

# **Application of Cellular Automata in Modelling Laterally Loaded Masonry Panel Boundary Effects**

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## **ABSTRACT**

In this paper the Cellular Automata (CA) technique is used to model the boundary effect on zones within a panel in order to select stiffness/strength correctors from a known panel (the base panel) for any new panels with and without opening and with different boundary conditions. In this CA model, an appropriate function (transition function) is proposed which propagates initial values representing boundary types, into each zone within the panel. Thus every zone within the panel is assigned with a state value. These state values of the panel are then used to establish zone similarities and assign corrector values for zones within the new panel. The research also investigates the effect of parameter values for different boundary types and the transition coefficient for use in the CA model. Finally the research examines the effect of correctors on the FEA results of the panels. It is discovered that by using this method considerable improvement in the prediction of failure loads and failure patterns of masonry panels, in comparison with their experimental results is achieved.

## **1. INTRODUCTION**

Research carried out by Lawrence in 1991 [1] indicated that it is essential to consider inherent random variation in masonry properties in any theoretical analysis to pursue an accurate prediction of the behaviour of laterally loaded masonry panels. In research carried out by Zhou in 2002 [2], it was established that apparent variation in masonry properties is mainly governed by the panel boundaries. Zhou therefore proposed the concept of stiffness/strength correctors, which quantifies this variation. The application of this concept successfully improved the FEA results of masonry panels by modifying globally smeared flexural rigidity or tensile strength (traditionally used in the analysis of panels), at various zones within the panel.

Stiffness/strength correctors are derived from the comparison of experimental results on full-scale panels with the non-linear FEA results of the panels. The values of correctors are discovered to be closely related to the boundary types of the panel and the locations of zones within the panel with respect to each boundary. Thus a concept of zone similarity is proposed to relate correctors to boundary types and the position of zones with respect to each boundary. The corresponding rules for determination of correctors for new panels are developed, based on the definition of zone similarities. Research by Zhou [2] and Rafiq et al [3] has shown that the proposed method can be used to manually select appropriate correctors from the base panel, which when applied to other panels greatly improves the FEA results of the panels. However, this manual method is not easy to operate as mapping the division of zones within the base panel and the new panel and accurately assigning corrector values requires a deeper understanding of the effect of panel boundaries on local zones. It also requires careful consideration of the sizes and positions of the zones within the base panel when the new panel is divided into the zones. There is a need to develop a comprehensive

automatic technique for dividing zones on the new panel and closely matching similar zones in the new panel with those on the base panel, in order to select appropriate correctors for the FEA of the new panel.

This paper presents detail of this method using the Cellular Automata (CA) techniques. Cellular Automata is selected as the tool used to implement this process because it efficiently propagates the effect of panel boundaries on the local zones within the panel. Thus every zone in the panel obtains a so-called “state value” based on the position of each zone with respect to panel boundaries and the effect of the neighbourhood zones on the zone under consideration. It should be noted that the state value, used by the CA, is different from any physical response calculated using the FEA. In other words, the effect of panel boundaries in the FEA is reflected in the actual physical response of the panel, but the boundary effect expressed in the CA is purely a set of numerical values, which best describes the extent that the boundaries of a panel can affect a zone within the panel in a given location. This state value is then used to establish zone similarities.

Cellular Automata is implemented to firstly propagate the effect of panel boundaries to individual zones within the base panel. This assigns unique state values to each zone on the base panel. The same process is then applied to a new panel which may have different boundary conditions and/or sizes from the base panel and may have openings. The rules proposed in this paper are then used to closely match similar zones within the new panel to those in the base panel. Finally it translates the state values on the new panel to actual corrector values, which is used to modify flexural rigidity or tensile strength of the zones within the new panel for the FE analysis. The research has examined the effect of parameter values describing boundary types and the value of a transition coefficient, used in the CA model and the corresponding rules for matching similar zones to efficiently match similar zones between panels.

Using the corrector values produced by the CA method to adjust the global masonry properties, the FEA results of panels are much closer to their experimental results.

## **CELLULAR AUTOMATA MODEL**

Cellular Automata (CA) are described as discrete space-time models that consist of cells in a lattice network [4]. The cells may be a one-dimensional, two-dimensional (including 2-D hexagonal), or three-dimensional (including cubic) array, with each cell capable of existing in one or more states (e.g., 0 to 6 for a hexagonal system) [5]. The “neighbourhood” consists of adjacent cells which will influence the behaviour of a particular cell state [6]. Figure 1 show an example of 2-D neighbourhood cell model developed by von Neumann [6]. The von Neumann cell (i, j) is affected by its four neighbourhood cells as shown in Figure 1.

The change in state from time  $t$  to time  $t+1$  is governed by some “local rules” [4] or “transition rules” [7]. For the CA, neighbourhood structures and transition rules need to be the same for all sites. These rules are not necessarily fixed. Updating the state values of the cells for a CA network must be performed by a “synchronous” or parallel mode [8]. Rucker and Rudy [9] summarise the properties of the CA as follows:

- Parallel: individual cell is updated independent of other cells;
- Locality: new cell state values depend on old cell state values, and values of its neighbourhood cells;
- Homogeneity: same rules are applied to all cells.

Halpern [10] formalized the cellular automata transition model in the case of the von Neumann neighbourhood as:

$$a_{i,j}^{(t+1)} = f(a_{i,j}^{(t)}, a_{i,j+1}^{(t)}, a_{i+1,j}^{(t)}, a_{i,j-1}^{(t)}, a_{i-1,j}^{(t)}) \quad (1)$$

where

$a$  = cell state value at a given time  
 $i, j = x, y$  cell coordinates  
 $t$  = time interval  
 $f$  = transition function related to iteration rule

### Insert Figure 1 Here

### 3. RULES FOR MATCHING ZONE SIMILARITIES

The types of panel boundaries and the positions of zones with respect to these boundaries were found to be the basis of similarities between zones in two panels [2, 3]. Based on this definition, the rule for matching zone similarities can be defined as: Firstly, for a zone  $i$  within a new panel

$$\{S_i^{new}\} = \{f(B_l, B_r, B_b, B_t; d_{li}, d_{ri}, d_{bi}, d_{ti})\} \quad (2)$$

$$\{S_k^{base}\} = \{f(B'_l, B'_r, B'_b, B'_t; d'_{lk}, d'_{rk}, d'_{bk}, d'_{tk})\} \quad (3)$$

$$S_{-Z_j} = \underset{k=1}{MN} \text{COMPARISON}(\{S_i^{new}\}, \{S_k^{base}\}) \quad (4)$$

where

$\{S_i^{new}\}$ : is a vector containing the state values related to the zone  $i$  on the new panel

