GENERALITY OF USING CORRECTORS TO PREDICT THE BEHAVIOUR OF MASONRY WALL PANELS

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ABSTRACT: The highly composite and anisotropic nature of masonry, which is a result of the variation in the properties of the masonry constituents, makes it very difficult to find an accurate material model to predict its behaviour satisfactorily. Current research by the authors has focused more closely on the behaviour of laterally loaded masonry wall panels using model updating techniques supported by artificial intelligence (AI) tools. They developed the concept of corrector factors which models the variation in the properties over the surface of masonry wall panels. This research resulted in methodologies, which enables designers to more confidently predict the behaviour of masonry wall panels subjected to lateral loading. The paper will demonstrate the generality of using these techniques to predict the behaviour of laterally loaded masonry wall panels tested by various sources.

KEYWORDS: corrector factors, evolutionary computation, cellular automata.

1 INTRODUCTION

Masonry is a highly composite and anisotropic material which is constructed from layers of brick joined by thin layers of cement and sand mortar. Research on masonry panels subjected to lateral loading, started from around 1970 and continues to the present date (West et al 1971, 1975, Baker & Franken 1976, Fried 1989, Lawrence 1991, Chong 1993, among others). These researchers have tried to find acceptable models for predicting the behaviour of laterally loaded masonry walls. To date these attempt have not produced a reliable and accurate technique which can confidently predict both failure load and load deflection relationship for laterally loaded masonry wall panels.

Model updating techniques, which are based on minimising the error between the experimental and analytical results to select a suitable analytical model from among many possible alternatives, have produced good results in structural damage detection. The majority of the research on model updating process involves computing sets of stiffness coefficients that help predict observed vibration modes of structures. The location and extent of damage are inferred through a comparison between the stiffness coefficients of damaged and undamaged structures. A comprehensive literature review of various model updating methods is presented by Robert-Nicoud et al (2005). Friswell & Mottershead (1995) provide a survey of model updating procedures in structural damage detection research, using vibration measurements. Recent papers published in this area include Brownjohn et al (2003), Castello et al (2002), Teughels et al (2002), Modak et al (2002), Hemez & Doebling (2001), Sohn & Law (2001), Hu et al (2001). The authors have used a numerical model updating technique to investigate the behaviour of masonry wall panels subjected to lateral loads (Rafiq et al 2006).

2 A BRIEF SUMMARY OF THE PROPOSED METHOD

Zhou (2002) and Rafiq et al. (2003) developed a numerical model updating technique that more accurately predicts the failure load and failure pattern of masonry wall panels subjected to lateral loading. In this research they introduced the concept of *stiffness/strength corrector factors,* which assigns different values of flexural rigidity or tensile strength to various zones within a wall panel. These modified rigidities or tensile strength values were then used in a non-linear finite element analysis (FEA) model to predict the deflection and failure load of the masonry panels subjected to lateral loading.

Corrector factors were defined from the comparison of laboratory measured and finite element analysis (FEA) computed values of displacements over the surface of the panel. In this investigation a number of experimental panels with different configuration, geometric properties, aspect ratios, and panels with and without opening were used, and stiffness corrector factors for these panels were determined. From a comparison of the contour plots of corrector factors on these panels it was discovered that there appeared to be regions, termed '*zones*'**,** with similar patterns of corrector factors, which are closely related to their positions within the panel from similar boundary types. In other words, zones within two panels appear to have almost identical corrector factors if these zones were located the same distance from similar boundary types

Rafiq et al. (2003). This pattern was observed for all panels with different boundary condition and geometrical configurations.

Based on this finding Zhou et al. (2003) developed methodologies to establish zone similarities between various panels. In order to achieve a more reasonable and automatic technique for establishing this zone similarity between a *base panel* and any new panel, a cellular automata (CA) model was developed. This CA model propagates the effect of panel boundaries to zones within the panel. The CA assigns a unique value the so called *'state value'* for each zone within the base panel and an unseen panel, based on their relative locations from various boundary types. The CA then identifies similar zones between two panels by comparing similar state values of zones on two panels. Zones on two panels are considered to be similar if they are surrounded by similar boundary types and have similar distances from similar boundary types, thus have similar *'state values'*.

Further investigation of corrector factors (Rafiq et al 2006), using evolutionary computation and regression analysis techniques, revealed that the pattern of corrector factors that modify flexural rigidities were mainly altered around the panel boundaries with relatively minor changes inside the panel. This was a major finding of this research.

