MAPPING CRACKING PATTERN OF MASONRY WALL PANEL BASED ON TWO-STEP CRITERION FOR MATCHING ZONE SIMILARITY

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Abstract:

This paper puts forward an innovative criterion in the cellar automata (CA) technique for both matching zone similarity and mapping failure pattern of masonry wall panel. The criterion proposed in this paper is a two-step matching method. Firstly, calculate the state values of the cells in the base and unseen panels using the CA technique. Then, the first step of the criterion is to take a cell and its eight neighbourhoods as a data block and choose all the best-match blocks within the base panel corresponding to a data block within the unseen panel, according to a proposed minimum risk principle. Finally, map cracking patterns of unseen panels use the criterion for mapping cracking pattern. The cracking patterns of unseen panels are mapped using the tested cracking patterns of several simply-supported base panels and the methods developed above. The mapped results are verified by the corresponding experimental results. The proposed criterion for matching zone similarity can greatly improve the existing CA technique for mapping the cracking pattern of an unseen panel; particularly, the convergence of the improved CA technique obtains a great improvement. Also, this mapping task is realized on the basis of the fine CA cell lattices of the panels, using the proposed method.

1 Introduction

In order to promote the structural safety, durability and energy efficiency, a great deal of fund has been drawn into the field of structural analysis with expensive tests all around the world. However, the existing conventional theories and methods have been difficult to deal with some complex engineering problems, such as the prediction of failure pattern of masonry wall panel and the relationship between structural failure pattern and failure load. The difficulty of these problems mainly lies in high variability and non-linearity in masonry, by which it is, in many cases, too hard to calculate out the accurate result of behavior and response of masonry wall panel.

In the past twenty years, some researchers have tried to apply artificial intelligence techniques, for instance, cellular automata and neural networks, to resolve these problems. In 2002, Zhou G. C. firstly

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proposed the concept of similar zone and the corrector of strength/stiffness, which lay a foundation for the use of CA technique in predicting the failure pattern of masonry wall panel (2002). In 2006, Zhou G. C. used the CA technique to predict the failure pattern of masonry wall panels under lateral loads, and obtained acceptable results (2006); in 2010, Zhang Y et al developed a technique combining ANN with CA, which predicts the cracking pattern of masonry wallets with different course angles subjected to vertical load, to a limited extent (2010).

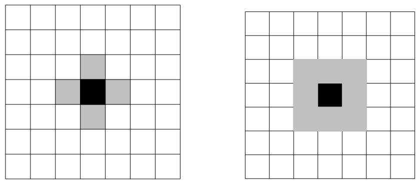
The research results above demonstrate that the CA technique has a promising future in the structural analysis. However, this CA technique at present has two aspects which are to be improved. Firstly, the precision in the predicting result sometimes is low, because of the low discrimination of the state function; secondly, the cracking pattern expressed by zones might bring error into the predicting process.

In view of these two aspects, this paper proposes a new criterion, called a two-step criterion, for matching zone similarity based on the minimum risk principle by introducing a new parameter - the threshold value. The proposed criterion improves the mapping precision and the convergence in mapping performance, which results in the failure pattern mapped from zones to lines. On the other hand, the choice of the base panel in Zhou's study is a man-made standard panel according to the experimental results, which may lead to information loss in the experimental panel. In this study, the failure pattern is directly based on the experimental result, without a man-made standard process; thus, the base panel contains all the experimental information and the predicting result is closer to the experimental appearance.

2 The CA technique for mapping cracking pattern of unseen wall panel

Cellular Automata is an artificial intelligent technique based on a discrete space-time lattice, introduced by von Neumann (1966). There are four ingredients in a CA model: the physical environment, the state of a cell, the neighborhoods of a cell, and a local transition rule (Sarkar 2000; Maerivoet and Moor 2005). Fig. 1 shows two common CA models, the von Neumann model and the Moore model, which have four and eight neighborhoods for a cell, respectively. This paper will use the von Neumann model to calculate the state values of all the cells, while the Moore model is used in the criterion of matching zone similarity.