$\{S_k^{base}\}$ : is a vector containing state values related to the zone  $k$  on the base panel

$B_l, B_r, B_b, B_t$ : the boundary type parameter at the left, right, bottom and top edges of the new panel respectively

$B'_l, B'_r, B'_b, B'_t$ : the boundary type parameter at the left, right, bottom and top edges of the base panel separately

$d_{li}, d_{ri}, d_{bi}, d_{ti}$ : the distance from the centre of the zone  $i$  to the left, right, bottom and top edges of the new panel respectively

$d'_{lk}, d'_{rk}, d'_{bk}, d'_{tk}$ : the distance from the centre of the zone  $k$  to the left, right, bottom and top edges of the base panel respectively

$S_{-Z_j}$ : the zone  $j$  on the base panel, which is similar to zone  $i$  on the new panel

$MN$ : the total number of zones on the base panel

$f$ : the function relationship

$COMPARISON$ : rules for matching similar zones between the base panel and the new panel

Thus, the corrector  $\mathbf{y}$  at zone  $i$  on the new panel has the same value as its similar zone  $j$  on the base panel. Finally, the flexural rigidity or tensile strength of the zone on the new panel can be modified as

$$\text{Modified flexural rigidity of the zone: } D' = \mathbf{y}D \quad (5)$$

or

$$\text{Modified tensile strength of the zone: } f' = \mathbf{y}f \quad (6)$$

where,  $D$  and  $f$  are the global smeared flexural rigidity and tensile strength values respectively.

After the modified flexural rigidity or the modified tensile strength for every zone within the new panel is obtained using Equations (5) and (6), a non-linear FEA program is used to calculate the failure load and failure pattern for the new panel.

#### 4. MODELLING BOUNDARY EFFECT USING CELLULAR AUTOMATA

Zhou [2] and Rafiq et al [3] showed that zone similarities between a new panel and a base panel are closely related to the panel boundary conditions and the location of each zone with respect to the panel boundaries. When compared with the properties of parallel, locality and homogeneity of the CA, the characteristics of zone similarities can be suitably described by these same space properties of CA. To describe this CA model, the following assumptions are made:

- (1) Panel SB01, tested by Chong [11] in the laboratory, is used as the base panel. This panel was divided into 36 zones based on the positions of experimentally measured points on the panel, see Figure 2 for details (the zones with the same colour indicate symmetrical zones);
- (2) The following parameters are used for each boundary type, 0.0 for free support, 0.2 for simple support and 0.4 for fixed support. Full justification for these values is given in [2] and briefly in Appendix A.

Figure 2 shows how the base panel SB01 is modelled using the CA:

- Each zone within the panel is a cell of the CA system. The boundaries are described as input cells with specified values (0.0 for a free edge, 0.2 for a simply supported edge and 0.4 for built-in edge).
- The position of each cell in the CA system corresponds to the position of a zone within the panel.
- Each cell (zone) receives the boundary effect from its neighbourhood cells (as shown in Figure 1) and in turn propagates the boundary effect to their neighbourhood cells.

**Insert Figure 2 here**

The properties of parallel, locality and homogeneity of CA are also valid for describing the properties of zone similarities. For the property of parallel: the state values of individual cells describing the similarities between individual zones can be updated independent of other cells/zones simultaneously, using Equations (7) and (8). For the property of locality: the new cell/zone state value depends on state values of its neighbouring cells/zones. For the property of homogeneity: the same rules are applied to each cell/zone within the panel. These rules are described by Equations (7) and (8) below. For a two-dimensional panel, the von Neumann model was found to be sufficient for describing the effect of different boundaries at the four edges of the panel used in this study. Therefore, the transition functions of the CA, which are represented in Equation (7), fully propagate the effect of panel boundaries on individual zones within the panel. Equation (8) sums up the effect of boundaries at the four edges of the panel on Zone ( $i, j$ ) within the panel. The equations are shown below:

$$\begin{aligned}
 L_{i,j} &= L_{i,j-1} + \mathbf{h}(1 - L_{i,j-1}) \\
 R_{i,j} &= R_{i,j+1} + \mathbf{h}(1 - R_{i,j+1}) \\
 B_{i,j} &= B_{i-1,j} + \mathbf{h}(1 - B_{i-1,j})
 \end{aligned} \tag{7}$$

$$T_{i,j} = T_{i+1,j} + h(I - T_{i+1,j})$$

where

$h$  = coefficient of transition

$L$  --- state value of zone defined from the propagated effect of the left boundary

$R$  --- state value of zone defined from the propagated effect of the right boundary

$B$  --- state value of zone defined from the propagated effect of the bottom boundary

$T$  --- state value of zone defined from the propagated effect of the top boundary

The local rules of CA, that is, the state value  $S_{i,j}$  of every zone of the panel is calculated as the average effect from its four adjacent cells:

$$S_{i,j} = \frac{(L_{i,j} + R_{i,j} + B_{i,j} + T_{i,j})}{4} \quad (8)$$

However, Equations (7) and (8) are not enough to completely describe zone similarities. In other words, if two zones have the same state value, calculated by Equations (7) and (8), these two zones do not necessarily have the same corrector, as zone similarities are defined by the state value of the cell and the values of its neighbourhood cells. For example, for the panel SB01 shown in Figure 2, state values at individual zones are calculated using Equations (7) and (8). The same cell colour in Figure 2 represents similar zones. The CA rules were applied to another panel with the same dimensions as the base panel SB01 having the following boundary types:

- (1) Free at top edge
- (2) Simply supported at left hand edge
- (3) Built-in in both bottom and right hand edges.

The result of the CA application for this new panel is shown in Table 1.

In Table 1, Zones D2 and A5 (or D3 and B7 or B3 and C9) have the same state value, but they are not similar zones because Zone D2 is adjacent to a fixed edge support and Zone A5 is adjacent to a free edge. Therefore, it is necessary to establish new rules to fully identify similar zones similarities between the base panel and the new panel.