Difficulties in correctly modelling boundary types is a well known problem even for materials like steel and concrete with well defined and well controlled joint details between various elements and supporting structures. This issue is more critical for masonry panels as standard boundaries such as fully fixed and simply supported boundary types, used in FEA models, are not realistic for masonry. The results of our research proved that a better prediction of panel response to lateral loading would be possible if the panel boundaries are modelled more accurately.

A closer study of the corrector factors revealed that a reduction in the corrector factor values around the fixed boundaries has a softening effect on the zones adjacent to this boundary type. This is a reality as it is impossible to have a fully fixed boundary for masonry panels as there is always some degree of rotation at these supports. Similarly an increase in corrector factors near the simply supported boundaries signifies a degree of restraint to rotation at these boundaries which is perfectly logical (Rafiq et al 2006).

In order to demonstrate the generality of this concept, a single panel (Panel SBO1 Rafiq et al 2006) tested by Chong (1993) was used as a '*base panel'*.

The corrector factor values for this panel are summarised in Table 1. These corrector factors from the base panel are then used to establish an estimate of the corrector factors for any *'unseen panels'* for which no laboratory tests are available. A cellular automata model was used to establish zone similarities between any unseen panel and the base panel. Zones on two panels are considered to be similar if they are surrounded by similar boundary types and having similar distances from similar boundary types.

Table 1. Corrector factor values for the base panel SB01.

SB01	**X1**	**X2**	**X3**	**X4**	**X5**	**X6**	**X7**	**X8**	**X9**
Y4	1.283	1.278	1.277	1.277	1.277	1.277	1.277	1.278	1.283
Y3	1.187	1.181	1.181	1.181	1.181	1.181	1.181	1.181	1.187
Y2	0.926	0.921	0.92	0.92	0.92	0.92	0.92	0.921	0.926
Y1	0.223	0.218	0.217	0.217	0.217	0.217	0.217	0.218	0.223

As was shown in this study, the major factor that affects the behaviour of a panel was the panel boundary types. The corrector factors not only model this, but also take care of the variation in the material and geometric properties and other unknown effects. One of the objectives of this research was to use these corrector factors to predict the behaviour of unseen panels with and without openings and panels for which the boundary conditions are different from the base panel.

3 GENERALIZATION

By generalization we mean to test the generality of the corrector factors for a number of new panels tested by other sources which may be totally different from the base panel in terms of size, aspect ratio, geometry, material and workmanship.

4 CASE STUDIES

In this section, a number of masonry wall panels with different boundary conditions, different dimensions and panels with and without openings, obtained from various sources, are analysed to demonstrate the generality of the proposed method. The corrector factors for any all masonry wall panels, presented in these case studies, are derived from those of the base panel shown in Table 1. A cellular automata model is used to establish zone similarity between the base panel and the new panel. The results of this study are summarised in the following section. For all examples used in these case studies, the material properties used are from the original sources. However, if these properties are not available, the data from tests carried out in the University of Plymouth (Chong 1993) are used.

4.1 *Analyses of panels tested in University of Plymouth*

In this section, two full scale single leaf masonry wall panels (SB02 & SB04), tested in the University of Plymouth (Chong 1993), are selected for validation purposes. These panels have the same dimensions and boundary conditions as SBO1, but panel SB02 has a single opening at its centre to simulate the existence of a window and panel SB04 has an opening to simulate the existence of a door. Details of the configurations of these panels are shown in Figures 1 & 2 respectively.

It should be noted that these panels were tested by Chong (1993) at the University of Plymouth. The reason for selecting these panels is that it is easy to compare the predicted and experimental result to check the validity of the proposed methods.

Corrector factor values for all panels used in the case studies are derived for the base panel (Table 1) using CA to establish zone similarities between new panels and the base panel.

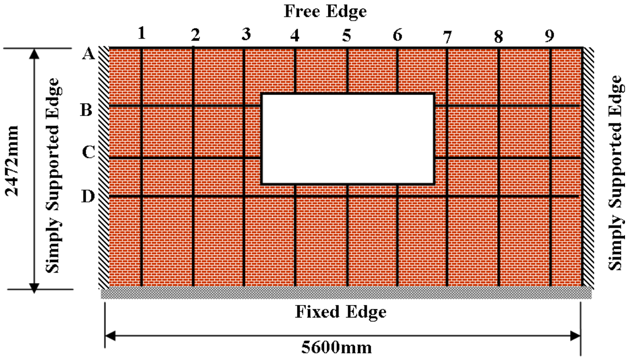

Figure 1. Panel SB02, measurement points at grid intersections.