Fig. 1 is also used as a representation of the CA model of a masonry panel, in which a cell indicates a zone. For the state values of individual zones within a panel, they can be calculated by Eq. (1) of the von Neumann model (Zhou, 2002). The transition functions in Eq. (1) propagate the effect of the boundaries exerted on individual zones within the panel.



(a) (b)

Figure 1. The CA model (a) von Neumann model; (b) Moore model.

$$
\begin{aligned}
& L_{i,j} = L_{i,j-1} + \eta\left(1 - L_{i,j-1}\right) \\
& \quad \left(i = 1, 2, \cdots, M\ ;\ j = 1, 2, \cdots, N\right) \\
& R_{i,j} = R_{i,j+1} + \eta\left(1 - R_{i,j+1}\right) \\
& \quad \left(i = 1, 2, \cdots, M\ ;\ j = N, N-1, \cdots, 1\right) \\
& B_{i,j} = B_{i-1,j} + \eta\left(1 - B_{i-1,j}\right) \\
& \quad \left(i = M, M-1, \cdots, 1;\ j = 1, 2, \cdots, N\right) \\
& T_{i,j} = T_{i+1,j} + \eta\left(1 - T_{i+1,j}\right) \\
& \quad \left(i = M, M-1, \cdots, 1;\ j = N, N-1, \cdots, 1\right)
\end{aligned}
\tag{1}
$$

Where $L_{i,j}$, $R_{i,j}$, $B_{i,j}$ and $T_{i,j}$ are the state values of a zone (i, j) on the panel calculated by the transition functions, which indicate the effect of the left, right, bottom and top boundaries on the zone respectively; $L_{i,0}$, $R_{i,N+1}$, $B_{0,j}$ and $T_{M+1,j}$ are the input initial values for the transition functions in Eq. (1), which are the boundary types: 0.0 for a free edge and 0.2 for a simply supported edge and 0.4 a fixed edge; η is the coefficient of transition, whose value is 0.2; M and N are the numbers of rows and columns of divided zones. For more details about the selection of these initial values, refer to Zhou (2002) and Zhou et al. (2003).

The state value $S_{i,j}$ of each cell is closely related to its four or eight adjacent cells and defined as the average effect from its four or eight neighborhoods, which is shown in Eq. (2).

$$S_{i,j} = \frac{L_{i,j} + R_{i,j} + B_{i,j} + T_{i,j}}{4} \quad (i = 1, 2, ..., M\,;\, j = 1, 2, ..., N) \tag{2}$$

The CA technique for mapping cracking pattern of masonry panels is based on the concept of zone similarity (Zhou, 2003). From the curves of ratios between the tested and FEA displacements at various measured points on the wall panel, Zhou found that these ratios tend to their individual stable values after the load has reached a certain level. Hence, these stable ratios were defined as the stiffness/strength correctors because they could be used to modify the global parameters of structural properties, such as the elastic modulus, to improve the FEA accuracy of the wall panels. Furthermore, from the contour plots of the correctors, it was found that the patterns of the corrector distribution in some zones are similar. It was conceptually verified that this zone similarity is related with similar boundary types and similar locations of zones. Thus, the concept of zone similarity and the criterion for matching similar zones within and between wall panels was proposed, whose details can be found in References (Zhou, 2002, 2006).