**Table 1** State Values Derived from Equations (7) and (8)

		1	2	3	4	5	6	7	8	9	
		0	0	0	0	0	0	0	0	0	
<b>A</b>	0.2	<b>0.558</b>	<b>0.585</b>	<b>0.605</b>	<b>0.62</b>	<b>0.624</b>	<b>0.625</b>	<b>0.62</b>	<b>0.609</b>	<b>0.592</b>	0.4
<b>B</b>	0.2	<b>0.583</b>	<b>0.61</b>	<b>0.629</b>	<b>0.64</b>	<b>0.649</b>	<b>0.649</b>	<b>0.644</b>	<b>0.634</b>	<b>0.616</b>	0.4
<b>C</b>	0.2	<b>0.596</b>	<b>0.623</b>	<b>0.642</b>	<b>0.65</b>	<b>0.661</b>	<b>0.662</b>	<b>0.657</b>	<b>0.646</b>	<b>0.629</b>	0.4
<b>D</b>	0.2	<b>0.597</b>	<b>0.624</b>	<b>0.644</b>	<b>0.66</b>	<b>0.663</b>	<b>0.664</b>	<b>0.659</b>	<b>0.648</b>	<b>0.631</b>	0.4
		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	

## 5. RULES FOR MATCHING ZONE SIMILARITIES USING THE CA NODEL

As shown in the previous section, the state values of individual zones within the panels, obtained by the CA method, need additional rules to properly establish zone similarities. In order to be able to use the state values of individual zones to match similar zones between the base panel and the new panel, it was necessary to simultaneously consider the state values of a zone along with its four neighbourhoods/zones. According to the above analysis, the rules of matching zone similarities are developed in the following sections.

In the present research, the pre-conditions are considered as:

- (1) The FEA for the new panel and the base panel uses the same FEA technique;
- (2) The new panel and the base panel have the same material properties;
- (3) The new panel and the base panel are subjected to uniformly distributed lateral load only.

To accurately match similar zones between two panels using the CA method, it is necessary to compare each zone of a new panel along with its four neighbourhood zones with every zone on the base panel along with its four neighbourhood zones using state values of these relevant zones on both panels. This is because the state value of a zone is closely related to its four neighbourhoods. Thus the following relationship is used to evaluate a comparison error:

$$E_{i,j \rightarrow new}^{k,l \rightarrow base} = \underset{m=1, n=1}{MIN}^{M,N} (|S_{i,j}^{new} - S_{m,n}^{base}| + |S_{i,j-1}^{new} - S_{m,n-1}^{base}| + |S_{i,j+1}^{new} - S_{m,n+1}^{base}| + |S_{i-1,j}^{new} - S_{m-1,n}^{base}| + |S_{i+1,j}^{new} - S_{m+1,n}^{base}|) \quad (9)$$

Once the values of the errors ( $E_{i,j \rightarrow new}^{k,l \rightarrow base}$ ) for a zone in the new panel with respect to every zone in the base panel is determined by Equation (9), the zone with the minimum error value on the base panel is defined as the sole similar zone to the zone on the new panel. The value of corrector in the base panel for this zone with the minimum error is then used for the zone on the new panel for the FEA process.

For more details please refer to reference [2] and appendix A in this paper.

## 6. EFFECT OF BOUNDARY PARAMETERS AND TRANSITION COEFFICIENT ON TRANSITION FUNCTION

In order to achieve better results for matching similar zones, a parametric study was conducted by changing the values of each boundary parameter and studying its effect on Equation (9).

Figure 3 shows that for small initial values of boundary parameter the propagation of the boundary effect is a steep curve and these curves gradually become less steep for large initial boundary values. This indicates that for smaller values of initial boundary parameters the propagation rate from zones closer to a boundary to zones further away from the boundary is more significant.

Figure 4 shows the effect of transition coefficient ( $\eta$ ) used in Equation (7) on the propagation of boundary effects to zones further away from the boundaries. It also shows that smaller values are more effective in propagating boundary effects to zones further away from the boundary.

To establish initial values for different boundaries and the effect of transition coefficient a parametric study was conducted (refer to reference [2] for details). The result of this parametric study showed that a value of 0.2 for the transition coefficient ( $\eta$ ) in Equation (7) produced very good results. The following values were more representative for the initial boundary values.

- (1) For a free edge 0.0
- (2) For a simply supported edge 0.2
- (3) For a built-in edge 0.4

The above values have been used throughout this paper.

## 7. CASE STUDIES: ANALYSIS OF WALLS USING CORRECTORS SELECTED FROM THE CELLULAR AUTOMATA METHOD

Two experimental walls, Wall 1a Control and Wall 1a (i) from the experiments conducted by Edgell [12], with simple supports at all edges, were used in this study. Table 2 gives the parameter details for each wall used in this study. Each panel was divided into 36 zones and appropriate corrector values for each zone were assigned

using the CA method, described in this paper. The results of the process are summarised in Figures 5 and 7. These values were used to modify the flexural rigidities or tensile strength of relevant zones within each panel using equations (5) and (6) respectively for the FEA process.

**Table 2: Parameters for walls used in the case study**

Parameter	Notation	Unit	Value - Wall 1a Control	Value - Wall 1a(i)
Dimension	$L \times H \times T$	mm	5500 × 2600 × 100	5500 × 2600 × 100 2800 × 1400 central opening size
Young's modulus	Brick	kN/mm <sup>2</sup>	12	12
Poisson's ratio	All materials		0.2	0.2
Tensile strength	Parallel to bed joint	N/mm <sup>2</sup>	2.28	2.28
	Normal to joint	N/mm <sup>2</sup>	0.965	0.965

The walls were analysed using a non-linear FEA program for masonry [11]. The program applied a biaxial stress failure criterion to track the failure patterns of panels. In this analysis the failure loads and failure patterns of the two panels were determined using the following cases:

- (a) globally smeared material properties (see Figures 6a and 8a)
- (b) modified flexural rigidities using correctors proposed by Zhou [2] (see Figures 6b and 8b) and
- (c) modified tensile strength respectively using the correctors proposed by Zhou [2] (see Figures 6c and 8b).

Comparison of the results from the analysis with the corresponding experimental results, for the above cases are summarised in Figures 6 and 8, for each wall panel respectively.

**Insert Figure 5 here**

**Insert Figure 6 here**

**Insert Figure 7 here**

**Insert Figure 8 here**

The comparison of the results shows that the application of correctors to modify the global flexural rigidity or tensile strength can make the FEA results much closer to their experimental results. In other words, the FEA using the biaxial stress failure criterion can predict both failure loads and failure patterns of laterally loaded wall panels more accurately, when the correctors selected by the CA method are used to modify the global flexural rigidity.

The results of the analysis using CA techniques give identical results to the manual method proposed by Zhou [2, 3]. This shows the robustness of the CA method.

