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A Rapid Post-earthquake Structural Damage Identification Method Based on Mode Shape Ratio Using Pattern Matching

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Abstract: This paper proposes a rapid identification method for post-earthquake structural damage based on mode shape ratio using pattern matching. In the first stage, the characteristic vector of mode shape ratio is calculated by modal analysis from the modal information of various damage scenarios to establish a pattern database. A small number of dynamic signals are collected for extracting the modal information to obtain the characteristic vector which is treated as the test pattern. Then the similarity between the test pattern and the pattern in the database is calculated using the Euclidean distance (ED). The damage location and severity of the measured structure are treated the same as the pattern corresponding to the minimum value of ED so that the damage is identified. Numerical simulations verify that the proposed method can well identify the damage. In addition, the matching results based on different sensor combinations demonstrate that the method can quickly identify the damage even using a limited number of sensors. The proposed method can provide support for the government to make a rapid post-earthquake emergency decision.

Key words: pattern matching; mode shape ratio; Euclidean distance; damage identification

1. Introduction

Earthquake disasters come in a sudden and unexpectedly, causing massive housing and building collapse, human casualties, and huge economic losses. Therefore, rapid identification of damage and assessment of post-earthquake damage grade can provide a scientific theoretical basis for the government to make an emergency decision and rescue after a post-earthquake, which can minimize human casualties and economic losses.

With the progress of science and technology, many structural damage identification methods have been developed. there are different classifications for different criteria. For example, according to the different signal identification domains, traditional damage identification methods can be divided into frequency-domain analysis methods, time-domain analysis methods, and time-frequency domain analysis methods.

However, the traditional structural damage identification methods cannot achieve rapid identification of post-earthquake damage to housing complexes. In this paper, a rapid post-earthquake structural damage identification method based on mode shape ratio using pattern matching is proposed innovatively.

At present, there are few studies in the field of structural damage identification using pattern matching methods, among which, the method to achieve better identification results has the following problems: (1) A large number of sensors are required; (2) The characteristic vector belongs to the time domain or is related to the excitation. It is impossible to establish a more comprehensive damage pattern database due to the stochastic nature of the response and excitation.

Based on the above reasons, only related to the modal information of the structure, the mode shape ratio is taken as the characteristic vector in this paper. In the process of pattern matching, the Euclidean distance (ED) is used to measure the similarity of the vectors. The damage of the corresponding pattern is consistent with the tested structure based on the minimum value of ED. Then the damage grade of the post-earthquake structure is evaluated by Table 1. The feasibility and accuracy of the proposed method are verified by numerical simulation of a simply supported four-story frame structure model.

Table 1. Different damage grades for damage index

Damage grade	Intact	Slight	Moderate	Severe	Collapse
Damage index	0-0.1	0.1-0.3	0.3-0.55	0.55-0.85	0.85-1.0

2. Experimental Study

2.1 Mode shape ratio

In this article, the sum of squares of the mode shape ratio of the first two orders is proposed to be used as the characteristic vector for pattern matching, with the following expression:

$$\alpha = \left(\frac{\emptyset_1^d}{\emptyset_1^u}\right)^2 + \left(\frac{\emptyset_2^d}{\emptyset_2^u}\right)^2 \qquad (1)$$

where $\emptyset_1^{\mathrm{u}}$ and $\emptyset_1^{\mathrm{d}}$ are the first-order mode shapes of the structure before and after the damage, respectively. $\emptyset_2^{\mathrm{u}}$ and $\emptyset_2^{\mathrm{d}}$ are the second-order mode shapes of the structure before and after the damage, respectively.

From the above equation, it can be seen that the damage can be identified by obtaining only the first two orders of mode shape information of the structure.

2.2 Pattern matching

There are various methods to measure the similarity in the process of pattern matching. The ED has a wide range of applications, therefore it is used in the paper. The ED between the test pattern, the unknown damage case (vectors x), and the pattern in the database (vectors y) is written as:

$$\boldsymbol{ED}^q = \left(\sum_{i=1}^{n} \left|\mathrm{x}_i - y_i^q\right|^2\right)^{\frac{1}{2}}, \qquad (2)$$

Where "n" is the number of sensors, y^{q} is the pattern of the qth damage scenario in the database, ED^{q} is the Euclidean distance between the unknown pattern and the pattern of the qth scenario.