3 Criterion for matching zone similarity and judging cracking zone

The past research result (Zhou, 2002) indicated that the cracking pattern/mode of wall panel is governed by the configuration of the structure, in other words, the cracking mode of wall panel is closely related with the effect of its boundary types and dimension. The yield line theory has also verified this conclusion as the ideal yield line mode like the cracking mode of a wall panel that could be used to calculate the failure load. A common expression of the cracking pattern/mode is to plot it on a lattice consisted of the zones divided on the wall panel surface. In fact, the cracking pattern/mode is a graph composed of cracking zones and non-cracking zones on the wall panel. Whether or not a zone is cracking, it depends on its state related to the boundary types and the orientation of the zone on the wall panel. Hence, this just coordinates with the CA state function, which can propagate the boundary constraint effect into the individual zones within the wall panel. This lattice is like the CA cell lattice, that is, individual cells in the CA lattice are like the zones on the wall panel. In this way, a CA state transition function and the corresponding formula were applied to express the state of a zone. The corresponding state value calculated by the CA function reflects and also quantifies the effect of the boundary and zone location on a zone.

In short, the above mentioned establishes a method describing the configurative state mode of a wall panel, combining with the CA technique. The CA method results in a CA numerical mode of the wall panel once all zones within the wall panel have their state values calculated by the CA state function. And then, using the established CA modes of base panel, new panel and both criterion of matching zone similarity and criterion for mapping cracking zone, the failure pattern of new panel can be mapped being directly based on the cracking pattern of the base panel.

3.1 Criterion for matching zone similarity

The criterion for matching zone similarity has two matching steps. In the first matching step, a block consists of a cell and its eight neighborhoods for the Moore model in Fig. 1b. The matched block is defined as a matching result using the following calculation and comparison:

(1) Calculate the error matrices $\mathbf{E}^{i,j}$ between a block (i, j) on the new wall panel and all the blocks on the base wall panel, by Eq. (3)

(2)

$$\mathbf{E}^{i,j} = \begin{bmatrix} E_1 & E_2 & E_3 \\ E_4 & E_5 & E_6 \\ E_7 & E_8 & E_9 \end{bmatrix}_{k,l}^{i,j} =$$

$$\left\| \begin{bmatrix} S^{\text{new}}_{i-1,j-1} & S^{\text{new}}_{i-1,j} & S^{\text{new}}_{i-1,j+1} \\ S^{\text{new}}_{i,j-1} & S^{\text{new}}_{i,j} & S^{\text{new}}_{i,j+1} \\ S^{\text{new}}_{i+1,j-1} & S^{\text{new}}_{i+1,j} & S^{\text{new}}_{i-1,j+1} \end{bmatrix} - \begin{bmatrix} S^{\text{base}}_{k-1,l-1} & S^{\text{base}}_{k-1,l} & S^{\text{base}}_{k-1,l+1} \\ S^{\text{base}}_{k,l-1} & S^{\text{base}}_{k,l} & S^{\text{base}}_{k,l+1} \\ S^{\text{base}}_{k+1,l-1} & S^{\text{base}}_{k+1,l} & S^{\text{base}}_{k-1,l+1} \end{bmatrix} \right\| \tag{3}$$

$$k = 1, 2, ...M, l = 1, 2, ...N$$

where, $S^{\text{new}}_{i,j}$ is the state value of the cell (i, j) on the new wall panel; $S^{\text{base}}_{k,l}$ is the state value of the cell (k, l) on the base wall panel; M, N are the row and column numbers on the base wall panel, respectively.

(2) Compare all the elements in the error matrices $\mathbf{E}^{i,j}$ with a given threshold value t_0, using Eq. (4)

$$E_i - t_0 \begin{cases} < 0 & T_i = 1 \\ \geq 0 & T_i = 0 \end{cases} \qquad i = 1, 2, \ldots 9 \tag{4}$$

If the value of the element in the error matrix is smaller than t_0, assign 1, otherwise 0, at the responding place to replace the original state value. Thus, the matrices $\mathbf{T}$ are obtained, with 3×3 in dimension and $M \times N$ in total.

(3) Find the sum $V_{k,l}$ of the 9 elements in each of the matrices $\mathbf{T}$, using Eq. (5)

$$V_{k,l} = \sum_{i=1}^{9} T_i^{k,l} \qquad k = 1, 2, \ldots M; l = 1, 2, \ldots N \tag{5}$$

Where, $T_i^{k,l}$ is the ith element value of the matrix (k, l) in the matrices $\mathbf{T}$.