In order to further investigate the validity and robustness of the CA method two additional experimental walls, Wall Case 7 Control and Wall 2a (i) with opening, from the experiments conducted by Edgell [12], were analysed. Table 3 gives the parameter details for each wall used in this study. One again, each panel was divided into 36 zones and appropriate corrector values for each zone were assigned from the base panel SB01 using the CA method, described in this paper. The results of the CA process is summarised in Figure 9 and 11. These values were used to modify the flexural rigidities or tensile strength of relevant zones within each panel using equations (5) and (6) respectively for the FEA process.

**Table 3 – Parameter Values of Walls**

Name of Panel	Dimension (mm) $L \times H \times T$	Young's modulus (kN/mm <sup>2</sup> )	Poisson's ratio	Tensile strength of masonry (N/mm <sup>2</sup> )
Wall Case 7. Control	5400 ´ 4500 ´ 100	12	0.2	2.28 Parallel to bed joint 0.965 Normal to joint
Wall 2a (i) with opening	5500 ´ 2600 ´ 100 2800 ´ 1400 central opening size			

Note: The panels are from Edgell's experiment [8].

The results of the FEA analysis are shown in Figures 10 and 12 respectively. Once again the results of the analysis for these two walls show that the proposed method of applying correctors to various zones to modify the flexural rigidities at each zone, give results which are much closer to the experimental results both in predicting failure loads and failure patterns for these wall.

By automating the process of determining corrector values using CA techniques considerable time has been saved in preparing the models, and human error associated with the manual selection of similar zone have been totally avoided. This analysis shows a confidence both in the use of the correctors and in the CA techniques proposed in this research.

## 8. CONCLUSIONS

The CA technique has been applied to model the effect of panel boundaries on the individual zones within the panel. Using the proposed rules, state values calculated from the proposed CA model at all zones within a panel, can be used to match similar zones between a base panel and a number of new panels. Correctors from the base panel are assigned to the corresponding similar zones on the new panel. Thus the modified flexural rigidities at local zones on the panel are obtained by using the corresponding corrector value for each zone. Finally the FEA analysis of the panel uses these modified rigidities to replace the globally smeared rigidity, and an accurate prediction of the response of the panel is achieved.

From the analysis and application of correctors, the following conclusions can be drawn:

- (1) This research has successfully introduced new methodologies for establishing zone similarities using the CA techniques to accurately model the effect of panel boundaries on each zone within the panel. The state values, determined by the CA techniques, as a result of the propagation of the effect of boundaries to zones within a new panel, are related to the zones with the common characteristics of structural variation in masonry properties within each zone.
- (2) The proposed rules for zone similarities can efficiently match similar zones between a new panel and a base panel.
- (3) Comparison of the results of a manual method [3] with a CA method showed both methods can provide identical results. This increases the confidence in using the CA method which is more robust and easy to use.
- (4) The CA techniques were used to assign corrector values to individual zones within any unseen new-panel, based on zone similarity between the new panel and the base panel.

- (5) The correctors, selected from a single experimental base panel using the proposed CA model and rules, can be used to modify the global flexural rigidity at similar zones within a new panel. This makes the FEA results of the new panel much more reliable and accurate.
- (6) It must be noted that only a single panel SB01 tested by Chong (1993) in the University of Plymouth has been used to establish corrector values for other panels with/without opening and different boundary conditions. The results obtained are a very good match with the corresponding experimental failure loads and failure patterns for the panels used in this study. If more test data becomes available, the results of the analysis and confidence in using the method would be enormously improved.
- (7) This study only covers the analysis of single leaf wall panels. With more experimental data, this technique can be extended to cavity walls and panels with other materials.

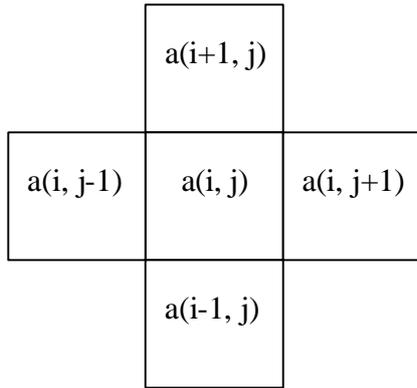
### ACKNOWLEDGEMENT

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**Figure 1 – Cellular Automata Neighbourhoods of von - Neumann**

	1	2	3	4	5	6	7	8	9	
	$T = 0.0$									
$L = 0.2$	0.5517	0.577	0.5942	0.6042	0.6075	0.6042	0.5942	0.577	0.5517	$R = 0.2$
$L = 0.2$	0.5764	0.6016	0.6189	0.6289	0.6321	0.6289	0.6189	0.6016	0.5764	$R = 0.2$
$L = 0.2$	0.5892	0.6144	0.6317	0.6417	0.6449	0.6417	0.6317	0.6144	0.5892	$R = 0.2$
$L = 0.2$	0.5908	0.616	0.6333	0.6433	0.6465	0.6433	0.6333	0.616	0.5908	$R = 0.2$
	$B = 0.4$									

