CELLULAR AUTOMATA METHOD FOR MAPPING CRACKING PATTERNS OF LATERALLY LOADED WALL PANELS WITH OPENINGS

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Abstract:

This study presents a cellular automata (CA) method to map the cracking patterns of laterally loaded masonry wall panels with openings. Firstly, the central point displacement of each CA cell is calculated from the finite element method (FEM). Then, the displacements are normalized to form the CA state value mode of the wall panel. Next, a maximum correlation coefficient criterion is proposed to match the zone similarity between the base (tested) and new (analyzed) wall panels. Finally, the criterion for judging cracking zone is adopted to map the cracking pattern of the new wall panel. The case studies indicate that the mapped cracking patterns of wall panels agree well with the testing results, which verify the validity of the criterion for matching zone similarity.

1 Introduction

Despite the long history and associated researches on the masonry wall panels, there is still disagreement over the suitability of the methods for predicting the failure loads and cracking patterns of masonry wall panels subjected to wind and other lateral loads, especially for wall panels with openings. The common method in analyzing the failure loads and cracking patterns of masonry wall panels is the Finite Element method (FEM) [1-5]. Also, the FEM is usually considered as the most accurate method with a rational mechanism for covering all the configuration and material parameters of the wall panel; but, when compared with the experimental results of laterally loaded masonry wall panels, the FEM results fail because of inaccurate prediction of masonry working behavior in many cases.

In the past twenty years, some researchers have tried to apply artificial intelligence techniques, for instance, cellular automata (CA) and artificial neural networks (ANN), to resolve the problems in the analysis of masonry structures [6-9]. In 2002, Zhou G. C. firstly proposed the concepts of similar zone and strength/stiffness corrector, which lay a foundation to the application of CA technique in analyzing the behavior of masonry wall panels [7]. In 2006, Zhou G. C. et al. realized the prediction of the failure patterns of masonry wall panels under lateral loads with acceptable accuracy, using the CA technique [8]. In 2010, Zhou G. C. et al built an ANN model which relates the failure load with the failure pattern of masonry wall panel subjected to the lateral load [9]. In the same year, Zhang Y. et al

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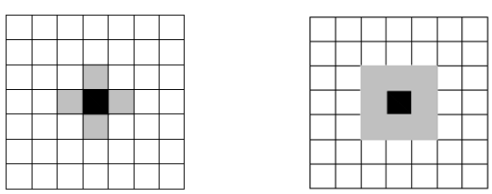
developed an ANN technique combining with CA numerical mode, and predicted the cracking patterns of masonry wallets with different course angles subjected to vertical load [10].

These recent research results indicate that the CA technique has a promising capability in the structural analysis, particularly in addressing high-nonlinear issues. However, the existing CA techniques have not been developed to map the cracking patterns of masonry wall panels with openings. This could be because the opening in the wall panel has some special features quite different from the solid wall panel. Hence, this study proposes a new criterion for matching zone similarity based on the maximum correlation coefficient. The new criterion develops the existing CA method and realizes the prediction of cracking patterns of masonry wall panels with openings for the first time.

2 Basic concepts

A CA model includes four components, the physical environment, the state value of a cell, the neighborhoods of a cell and a local transition rule. The von Neumann model and the Moore model are two common CA models which have four and eight neighborhoods around a central cell respectively, as shown in Fig. 1. Here, the Moore model is used to establish the CA model of wall panel and to match zone similarity.



a) von Neumann model *b) Moore model*

Figure 1. The CA models.

The base wall panel is the one tested in the laboratory. The cracking pattern of the base panel is used as the basis for mapping the cracking patterns of new panels. Aiming at the verification and comparison of the mapping results, a new/unseen wall panel is also one tested in the laboratory and with the tested/known cracking pattern.