(4) Search for the maximum V among $V_{k,l}(k = 1, 2, \ldots M; l = 1, 2, \ldots N)$, using Eq. (6)

$$V = \max(V_{k,l}) \qquad k = 1, 2, \ldots M; l = 1, 2, \ldots N \tag{6}$$

The blocks on the base wall panel, corresponding to the maximum V, is defined as the matching blocks. In other words, the block (i, j) on the new wall panel has had its matching blocks through Eqs. (3) - (6) on the base panel. In general, a block may have a few matching blocks. Here, the first matching step has finished.

In the second matching step of the two-step criterion, the similar zone is to be found on the base wall panel corresponding to the zone (i, j) on the new wall panel, from the matching blocks obtained in the first matching step. Eq. (7) is the second step for matching zone similarity

$$Z_{p,q} \Leftarrow \min \left| B\_S_{i,j}^{\text{new}} - (B\_S^{\text{base}})_t \right| \qquad t = 1, 2, \ldots N_b \tag{7}$$

Where, $Z_{p,q}$ is the similar zone (p, q) of the zone (i, j); $B\_S_{i,j}^{\text{new}}$ is the state value of the central-cell in the block (i, j) on the new wall panel; B_S^{base} is the state value of the central-cell of a matched block on the base wall panel; N_b is the number of the matching blocks.

Eq. (7) determines the zone (p, q) on the base wall panel as the similar zone of the zone (i, j) on the new wall panel. For all the zones on the new wall panel, continually using this two-step criterion for matching zone similarity, similar zones may be found on the base wall panel.

3.2 Criterion for judging cracking zone

The criterion for judging cracking zone within the panels assumes that similar zones between two panels demonstrate the same behavior, that is to say, if a zone on the base panel is cracked, its similar zones on the new panel that match those of the base panel are also cracked.

3.3 The CA method for mapping cracking pattern of masonry wall panel

The diagram of the CA method for mapping the cracking pattern of the masonry wall panel is shown in Fig. 2 and the steps are described as follows:

1) Lattice the base wall panels to obtain its CA model. Then, the numerical cracking pattern of the base wall panel is obtained by setting "0" and "1" at the failure and non-failure zones, respectively.

2) According to Eqs. (1) and (2), calculate out the state value of each zone on both base and new wall panels, respectively.

3) Using the proposed criteria for matching zone similarity, Eqs. (3)-(7), obtain the similar zones on the base wall panel corresponding to all the zones on the new wall panel.

4) Using the criterion for judging failure zone, map the cracking pattern of the new wall panel.

4 Case study on mapping cracking patterns of masonry panels

The experimental wall panels tested in the laboratory (Lawrence 1983) are taken to verify the proposed method. The so-called new panels have the same type of load and boundary conditions with the base panels except for their lengths and widths. The size of the base panel is 6m by 3m, and its thickness is 110mm. The size of the new panel is 2.5m by 2.5m, and its thickness is also 110mm.

When leaving out the initial imperfection of the panel itself, the cracks of the new panel are simulated out along the diagonals by the FEA method. When using the shell element model, the new panel's maximum principal stresses nephogram is shown in Fig. 3.