**State Values at Various Zones with the Panel calculated by Equations (7) and (8)**

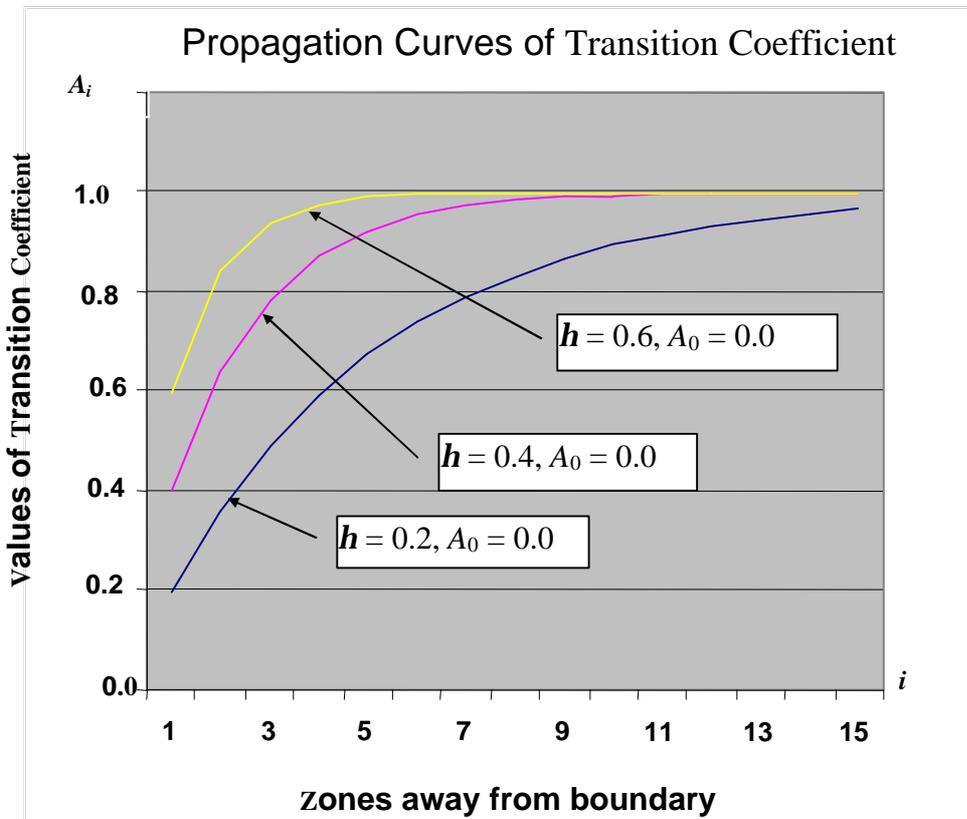
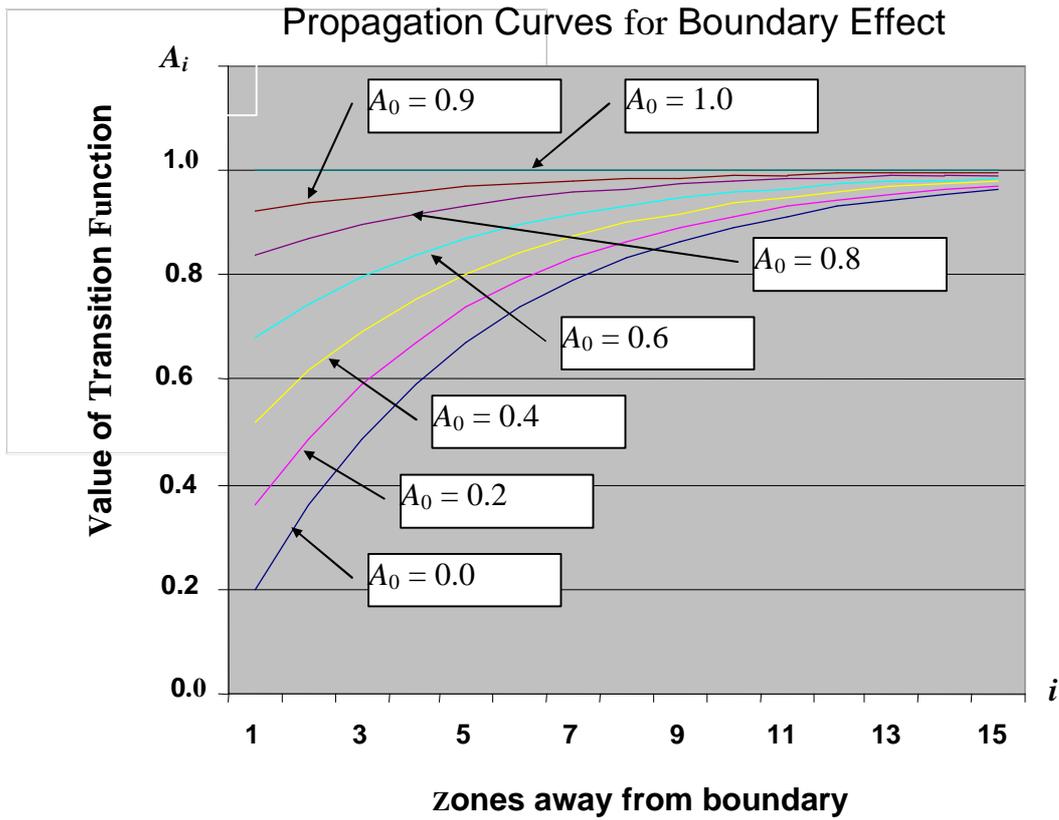
— free edge;      **—** simple support;      **—** fixed support

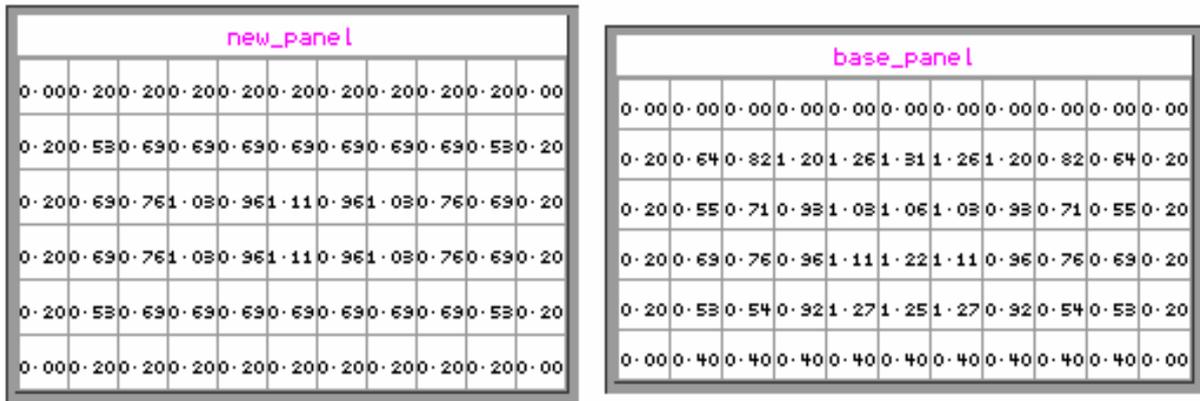
Note: Boundary Parameters (appropriate values are: free edge 0.0, simply supported edge 0.2, and built-in edge 0.4);

$L$  = boundary parameter on the left edge;  $R$  = boundary parameter on the right edge;

$B$  = boundary parameter on the bottom edge;  $T$  = boundary parameter on the top edge.