Corrector factor values for panel SB02 and SB04, derived from the base panel (Table 1), are shown in Tables 2 and 3 respectively. These corrector factors are used to modify the flexural rigidity of each zone in the panel. In this study, for ease of use in the FEA models, only the modulus of elasticity of each zone is multiplied by the corrector factor value of each zone. These corrected values of modulus of elasticity are then used in a non-linear finite element analysis model to evaluate the predicted deflection at the corners of each zone and the failure load for the panel. The corrector factors not only model the boundary effects, but also model variation in the material and geometric properties and other unknown effects.

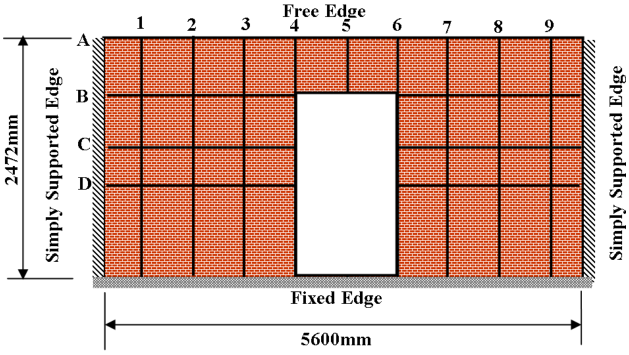

Figure 2. Panel SB04, measurement points at grid intersections.

Table 2. Panel SB02 zone divisions and corrector factors.

SBO2	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Y5	1.283	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.283
Y4	1.187	1.181	1.278					1.278	1.181	1.187
Y3	1.187	1.181	1.278					1.278	1.181	1.187
Y2	1.187	1.181	1.181	1.277	1.277	1.277	1.277	1.181	1.181	1.187
Y1	0.223	0.217	0.217	0.218	0.218	0.218	0.218	0.217	0.217	0.223

Table 3. Panel SB04 zone divisions and corrector factors.

SBO4	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Y5	1.283	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.283
Y4	1.187	1.181	1.181	1.278			1.278	1.181	1.181	1.187
Y3	1.187	1.181	1.181	1.278			1.278	1.181	1.181	1.187
Y2	1.187	1.181	1.181	1.278			1.278	1.181	1.181	1.187
Y1	0.223	0.218	0.218	1.278			1.278	0.218	0.218	0.223

Figure 3 shows a 3D deformed shape of the panel, comparing the experimental and FEA predicted displacements at various locations on the panel SB02. Apart from minor discrepancies in locations near the boundaries of the opening, FEA results give a good prediction of the displacement over the entire surface of the panel. It should be noted that the 3D plots cover only regions of the panel where load deflection data were available, they do not extend to the boundaries of the panel (e.g. for panel SB02 it covers regions from A1- A9 to D1-D9).

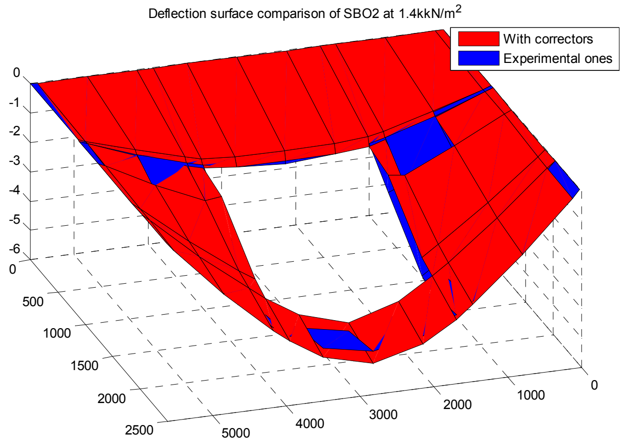

Figure 3. Panel SB02, comparison of 3D deformed shape showing experimental and the FEA results at 1.4kN/m^2.

Figure 4 shows similar information for panel SB04. Once again there is a very good match between experimental and FEA predicted deformed shapes.