3. Numerical Simulation

To verify the feasibility and reliability of this method, a four-layer centralized mass model is simulated, as shown in Figure 1. The structure has a layer height of 0.2 m. Beam3 and Mass21 cells are used to model the finite element model with a density of 7850 $\mathrm{kg/m^3}$, a Poisson's ratio of 0.288, and the elastic modulus is 210 Gpa by ANSYS. The damage is set by varying the width of the beam cells in the real constants. S1, S2, S3, S4 are used to label the four acceleration sensors respectively with an increasing order in labeled numbers from the bottom to the top of the structural model.

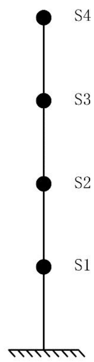


Figure 1. Four-layer structure model

Three damage levels of 20%, 40%, and 60% are considered in the simulation, which represents minor damage, moderate damage, and severe damage, respectively. Based on the location and severity of the damage, the various damage scenarios with damage labels are permuted in the pattern database. When the modal information of each damage scenario is obtained by modal analysis, the parameter of mode shape ratio is calculated using the first two modes, which are stored in the subheadings of the corresponding damage. As listed in Table 2, there are a total of 73 damage scenarios.

Table .2 Pattern database of the structure of four floors

No.	scenarios	No.	scenarios	No.	scenarios	No.	scenarios
1	0-0-0-0	21	20-0-0-40	41	0-40-20-0	61	0-60-60-0
2	20-0-0-0	22	20-0-0-60	42	0-40-40-0	62	0-60-0-20
3	40-0-0-0	23	0-20-20-0	43	0-40-60-0	63	0-60-0-40
4	60-0-0-0	24	0-20-40-0	44	0-40-0-20	64	0-60-0-60
5	0-20-0-0	25	0-20-60-0	45	0-40-0-40	65	0-0-60-20
6	0-40-0-0	26	0-20-0-20	46	0-40-0-60	66	0-0-60-40
7	0-60-0-0	27	0-20-0-40	47	0-0-40-20	67	0-0-60-60
8	0-0-20-0	28	0-20-0-60	48	0-0-40-40	68	20-0-20-20
9	0-0-40-0	29	0-0-20-20	49	0-0-40-60	69	40-40-0-40
10	0-0-60-0	30	0-0-20-40	50	60-20-0-0	70	0-60-60-60
11	0-0-0-20	31	0-0-20-60	51	60-40-0-0	71	20-0-40-60
12	0-0-0-40	32	40-20-0-0	52	60-60-0-0	72	20-0-20-40
13	0-0-0-60	33	40-40-0-0	53	60-0-20-0	73	20-0-40-40
14	20-20-0-0	34	40-60-0-0	54	60-0-40-0		
15	20-40-0-0	35	40-0-20-0	55	60-0-60-0		
16	20-60-0-0	36	40-0-40-0	56	60-0-0-20		
17	20-0-20-0	37	40-0-60-0	57	60-0-0-40		
18	20-0-40-0	38	40-0-0-20	58	60-0-0-60		
19	20-0-60-0	39	40-0-0-40	59	0-60-20-0		
20	20-0-0-20	40	40-0-0-60	60	0-60-40-0		

* Damage conditions from left to right correspond to one to four floors of damage, for example, "20-20-0-0" means: 20% damage on the first floor, 20% damage on the second floor, and so on.

A white Gaussian noise excitation is applied on the second floor, which simulates the vibration of the structure under the environmental load. In order to demonstrate the effectiveness of the method using the limited number of sensors, different sensor combinations are applied. Data from three sensors in one sensor combination are taken for modal parameters identification using the eigensystem realization algorithm (ERA) to obtain the characteristic vector. Using the proposed method, the matched damage scenarios are shown in Table 3, including two single damage(SD) scenarios and two multiple damage(MD) scenarios. Single damage scenario 1(SD1) corresponds to the damage of the No.3 pattern in the database while SD2 corresponds to the No.10 pattern. Multiple damage scenario1(MD1) matches with the No.62 pattern in the database while MD2 matches with the No.37 pattern.