**Figure 2 – Panel SB01 is modelled as a CA system.**

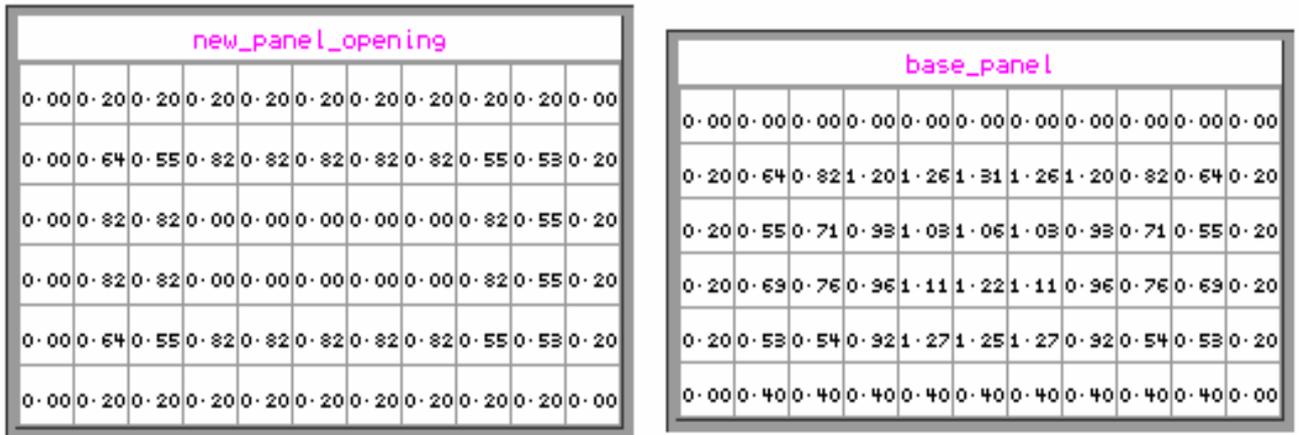




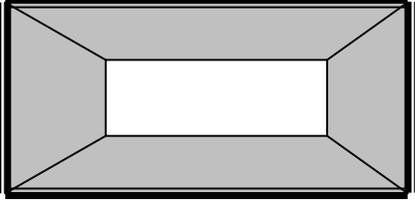
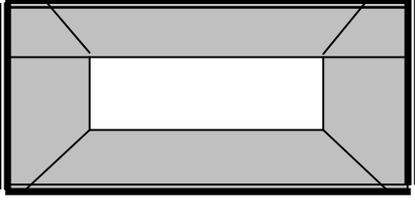
**Figure 5 – The similar zones and the corresponding corrector values between Wall 1a. Control and the base panel SB01**

—— free edge;      **=====** simple support;      **=====** fixed support

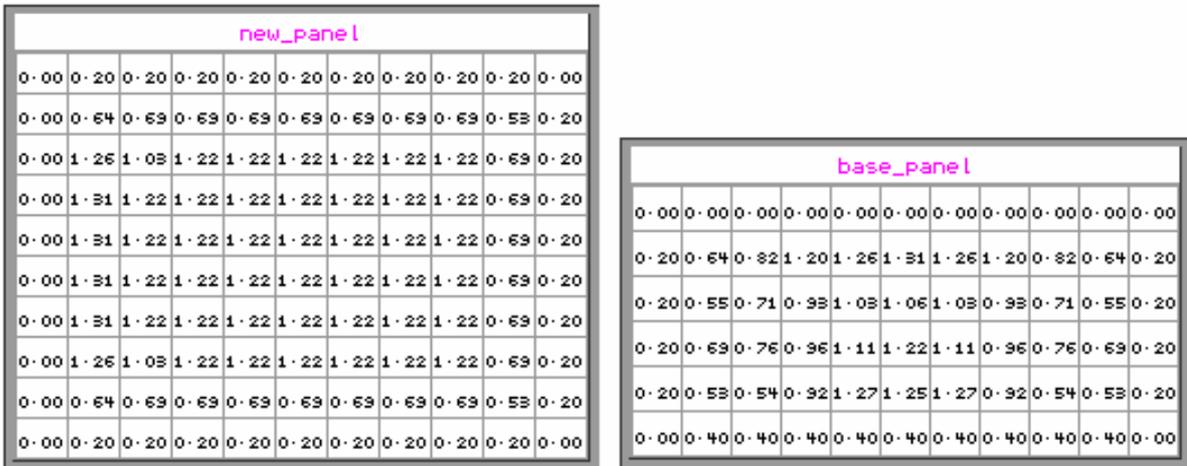
Case Result	Failure Pattern	Failure Load
(a) Global Flexural Rigidity (D) and Tensile Strength (f)		3.0 kN/m <sup>2</sup>
(b) Global <i>f</i> and Modified D'		
(c) Global D and Modified <i>f</i>		(CA-Selecting Correctors)  2.0 kN/m <sup>2</sup>  (CA-Selecting Correctors)
(d) Experimental result		2.6 kN/m <sup>2</sup>



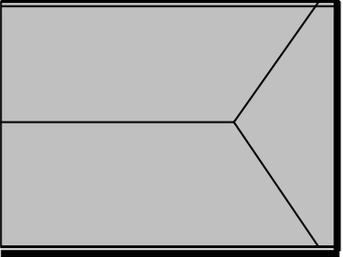
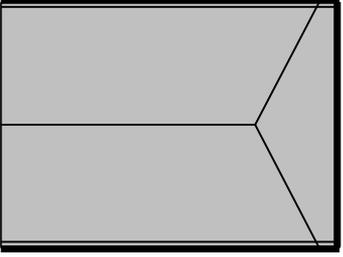
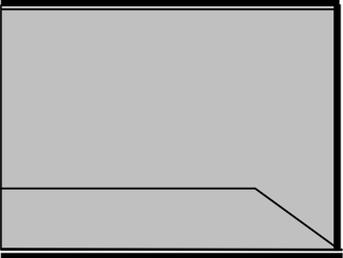
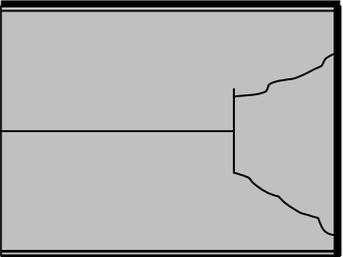
**Figure 7 – The similar zones and the corresponding corrector values between Wall 1a (i) and the base panel SB01**

Case	Failure Pattern	Failure Load
Result  (a) Global D and <i>f</i>		2.4 kN/m <sup>2</sup>
(b) and (c) Mofied D' or Modified <i>f</i>		1.8 kN/m <sup>2</sup> CA-Selecting Correctors From SB01
(d) Experimental result		2.0 kN/m <sup>2</sup>