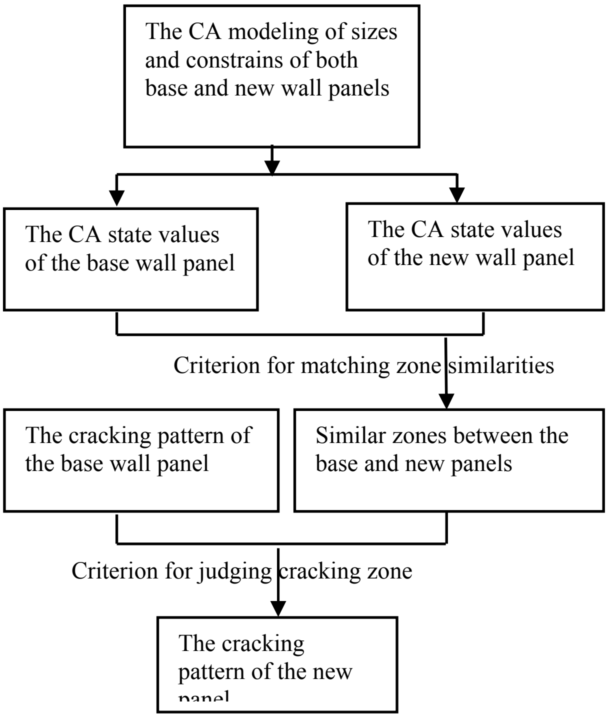


Figure 2. The procedure for the CA method.

In fact, even the panels have the same sizes, boundary conditions and loading case, their failure patterns are still different from each other because of the initial imperfection and the variability.

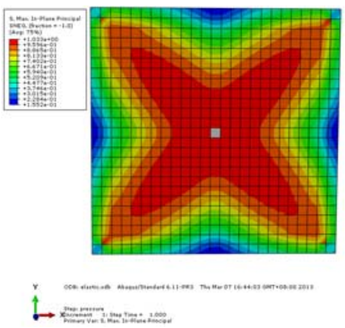
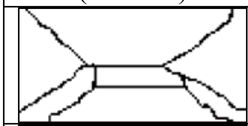
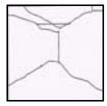
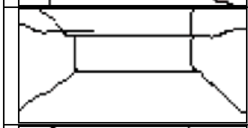
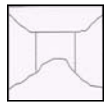
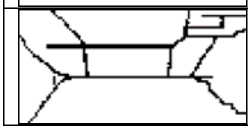
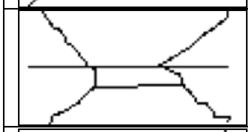
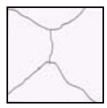
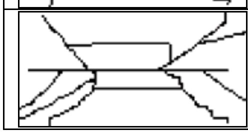
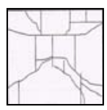


Figure 3. The maximum principal stress of the new panel.

The CA method directly uses the testing result of the base panel as input, and the mapping result of the new panels are listed in Table 1. In Table 1, the first column replaces the failure patterns of the base panels obtained from the experiments; the second column shows the mapped cracking patterns of the new panels; the last column shows the experimental failure patterns of the new panels to verify the effectiveness of the CA method. There is a specification that all the threshold valves in the cases given in this paper are 0.001.

Table 1. Failure patterns of base panels and the mapping results

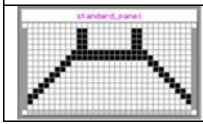
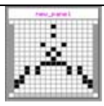
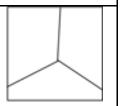
The testing patterns of base panels (6m×3m)	The mapping patterns	The testing patterns (2.5m×2.5m)
		
		
		
		
		

Comparing the results in the 2nd and 3rd columns in Table 1, it is obviously that the mapped results are close to the testing cracking patterns. The comparison indicates that the proposed criterion, that is, the two-step criterion, can be valid in mapping the failure pattern of the new panel based on failure pattern of the base panel.

Form the mapping results in Table 1, it could be comprehended that any cracking zones in the wall panel depend on their positions relative to the boundary constraints and the types of boundary constraints. Hence, the cracking pattern of the base wall panel could be applied to map the cracking pattern of the new wall panel, according to their similar zones.

The 2nd column in Table 2 shows the predicting results of Zhou given in 2006 (Zhou 2006), the 3rd column is the mapping result by the proposed method. The comparison between the two results shows that precision of the proposed method is higher, and what is more, the convergence is better.

Table 2. A comparison between Zhou's method (Zhou 2006) and the proposed method.