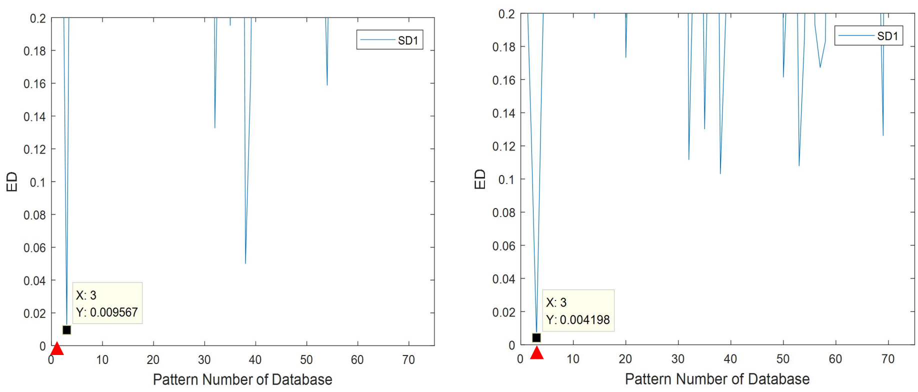
Table 3. Table of damage scenarios of four-layer structure

Pattern No.	Label	Scenarios	Sensor positions
3	SD1	40% damage on the first floor	S1, S2, S3 S2, S3, S4
10	SD2	60% damage on the third floor	S1, S2, S3 S2, S3, S4
62	MD1	60% damage on the second floor while 20% damage on the fourth floor	S1, S2, S3 S2, S3, S4
37	MD2	40% damage on the first floor while 60% damage on the third floor	S1, S2, S3 S2, S3, S4

Based on the combination of S1, S2, S3, and S2, S3, S4, the modal parameters information is identified to obtain the mode shape ratio, which is matched sequentially with the database. The location and severity of the measured structure are the same as the pattern corresponding to the minimum value of ED.

As shown in Figure 2, the No.3 pattern is matched out in Figure 2(a) using sensors S1, S2, and S3. According to Table 2, there is 40% damage on the first floor. In Figure 2(b), the No.3 pattern is matched out too, using sensors S2, S3, and S4. Therefore, for the case of SD1, the location and severity of the damage are identified by using three sensors in two different sensor combinations. Querying Table 1, the damage grade of the first floor of the structure is moderate, which is consistent with the real situation. Likewise, the No.10 pattern is matched out in Figures 2(c)-(d) for the case of SD2, which is 60% damage on the third floor, assessing that the damage grade of the third floor is severe.

In MD1, the No.62 pattern is matched out and corresponding to the minimum value of ED in Figures 3(a)-(b), which indicates that there is 60% damage on the second floor while 20% damage on the fourth floor. In other words, the damage grade on the second floor is severe and on the fourth floor is slight. Similarly, as shown in Figures 3(c)-(d), the No.37 pattern is matched out for case MD2, which means the damage grade of the first floor is moderate and on the third floor is severe. These results indicate that the proposed method can accurately identify the damages.



（a） （b）

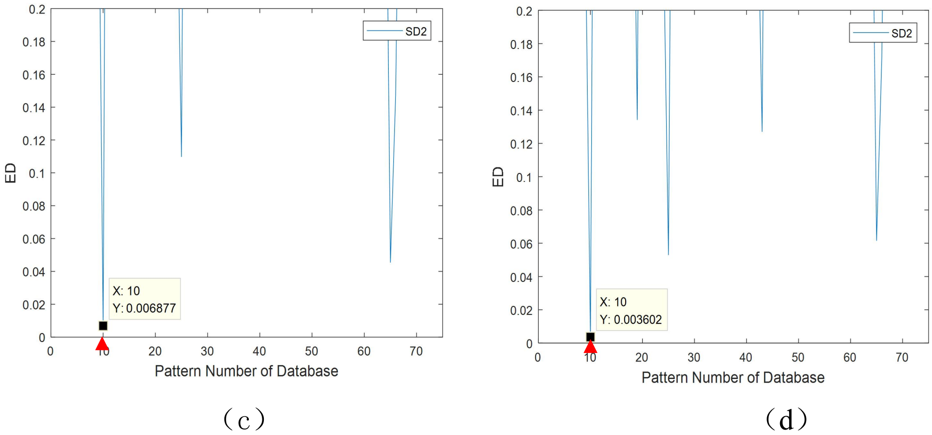


Figure 2. Single damaged detection results with different sensor combinations: (a) SD1: S1, S2 and S3 (b) SD1: S2, S3 and S4 (c) SD2: S1, S2 and S3 (d) SD2: S2, S3, and S4