**Figure 8 – The FEA and experimental results of Wall 1a (i)**



**Figure 9– The similar zones and the corresponding corrector values between Wall Case 7. Control and the base panel SB01**

Case Result	Failure Pattern	Failure Load
(a) Global $D$ and $f$		1.6 kN/m <sup>2</sup>
(b) Global $f$ , modified $D'$		1.4 kN/m <sup>2</sup>
(c) Global $D$ , modified $f'$		1.6 kN/m <sup>2</sup>
(d) Experimental case		1.5 kN/m <sup>2</sup>

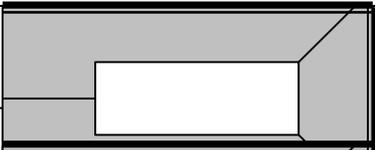
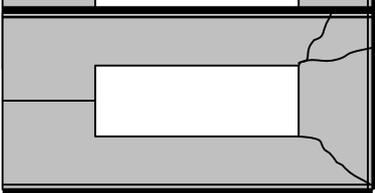
**Figure 10 – The FEA and experimental results of Wall Case 7. Control**

**Figure 11– The similar zones and the corresponding corrector values between**

new_panel_opening											
0	000	200	200	200	200	200	200	200	200	200	00
0	200	530	550	820	820	820	820	820	550	530	20
0	200	550	820	000	000	000	000	000	820	550	20
0	200	550	820	000	000	000	000	000	820	550	20
0	200	530	550	820	820	820	820	820	550	530	20
0	000	200	200	200	200	200	200	200	200	200	00

base_panel											
0	000	000	000	000	000	000	000	000	000	000	00
0	200	640	821	201	261	311	261	200	820	640	20
0	200	550	710	931	031	061	030	930	710	550	20
0	200	630	760	961	111	221	110	960	760	630	20
0	200	530	540	921	271	251	270	920	540	530	20
0	000	400	400	400	400	400	400	400	400	400	00

**Wall 2a (i) with an opening and the base panel SB01**

Case	Failure Pattern	Failure Load
Result		
(a) Global $D$ and $f$		1.2 kN/m <sup>2</sup>
(b) Global $f$ , modified $D'$		
(c) Global $D$ , modified $f$		1.0 kN/m <sup>2</sup>
(d) Experimental case		0.95 kN/m <sup>2</sup>

## Appendix A

### A1. EFFECT OF NEIGHBOURHOOD ORIENTATION ON EQUATION FOR MATCHING SIMILAR ZONES

In order to assess whether Equation (9) can accurately locate similar zones within a panel, it is necessary to verify its validity. To do this the best test would be to apply this rule to the base panel SB01 and check if this rule can perfectly match similar zones in both sides of the line of symmetry.

The base panel SB01 (Figure 2) was divided into thirty-six zones based on the experimental measured points A1 – A9, B1 – B9, C1 – C9 and D1 – D9. Considering the symmetry of the panel along the vertical central line, there are only 20 different zones on the panel, for instance, Zone D2 is similar to itself and Zone D8.

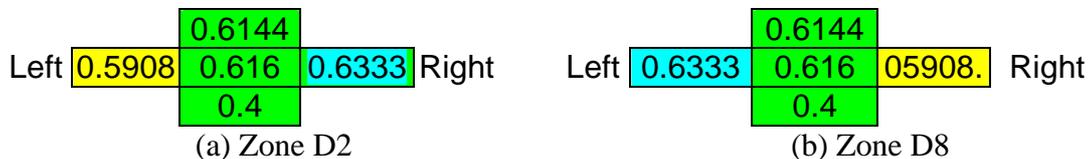
For this investigation, Zones D2 and D8 are used. By inspection, Zone D2 must match Zone D8. The CA method is used to establish state values for each zone in the panel using Equations (7) and (8). Results of the CA analysis are summarised in Table 1A. Equation (9) is then applied to calculate errors between Zones D2 along with their four neighbourhood zones with every other zone and their corresponding four neighbourhoods on the panel. Results of this analysis for Zone D2 are summarised in Table 2A.

**Table 1A** – State Values of Panel SB01 Calculated by Equations (7) and (8)

State Values		1	2	3	4	5	6	7	8	9	
		0	0	0	0	0	0	0	0	0	
A	0.2	0.5517	0.577	0.5942	0.6042	0.6075	0.6042	0.5942	0.577	0.5517	0.2
B	0.2	0.5764	0.6016	0.6189	0.6289	0.6321	0.6289	0.6189	0.6016	0.5764	0.2
C	0.2	0.5892	0.6144	0.6317	0.6417	0.6449	0.6417	0.6317	0.6144	0.5892	0.2
D	0.2	0.5908	0.616	0.6333	0.6433	0.6465	0.6433	0.6333	0.616	0.5908	0.2
		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	

**Table 3** - Errors of Zone D2 to all other zones calculated using Equation (9)

SB01	1	2	3	4	5	6	7	8	9
A	1.0745	0.6803	0.752	1.2062	1.3278	1.1993	0.752	0.6872	1.0745
B	0.8413	0.6059	1.0839	1.8016	2.2591	1.8016	1.0839	0.6059	0.8414
C	0.8676	0.6193	1.1389	2.0001	2.477	2.0001	1.1389	0.6193	0.8676
D	0.4332	0	0.1445	0.6852	0.6878	0.6002	0.0939	0.085	0.4838



**Figure 1A** - State values of Zones D2 and D8 along with their four neighbourhood zones

The results of matching similar zone in Table 2A clearly shows that the minimum error for matching Zone D2, using Equation (9), to every other zone within the panel is Zone D2 itself with the error value of 0.0, and another similar zone D8 with the error value of 0.085. Therefore, it can be concluded that Equation (9) was able to effectively locate two similar zones within the panel. In order to establish the robustness and generality of Equation (9) and to ensure that the CA is able to locate all possible occurrences of similar zones within a panel it would be necessary to have

a closer look into the orientation of the neighbourhood zones according to their positions from the boundaries of the panel, and make sure that these factors are included in Equation (9). To explain this point better, Figure 1A(a) and (b) show the state values of Zone D2 and its identical symmetrical zone D8 along with their four neighbourhoods with one difference that the state value of the neighbourhood zone on the right of Zone D2 is the same as that of the zone on the left of Zone D8. Therefore, in order to calculate the minimum error using Equation (9) the order of zones on the left and right hand sides of Zone D8 must be reversed.