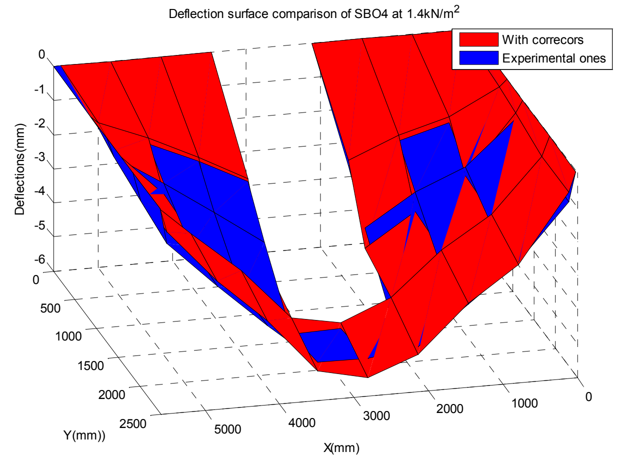

Figure 4. Panel SB04, comparison of 3D deformed shape showing experimental and the FEA results at 1.4kN/m^2.

To demonstrate the generality of the proposed method, 2D load displacement plots at various locations on the panels SB02 and SB04 are presented in Figures 5 and 6. The reason for selecting these plots is to investigate if there is a consistent correlation between experimental and the FEA predicted deflection at various load levels and at various locations on the panel. The points were selected to be representative of the entire surface. In these Figures three different curves are plotted (1) the experimental load deflection curve; (2) the predicted load deflection curves using corrector factor values derived from a single base panel (SB01) and the standard smeared material model normally used in FEA analysis. A very good correlation is observed between the experimental and analytical results using the corrector factors. The result from the predicted load deflection using corrector factors is much closer to the experimental results than that of the smeared material model. Moreover, the predicted failure loads for both panels, using corrector factors, are much better than those of the smeared model.

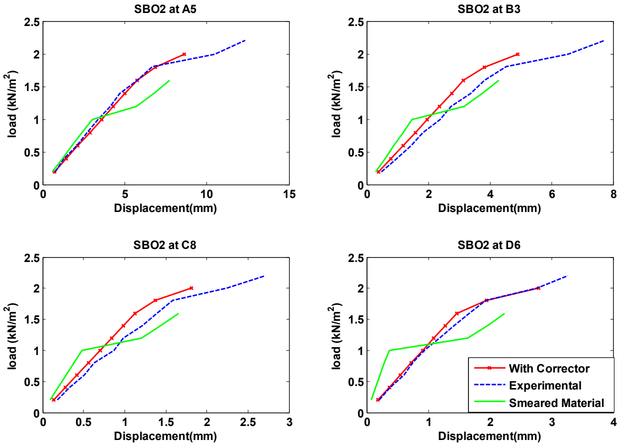

Figure 5. Panel SB02, Comparison of the load deflection relationship showing experimental and the FEA results.

From this investigation it can be concluded that the proposed method results in an improved prediction of both failure load and load displacement of a panel even if the geometries of the new panels are different from the base panel.

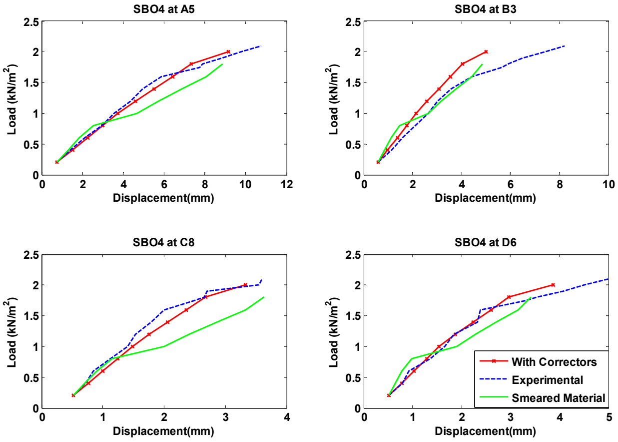

Figure 6. Panel SB04, Comparison of the load deflection relationship showing experimental and the FEA results.

To further examine the generality of the proposed method presented in this paper, a number of panels tested by other sources, for which little or no information on material properties and testing methods were available, are selected. Corrector factors for all these panels were derived from a single base panel (SB01), as has been introduced in this paper. It should be noted that these panels have different dimensions, configuration and boundary conditions than the base panel (SB01).