3 State values

Zhou's CA state value of each cell is calculated by a given transition function describing the configurational state of the wall panel and the effect of the structural constraints on the zones/cells within the wall panel [6]. In this study, the CA state value of a cell is its generalized displacement at its center point in *z* direction. Thus, the CA state value is a mechanical result including the effect of both the structural configuration and loading case on the individual CA cells/zones within the wall panel. The calculation method of the state value is given as following:

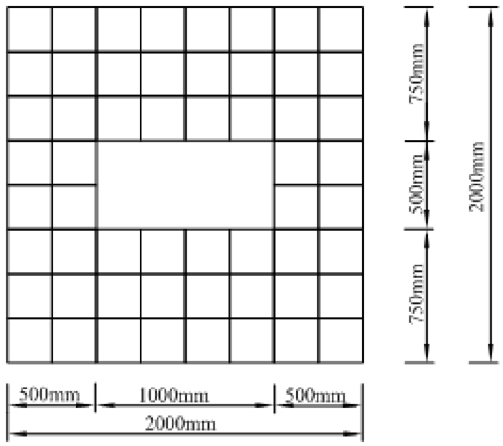
1) Establishing the CA lattice for the wall panel, according to its dimensions;
2) Establishing the FEM model of the wall panel under evenly unit uniform load and calculating out the FEA displacements of the cells;
3) Normalizing the FEM displacements by dividing the maximum displacement among them, as shown in Eq. (1)

$$S_{i,j} = \frac{u_{i,j}^s}{\max(u_{i,j}^s)} \quad i = 1,2\cdots M,\ j = 1,2\cdots N \qquad (1)$$

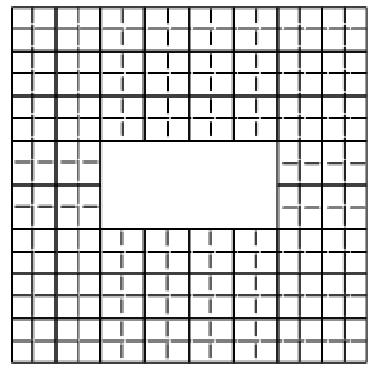
where, $S_{i,j}$ is the state value of the cell (*i*, *j*); $u_{i,j}^5$ represents the FEM displacement of the cell (*i*, *j*); M, N are the row and column numbers of the CA lattice of the wall panel, respectively; $\max(u_{i,j}^5)$ is the maximum FEM displacement value among all the cells.

The normalized displacement of each cell forms the CA state value mode of the wall panel, which might reflect the stressing state of the wall panel.

Take PANEL1 as an example of calculating the state values. The geometrical feature of PANEL1, such as the position and the dimension of the opening, is shown in Fig. 2 a). The CA lattice is 8×8. To obtain the displacement of each cell at its central point, the FEM mesh of the wall panel is 16×16 as shown in Fig. 2 b). It can be seen that the crossover point between two dotted lines is the central point of the cell in the CA lattice. The displacements calculated by the FEM are given in Table 1 and the normalized displacements are given in Table 2. The state values (i.e., normalized displacements) at boundary are bolt in Table 2, for the constraint edges, the state values are 0, while for the free edge, the state values are equal to their neighborhood's state values. In the corner, the state value is the average value of the two cross edges.



a) CA Lattice



b) FEA mesh

Figure 2. CA lattice and the FEA mesh of PANEL1.

Table 1. Displacements of the CA cells at their center point on PANEL1.

-12.883	-36.330	-53.914	-63.321	-63.321	-53.914	-36.330	-12.883
-11.371	-32.230	-48.117	-56.763	-56.763	-48.117	-32.230	-11.371
-9.873	-28.090	-42.517	-50.956	-50.956	-42.517	-28.090	-9.873
-8.174	-23.305	-35.786	0.000	0.000	-35.786	-23.305	-8.174
-6.217	-17.712	-27.211	0.000	0.000	-27.211	-17.712	-6.217
-4.055	-11.507	-17.418	-20.610	-20.610	-17.418	-11.507	-4.055
-1.899	-5.349	-7.931	-9.308	-9.308	-7.931	-5.349	-1.899
-0.284	-0.801	-1.164	-1.353	-1.353	-1.164	-0.801	-0.284

Table 2. The state value of each cell on PANEL1.