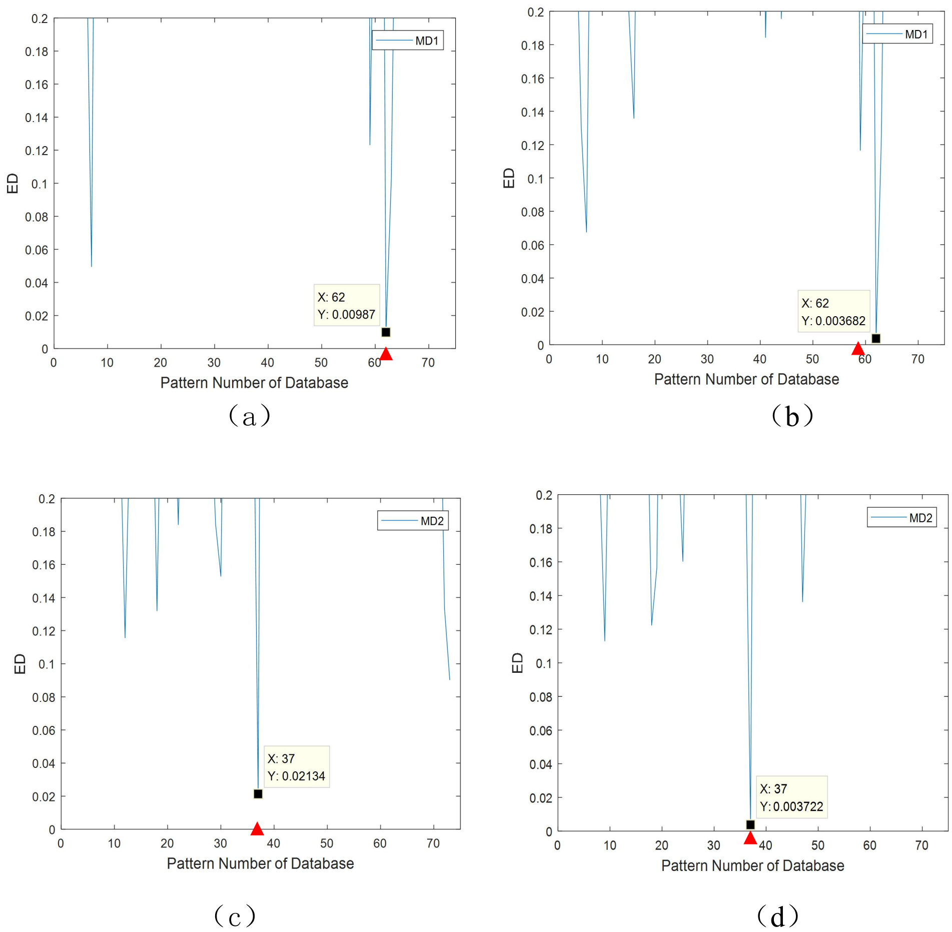


Figure 3. Double damaged detection results with different sensor combinations: (a) MD1: S1, S2, and S3 (b) MD1: S2, S3, and S4 (c) MD2: S1, S2, and S3 (d) MD2: S2, S3, and S4.

4. Conclusion

This paper proposes a rapid identification method for post-earthquake structural damage based on mode shape ratio using pattern matching. Since the mode shape ratio is analytically related to the mode shape of the structure, it is not affected by external excitation. The first two orders of modal information are obtained by modal analysis, and the mode shape ratio vectors for various damage scenarios form the pattern database. The characteristic vectors identified from the acceleration responses of a limited number of sensors are used to measure the similarity with the database in turn. The location and severity of the measured structure are identified the same as the pattern corresponding to the minimum value of Euclidean distance. Then the damage grade of the post-earthquake structure is evaluated. Both single damage and multiple damages scenarios are simulated. The results indicate that the proposed approach can identify the damage location and severity by different sensor combinations under the environmental load. In addition, the process of establishing a modal analysis-based pattern database is faster and more convenient, indicating the proposed method is effective. However, the method has not been applied in the experiment. Therefore, much more work should be carried out to further verify the proposed method.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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