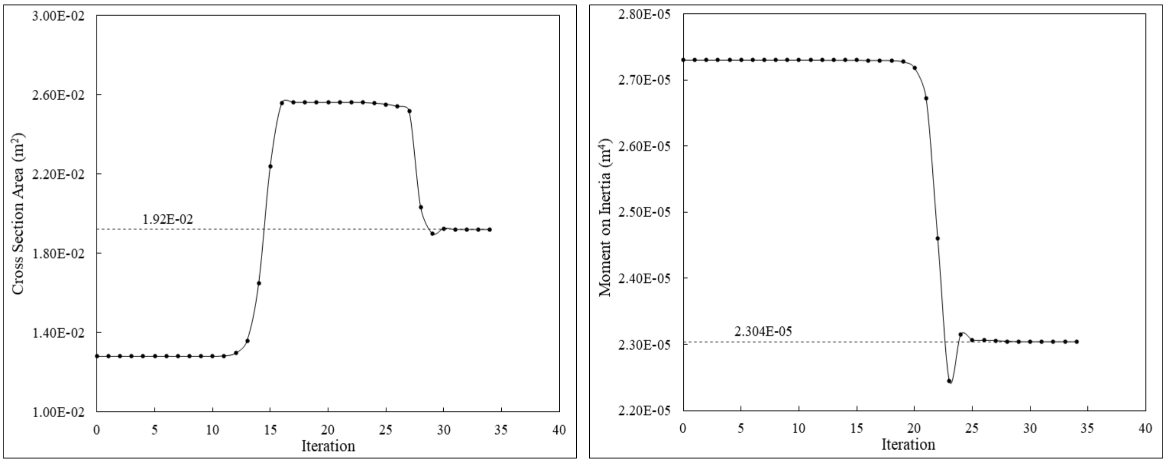
(a) Cross-sectional area

(b) Moment of inertia

Figure 2. Function of the iteration for Case 1

Fig. 3 illustrates the plots of A_2 and I_2, which is the cross-sectional areas and moment of inertia of damaged member, as a function of the iteration for case 2. The horizontal axis represents the iteration steps, while the vertical axis represents the values of A_2 and I_2. The process of searching the cross-sectional area and moment of inertia of the damaged member using the interior point method are shown in Figure. 3(a) and Figure. 3(b), respectively.

The cross-sectional parameters of the frame's damaged member are 1.28×10^{-2} m^2 and 2.304×10^{-5} m^4, respectively. The results indicate that the final optimal value of A and I are identified and consistent with the "as-is"condition.



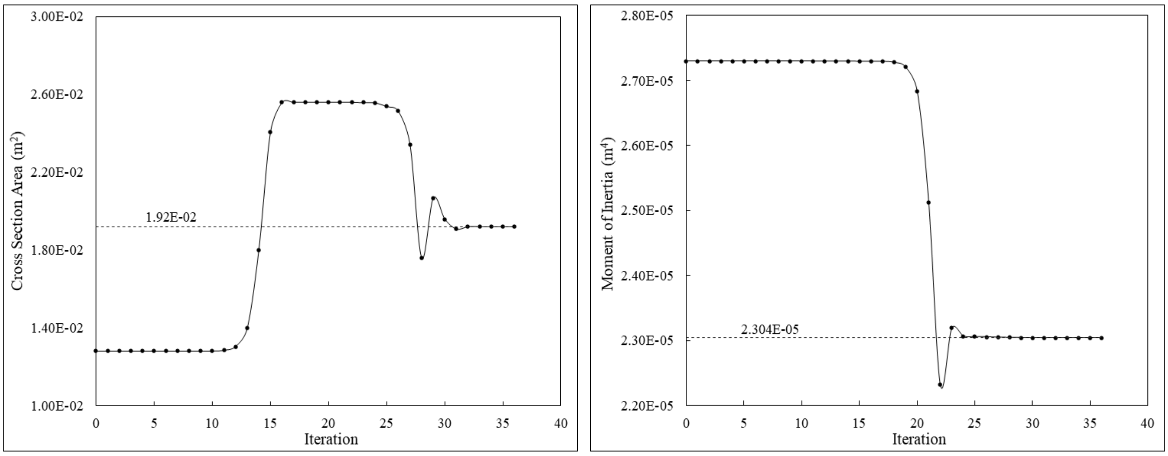
(a) Cross-sectional area

(b) Moment of inertia

Figure 3. Function of the iteration for Case 2

The changes in A_2 and I_2 during the optimization process for Case 3 is displayed in Fig. 4. The horizontal axis represents the iteration steps, while the vertical axis represents the values of A_2 and I_2. Fig. 4(a) and Fig. 4(b) show that the process of searching the cross-sectional area and moment of inertia of the frame's damaged member using the interior point method.