It is also worthwhile mentioning that load deflection data for the panels presented in the following sections were limited to a few points over the surface of the panel, which was not enough to generate an acceptable 3D load deflection surface plot, therefore, the comparisons were restricted to 2D load deflection plots only.

4.2 *Analyses of panels tested by (CERAM)*

In the UK, CERAM is a reliable source of information on various aspects of masonry. CERAM has been involved in testing of full scale masonry panels investigating various material types, boundary conditions, aspect ratios etc. for over 25 years. In this paper the authors have selected two panels, one solid panel (CR1) and one panel with a single central opening (CR2), to investigate the generality of the proposed method. The results of the investigation on both panels are presented in the following sections.

4.2.1 Panel CR1

Wall CR1 (Edgell 1995b) is a single leaf masonry panel constructed with Fletton brick with three sides simply supported and the top edge free. This panel has a dimension of 2800mm x 3600mm. The configuration of wall CR1 is as shown in Figure 7. Measurements of load deflection were recorded at 11 locations on this panel.

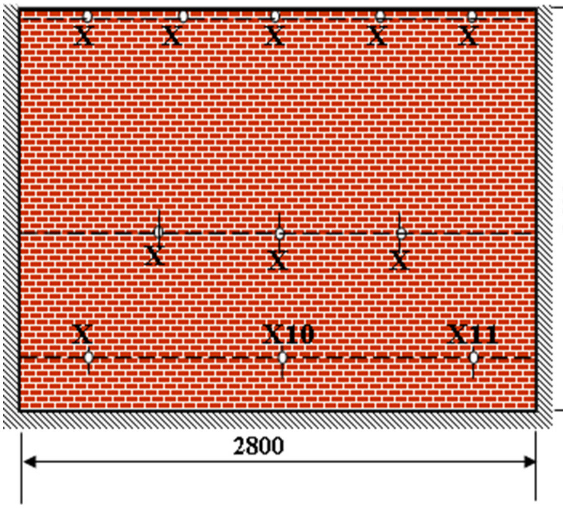

Figure 7. Configuration of Wall CR 1.

The flexural strengths measured from the wallet tests for this panel are given as: 1.40N/mm^2 perpendicular to the bed-joints and 0.40N/mm^2 parallel to the bed-joints. No information was available for the elastic modulus and Poisson's ratio. Therefore, the elastic modulus and Poisson's ratio are assumed to be the same as the base panel SB01. Corrector factors for this panel, also derived from panel SB01, are shown in Table 4. From Figure 8, it can be concluded that:

The smeared material model gives a poor correlation with the experimental results.

The corrector factors improve both load deflection and failure load results which are close to the experimental results at a number of locations.

The correlation between load deflection at the location of maximum deflection is much better than other locations. This is a good measure of comparison as in practice maximum deflection and stresses are critical design requirements.

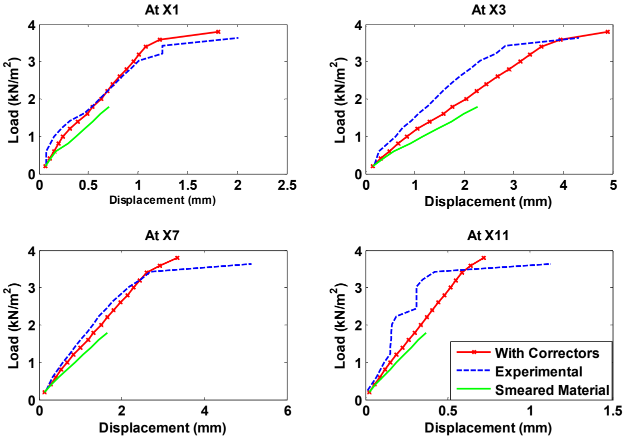

Figure 8. Panel CR1 Comparison of the load deflection relationship showing experimental and the FEA results.

Table 4. Corrector Factors of Wall CR1

Wall CR1	X1	X2	X3	X4	X5	X6
Y5	1.283	1.278	1.278	1.278	1.278	1.283
Y4	1.187	1.181	1.181	1.181	1.181	1.187
Y3	1.187	1.181	1.181	1.181	1.181	1.187
Y2	1.187	1.181	1.181	1.181	1.181	1.187
Y1	1.187	1.187	1.187	1.187	1.187	1.187

4.2.2 Panel CR2

Wall CR2 (Edgell 1995a) is a single leaf masonry wall panel with a single central opening. This panel was also tested by CERAM. The panel was constructed with Fletton brick with three sides simply supported and the top edge is free. The panel dimensions are 5500mm x 2800mm with the opening size 2000mm x 1200mm. Details of the wall and location of measurement points are shown in Figure 9.