## A2. FURTHER IMPROVEMENT OF MATCHING ZONE SIMILARITY METHOD

The following section proposes some improvements in using Equation (9) in order to ensure the robustness and generality of this equation and make sure that the manual process of dividing the panel into several regions can be avoided and enables the CA to automate the process of matching similar zones within the panels.

From the investigation presented in Appendix A it is clear that for proper matching of similar zones the orientations of the four neighbouring zones were essential in matching similar zones within a panel.

Considering a fixed orientation for zones within the base panel, each zone within a new panel has eight possible orientations that match the boundaries of the base panel (four facing the front of the panel and four facing the back of the panel. These eight possible orientations are shown in Figures 1B and 2B.

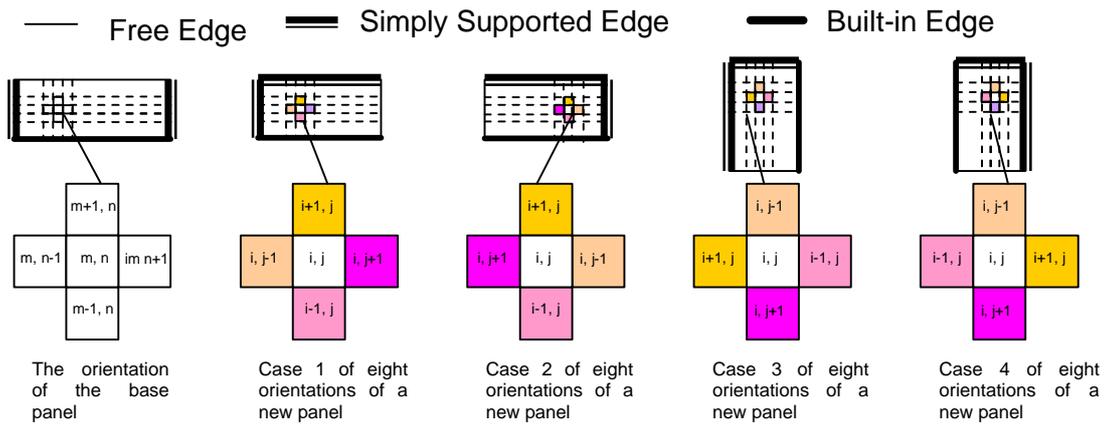


Figure 1B: Four possible for orientations facing the front of the wall

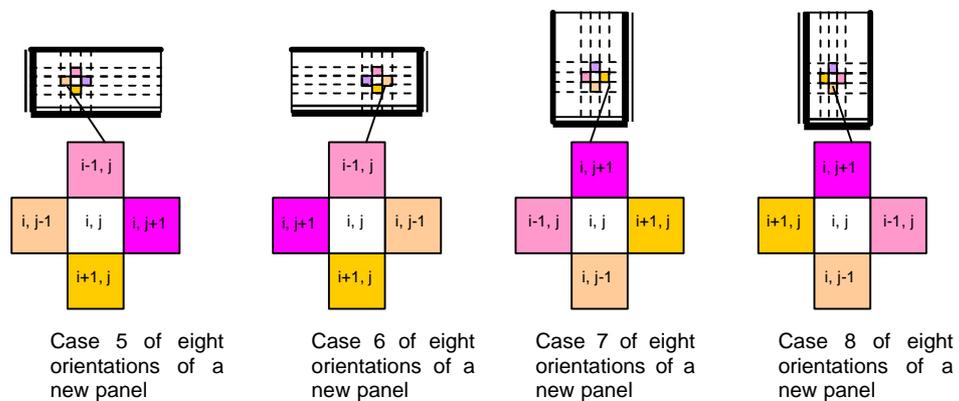


Figure 2B: Four possible for orientations facing the back of the wall

Figure 4 - Eight orientations of a new panel to the base panel

Thus, for a zone and its four neighbourhood zones on the new panel, and every zone and its four neighbourhoods on the base panel, Equation (9) is repeatedly used to calculate the errors of the state values of the corresponding zones for eight different orientations for zones on the new panel. For instance, for case 1 of the eight orientations of a new panel to the base panel, the corresponding equation of the error  $E_{k,l,1}^1$  is shown in Equation (10).

$$E_{k,l,1}^1 = \underset{m=1, n=1}{MIN}^{M, N} \left( \left| S_{i,j}^{new} - S_{m,n}^{sta} \right| + \left| S_{i,j-1}^{new} - S_{m,n-1}^{sta} \right| + \left| S_{i,j+1}^{new} - S_{m,n+1}^{sta} \right| + \left| S_{i-1,j}^{new} - S_{m-1,n}^{sta} \right| + \left| S_{i+1,j}^{new} - S_{m+1,n}^{sta} \right| \right) \quad (10)$$

where

M – the row number of zones within the base panel;

N – the column number of zones within the base panel;

( $kI, lI$ ) – the similar zone within the base panel with Zone ( $i, j$ ) within the new panel under Case  $I$ .

For case 2 of the eight orientations of a new panel to the base panel, rearrange the corresponding items in Equation (9), based on the orientation of the new panel in this case (see Figure 4), and obtain the error  $E_{k,l,2}^2$  as shown in Equation (11)

$$E_{k,l,2}^2 = \underset{m=1, n=1}{MIN}^{M, N} \left( \left| S_{i,j}^{new} - S_{m,n}^{sta} \right| + \left| S_{i,j+1}^{new} - S_{m,n+1}^{sta} \right| + \left| S_{i,j-1}^{new} - S_{m,n-1}^{sta} \right| + \left| S_{i-1,j}^{new} - S_{m-1,n}^{sta} \right| + \left| S_{i+1,j}^{new} - S_{m+1,n}^{sta} \right| \right) \quad (11)$$

Similarly, Errors  $E_{k,l,3}^3, \dots, E_{k,l,8}^8$  can be calculated based on their orientations.

Once eight error values,  $E_{k,l,1}^1, E_{k,l,2}^2, \dots, E_{k,l,8}^8$ , are calculated then, the minimum of these eight errors is obtained by:

$$E_{k,l} = \underset{p=1}{MIN}^8 (E_{kp,lp}^p) \quad (12)$$

Thus the zone ( $i, j$ ) in the new panel is similar to the zone ( $k, l$ ) in the base panel, which corresponds to the minimum error, see [2] for full details. Once a similar zone on the base panel is located for a zone on the new panel, the value of the corrector which corresponds to this zone on the base panel is assigned for the zone on the new panel and the flexural rigidity or tensile strength of the zone in the new panel is modified using its corrector factor for the FEA analysis.