0.102	**0.203**	**0.574**	**0.851**	**1.000**	**1.000**	**0.851**	**0.574**	**0.203**	**0.102**
0.000	0.203	0.574	0.851	1.000	1.000	0.851	0.574	0.203	**0.000**
0.000	0.180	0.509	0.760	0.896	0.896	0.760	0.509	0.180	**0.000**
0.000	0.156	0.444	0.671	0.805	0.805	0.671	0.444	0.156	**0.000**
0.000	0.129	0.368	0.565	0.685	0.685	0.565	0.368	0.129	**0.000**
0.000	0.098	0.280	0.430	0.378	0.378	0.430	0.280	0.098	**0.000**
0.000	0.064	0.182	0.275	0.325	0.325	0.275	0.182	0.064	**0.000**
0.000	0.030	0.084	0.125	0.147	0.147	0.125	0.084	0.030	**0.000**
0.000	0.004	0.013	0.018	0.021	0.021	0.018	0.013	0.004	**0.000**
0.000	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**

4 Criterion for matching zone similarity based on maximum correlation coefficient

The correlation coefficient reflects the similarity between two variable quantities, which varies from -1 (perfect negative correlation) through 0 (no correlation) to +1 (perfect positive correlation). The closer to 1 the correlation coefficient is, the more similar the two variables are. Hence, a criterion for zone similarity matching is proposed based on the maximum correlation coefficient, that is, if a zone on the base panel has the maximum correlation coefficient matching with the zone on the new panel, the two zones are defined as the similar zones.

For a Moore model, the criterion for matching zone similarity is described as Eqs. (2) to (4)

$$\overline{S}_{i,j}^{new} = \frac{1}{9}\sum_{u=-1}^{1}\sum_{v=-1}^{1} S_{i+u,j+v}^{new} \tag{2}$$

$$\overline{S}_{m,n}^{base} = \frac{1}{9}\sum_{u=-1}^{1}\sum_{v=-1}^{1} S_{m+u,n+v}^{base} \tag{3}$$

$$E_{i,j\to new}^{m,n\to base} = \underset{m=1,n=1}{\overset{M,N}{MAX}} \frac{\sum_{u=-1}^{1}\sum_{v=-1}^{1}(S_{i+u,j+v}^{new}-\overline{S}_{i,j}^{new})(S_{m+u,n+v}^{base}-\overline{S}_{m,n}^{base})}{\sqrt{\sum_{u=-1}^{1}\sum_{v=-1}^{1}(S_{i+u,j+v}^{new}-\overline{S}_{i,j}^{new})^2}\sqrt{\sum_{u=-1}^{1}\sum_{v=-1}^{1}(S_{m+u,n+v}^{base}-\overline{S}_{m,n}^{base})^2}} \tag{4}$$

where, $E_{i,j\to new}^{m,n\to base}$ is the maximum correlation coefficient between Zone (i, j) on the new wall panel and individual zones on the base wall panel; $S_{i,j}^{new}$ is the state value of Zone (i, j) on the new wall panel; $S_{m,n}^{base}$ is the state value of Zone (m, n) on the base wall panel; $\overline{S}_{i,j}^{new}$ is the average of the state values of Zone (i, j) and its eight neighborhoods on the new wall panel; $\overline{S}_{m,n}^{base}$ is the average of the state values of Zone (m, n) and its eight neighborhoods on the base wall panel.

5 Criterion for judging cracking zone

The criterion for judging the cracking zone within the wall panel assumes that the similar zones between the base and new panels have the same behavior, that is to say, if the zone on the base panel is failed, its similar zone on the new panel is also failed.