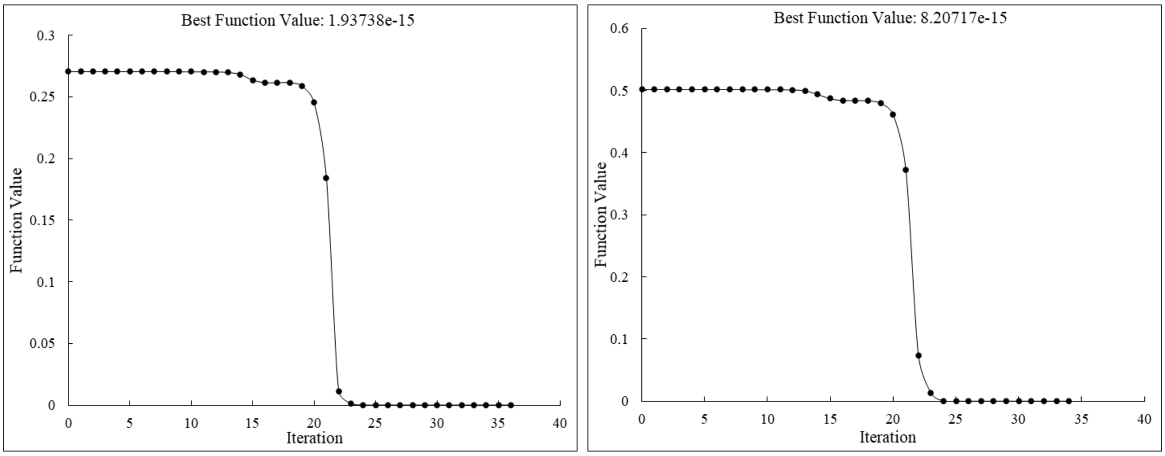
The cross-sectional area and moment of inertia of the frame's damaged member are 1.28×10^{-2} m^2 and 2.304×10^{-5} m^4. The identification results show that the final optimal value of A and I are identified and consistent with the frame's "as-is" condition.



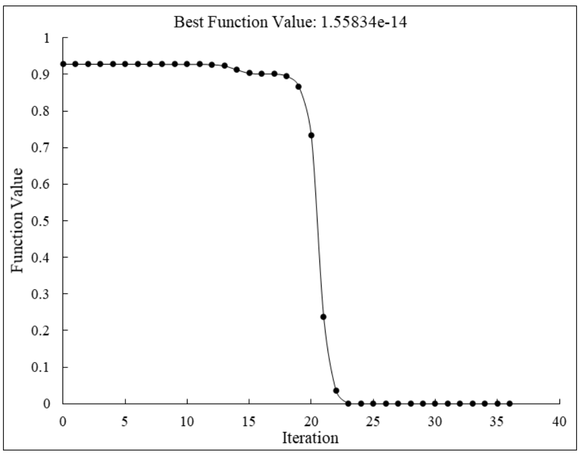
(a) Cross-sectional area (b) Moment of inertia

Figure 4. Function of the iteration for Case 3

The changes in function value during the optimization process for Cases 1–3 are shown in Fig 5(a), Fig 5(b), and Fig. 5(c), respectively. With the process of optimization, the function value of the objective function gradually decreases to the best function value. The best function values are 1.93738×10^{-15}, 8.20717×10^{-15}, and 1.55834×10^{-14}, respectively. For Cases 1–3, the best function value of the objective function becomes larger with the increase of the number of frame's measured displacements.



(a) Function value for Case 1 (b) Function value for Case 2



(c) Function value for Case 3

Figure 5. Function value for Cases 1–3

As can be seen from Figs. 2–5, The numbers of iteration steps for Cases 1–3 are 36, 34, and 36, respectively, which means that adding a large number of frame's measured displacements does not significantly improve the parameter-identification efficiency.

IV. Conclusions

In this study, the parameter-identification method for a frame structure was analyzed using static displacement measurements. The structural parameter identification requires sufficient measured displacement data, but when the parameter identification is successful, adding more measured displacements does not significantly improve the optimization efficiency. Further, the number of the sensors should be optimized before the installation.

Conflict of Interest

The authors declare that they have no conflicts of interest.

Author Contributions

Weiwei Zhu and Feng Xiao conceived and designed the experiments; Weiwei Zhu analyzed the data; Weiwei Zhu wrote the paper. All authors had approved the final version.

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