The standard base panel	Zhou's method	The proposed method	Testing result
			

5 The determination of the threshold

There is a problem arising from the need to resolve the method introduced in the section 3.1, that is the determination of the threshold value. In order to determine the threshold value, the conception of similarity level proposed by Zhou in 2010 is introduced in this paper (2010).

Assume that two matrices **M** and **N** have the same dimension, then $M_{i,j} \le 0$, $M_{i,j} \in \mathbf{M}$ and $N_{i,j} \le 0$, $N_{i,j} \in \mathbf{N}$; calculate $\Delta^k_{i,j} = \left| M_{i,j} - N_{i,j} \right|$ and $E^k_{i,j} = M_{i,j} + N_{i,j}$ $(k = 1, 2, \cdots, n)$; if $E^k_{i,j} \neq 0$, the similarity level between two elements $M_{i,j}$ and $N_{i,j}$ is $\eta_k = 1 - \Delta^k_{i,j} / E^k_{i,j}$ and the similarity level between two matrices **M** and **N** can be expressed in Eq. (8); evidently, the similarity level of two matrices $\eta \in (0,1]$.

$$\eta_{\mathrm{M,N}} = \frac{1}{n}\sum_{k=1}^{n} \eta_k = 1 - \frac{1}{n}\sum_{k=1}^{n} \frac{\Delta^k_{i,j}}{E^k_{i,j}} \qquad (8)$$

For the five given examples, the similarity level and threshold values are listed in Table 3; the relationship between threshold values and the similarity is showed in Fig. 4. It should be noted that the x axis in Fig. 4 is the logarithmic coordinate, that is because of the variation range of the x is large.

Each curve has only one peak value for all the five predictions, and the peak values are all close to 0.001, which is to say, for all the five predictions listed in this paper have the same threshold values, and the similarity level is the highest when using this threshold value to mapping the failure pattern. The peak values indicate that all the predicting results have the 85 to 90 percent of similarity level.

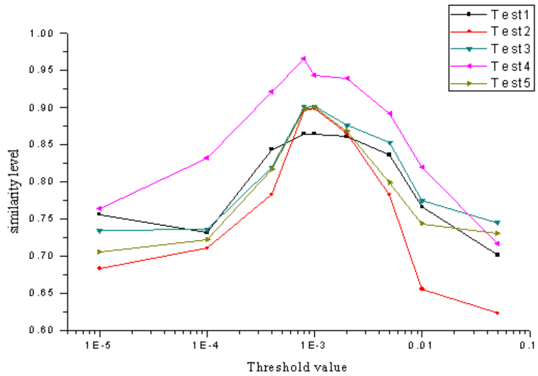


Figure 4. The curves of threshold values and the similarity level.

Table 3. Threshold value and the similarity level of the five examples

	Similarity level				
Threshold Values($\times 10^{-5}$)	Test1	Test2	Test3	Test4	Test5
1	0.7566	0.6841	0.6693	0.7347	0.7640
10	0.7321	0.7109	0.7250	0.7365	0.8326
40	0.8440	0.7834	0.7641	0.8196	0.9214
80	0.8647	0.8970	0.8427	0.9011	0.9657
100	0.8649	0.8991	0.8454	0.9021	0.9440
200	0.8611	0.8659	0.8165	0.8767	0.9400
500	0.8368	0.7831	0.7199	0.8535	0.8918
1000	0.7665	0.6565	0.6624	0.7751	0.8195
5000	0.7018	0.6236	0.6549	0.7456	0.7167

6 Conclusions

From the predicting results and the analysis of the threshold values, it can be concluded as follows:

1. The proposed two-step criterion for matching zone similarity could be valid and relatively accurate to reflect the property of zone similarity in the CA numerical model of the wall panel.
2. The mapped cracking pattern of an unseen wall panel is closer to the result from the corresponding lab test, based on the zone similarity calculated by the two-step criterion, when compared with the existing matching criterion.
3. The proposed two-step criterion for matching zone similarity greatly improves the convergence of the CA technique for mapping the cracking pattern of the unseen wall panel.

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