6 CA method for mapping cracking pattern of masonry wall panel with opening

The procedure of the CA method for predicting the cracking pattern of the masonry wall panel is shown in Fig. 3:

1) Lattice the base and new wall panels to obtain their CA models. The cells on the new wall panel have the same size with the cells on the base wall panel;
2) Set "0" and "1" at the cracking and non-cracking zones, respectively, to obtain the numerical cracking pattern of the base wall panel;
3) According to Eq. (1), calculate out the state value of each zone/cell on both base and new wall panels, respectively;
4) Using the proposed criteria for matching zone similarity, Eqs. (2)-(4), obtain the similar zones on the base wall panel corresponding to all the zones/cells on the new wall panel;
5) Using the criterion for judging cracking zone, map the cracking pattern of the new wall panel.

7 Case studies

The masonry wall panels with openings tested by V. L. Chong in the University of Plymouth [1] are used to validate the method proposed in this study. Two types of masonry wall panels are chosen: the first type of wall panels is top edge free and the other three edges constrained, and the second type of wall panels is four edges constrained. The orientations and sizes of the openings in the wall panels are shown in Fig. 4. For the three edges constrained wall panels, the dimensions are 5615 mm × 2475 mm in plane and the detailed parameters are listed in Table 3; for the four edges constrained wall panels, the dimensions are 2900 mm × 2450 mm in plane and the detailed parameters are listed in Table 4.

All the wall panels are made of common bricks and unified mortar through the same engineering procedure. The four wall panels are selected in consideration of the positions and sizes of the doors and windows whose ratios of aperture are from 10% to 20%. The wall panels are loaded by airbag and the cracking patterns tested in the lab are shown in Fig. 5.

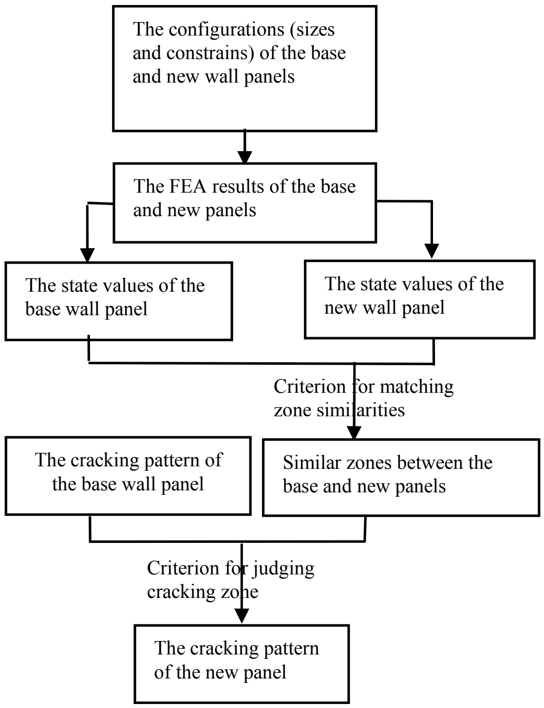


Figure 3. The procedure of the CA method.

7.1 Mapping the cracking pattern of masonry wall panel with opening taking a solid wall panel as the base wall panel

For the wall panels with openings, SB02, SB03, SB04 and SB09, map their cracking patterns taking the solid wall panels SB01 and SB05 as the base panels, respectively.

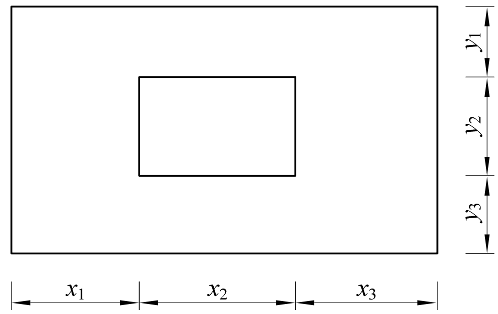


Figure 4. The orientation and size of the opening.

The mapped and tested cracking patterns are shown in Figs. 6 to 9. Figs. 6 to 9 indicate:

1) The mapped cracking patterns of the new wall panels are close to their tested results. Almost all the main cracking patterns are mapped out by the proposed CA method;
2) Both the wall panels SB01 and SB05 can be used as the base panels to map the cracking patterns of new wall panels with openings;
3) The mapping results are closer to the testing results taking SB05 as the base wall panel than those using SB01 as the base panel.

7.2 Mapping the cracking patterns of masonry wall panels with openings taking a wall panel with opening as the base wall panel

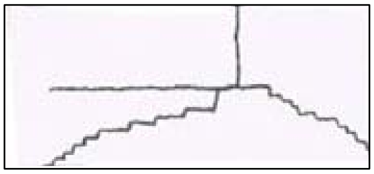
For the wall panels with openings, SB03, SB04 and SB09, map their cracking patterns taking the wall panel SB02 with opening as the base wall panel.

Table 3. The sizes of the 1st type of wall panels.

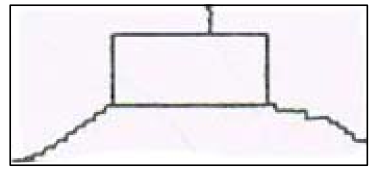
No.	x_1 [mm]	x_2 [mm]	x_3 [mm]	y_1 [mm]	y_2 [mm]	y_3 [mm]
SB01	5615	0	0	0	0	2475
SB02	1677	2260	1678	450	1125	900
SB03	1340	2935	1340	450	525	1500
SB04	2352	910	2353	450	2025	0
SB05	5615	0	0	0	0	2475
SB09	3815	900	900	675	900	900

Table 4. The sizes of the 2nd type of wall panels.

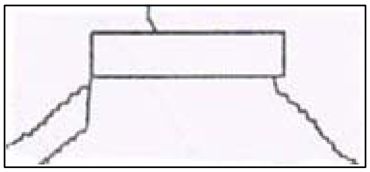
No.	x_1 [mm]	x_2 [mm]	x_3 [mm]	y_1 [mm]	y_2 [mm]	y_3 [mm]
SB06	2900	0	0	0	0	2450
SB07	1000	900	1000	650	900	900



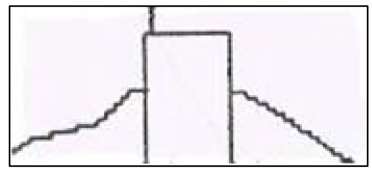
a) The cracking pattern of SB01



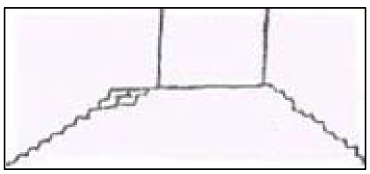
b) The cracking pattern of SB02



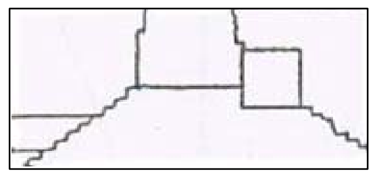
c) The cracking pattern of SB03



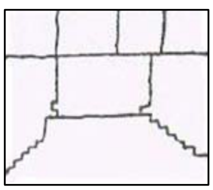
d) The cracking pattern of SB04



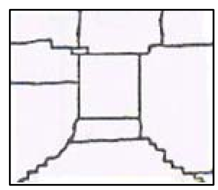
e) The cracking pattern of SB05



f) The cracking pattern of SB09

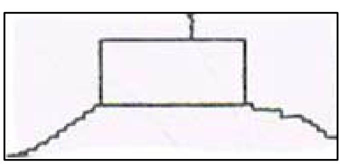


g) The cracking pattern of SB06

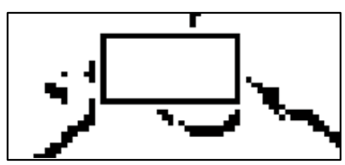


h) The cracking pattern of SB07

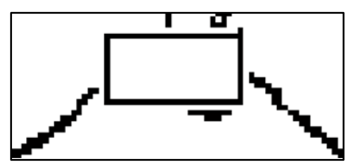
Figure 5. The cracking patterns of masonry wall panels.



a) The tested cracking pattern of SB02

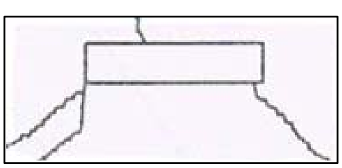


b) The mapped cracking pattern of SB02 (the base panel is SB01)

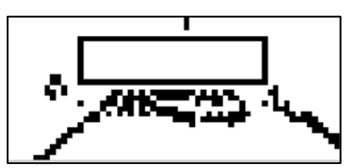


c) The mapped cracking pattern of SB02 (the base panel is SB05)

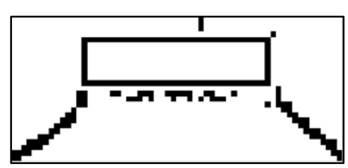
Figure 6. The mapped cracking patterns of SB02.



a) The tested cracking pattern of SB03

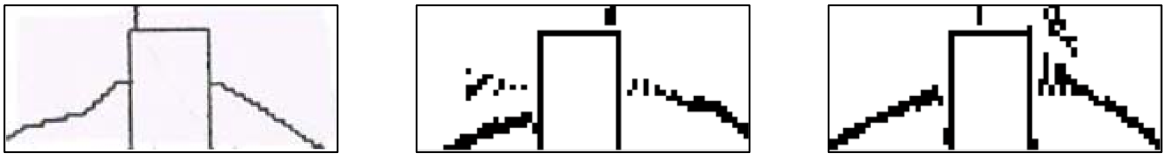


b) The mapped cracking pattern of SB03 (the base panel is SB01)



c) The mapped cracking pattern of SB03 (the base panel is SB05)

Figure 7. The mapped cracking patterns of SB03

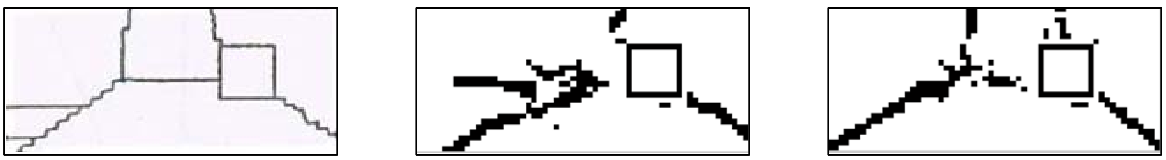


a) The tested cracking pattern of SB04

b) The mapped cracking pattern of SB04 (the base panel is SB01)

c) The mapped cracking pattern of SB04 (the base panel is SB05)

Figure 8. The mapped cracking patterns of SB04.



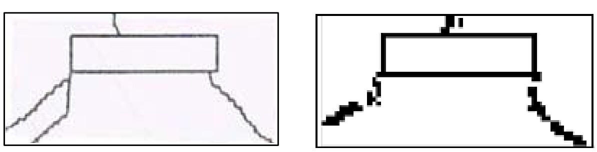
a) The tested cracking pattern of SB09

b) The mapped cracking pattern of SB09 (the base panel is SB01)

c) The mapped cracking pattern of SB09 (the base panel is SB05)

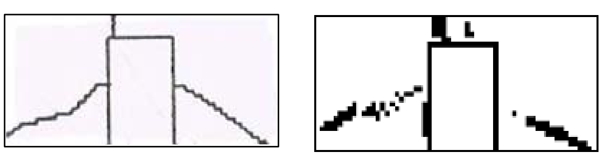
Figure 9. The mapped cracking patterns of SB09.

The mapping and tested results are shown in Fig. 10. Fig. 10 indicates that the mapped cracking patterns of the wall panels with openings are close to their tested results. The main cracking patterns are also mapped out by the proposed CA method.



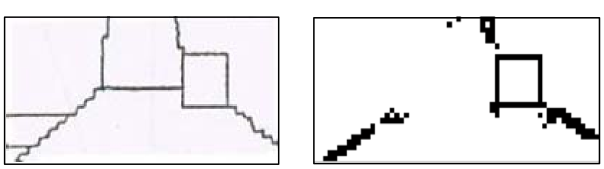
a)The tested cracking pattern of SB03

b)The mapped cracking pattern of SB03



c) The tested cracking pattern of SB04

d)The mapped cracking pattern of SB04



e) The tested cracking pattern of SB09

f) The mapped cracking pattern of SB09

Figure 10. The cracking patterns of Wall Panels SB03, SB04 and SB09.

The case studies indicate the validity of the proposed maximum correlation coefficient criterion in mapping the cracking patterns of new panels with different openings.

8 Conclusions

1) The existing CA technique is extended to map the cracking patterns of wall panels with openings, and the corresponding case study verifies the validity of this extension.
2) Two innovative manners contribute to the new application of the CA technique, one is the proposed maximum correlation coefficient criterion for matching zone similarity, and the other is the CA state mode of the wall panel, coordinating with the FEA model.

It should be noted that the CA method needs to further reveal the inherent mechanism.

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References

[1] Chong, V. L.: *The Behavior of Laterally Loaded Masonry Panels with Openings*, PhD thesis, University of Plymouth, UK, 1993.

[2] Laurenco, P. B.: *Anisotropic softening model for masonry plates and shells*, Journal of Structural Engineering, 126 (2000), 9, 1008-1016.

[3] Milani, G., Lourenço, P. B.: *A simplified homogenized limit analysis model for randomly assembled blocks out-of-plane loaded*, Computers & Structures, 88 (2010), 11-12, 690-717.

[4] Rabinovitch, O., Madah, H.: *Finite element modeling and shake-table testing of unidirectional infill masonry walls under out-of-plane dynamic loads*, Engineering Structures, 33 (2011), 9, 2683-2696.

[5] Čanađija, M., Brčić, M., Brnić, J.: *Bending behavior of single-layered grapheme nanosheets with vacancy defects*, Engineering Review, 33 (2013), 1, 9-14.

[6] Taha, M. M, Noureldin, A., El-Sheimy, N., Shrive, N.G.: *Artificial neural networks for predicting creep with an example application to structural masonry*, Canadian Journal of Civil Engineering, 30 (2003), 3, 523-532.

[7] Zhou, G. C.: *Application of stiffness/strength corrector and cellular automata in predicting response of laterally loaded masonry panels*, PhD thesis, University of Plymouth, UK, 2002.

[8] Zhou, G. C., Rafiq, M. Y., Bugmann, G. C., Easterbrook D. J.: *Cellular automata model for predicting the cracking pattern of laterally loaded masonry wall panels*, Journal of Computing in Civil Engineering, 20 (2006), 6, 400-409.

[9] Zhou, G. C, Pan, D., Xu, X., Rafiq. M. Y.: *Innovative ANN Technique for Predicting Failure/Cracking Load of Masonry Panel under Lateral Load*, Journal of Computing in Civil Engineering, 24 (2010), 4, 377-387.

[10] Zhang, Y., Zhou, G. C., Xiong, Y., Rafiq, M. Y.: *Techniques for Predicting Cracking Pattern of Masonry Wallet Using Artificial Neural Networks and Cellular Automata*, Journal of Computing in Civil Engineering, 24 (2010), 2, 161-172.