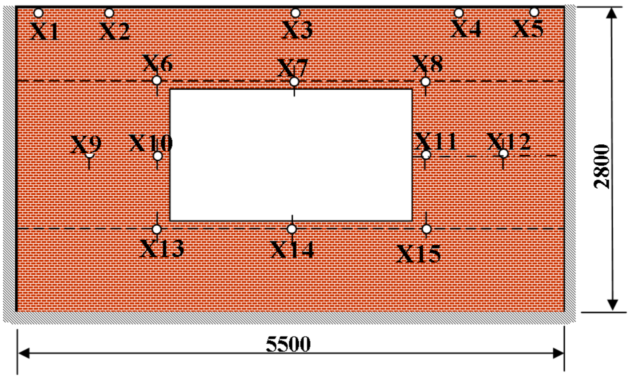

Figure 9. Configuration of Wall CR 2.

The mean flexural strengths for this wall measured from the wallette tests are: fx =1.37N/mm^2 and fy=0.42 N/mm^2. However, the elastic modulus E and Poisson's ratio are not included in the original data, therefore material properties are assumed to be : E=12.0kN/mm^2, ν=0.2, same as the base panel.

The corresponding corrector factors for this panel, derived from panel SB01, are as shown in Table 5. Figure 10 shows load deflection plots at 4 selected locations on the panel. From Figure 10, it is clear that using corrector factors, both the failure load and load deflection curves are much closer to the experimental results.

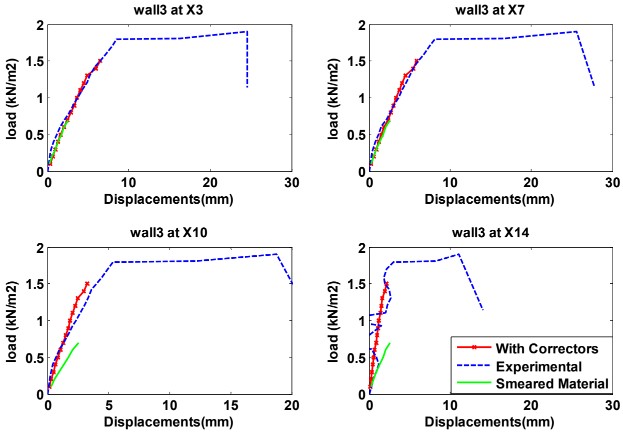

Figure 10. Load deflection relationships of Wall CR 2 using correctors.

Table 5. Zone Division and Correctors for Wall CR 2.

Wall CR2	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10
Y4	1.283	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.278	1.283
Y3	1.187	1.181	1.278					1.278	1.181	1.187
Y2	1.187	1.181	1.278					1.278	1.181	1.187
Y1	1.187	1.187	1.187	1.187	1.187	1.187	1.187	1.187	1.187	1.187

4.3 *Analyses of panels tested by University of Edinburgh*

It is worth mentioning again that like the majority of the masonry panels tested around the world the information obtained from panels tested in the University of Edinburgh measures only deflection at a single critical location in the panel. Therefore for the panel presented in this section, only 2D plots of load deflection at the location of maximum displacement are presented.

4.3.1 Panel wall 9

Wall 9 is a single leaf masonry wall panel, tested in the University of Edinburgh (Liang 1999). This panel is simply supported on its 3 edges and the top edge is free. The Panel dimension is 795mm x 1190mm. The reason for selecting this panel for investigation is that this is a much smaller panel than the base panel SB01 and its aspect ratio is also different. If the corrector factors from the base panel SB01 are suitable for predicting the failure load and load deflection for this panel then this would give us more confidence on the validity of the proposed method.

Table 6. Correctors of Wall 9.

Wall 9&13	X1	X2	X3
Y1	1.283	1.278	1.283
Y2	1.187	1.181	1.187
Y3	1.187	1.181	1.187
Y4	1.187	1.181	1.187
Y5	1.187	1.187	1.187

The flexural strength parallel and perpendicular to the bed joints were obtained from the wallette test, which are respectively 3.5N/mm^2 and 0.98 N/mm^2. The values of corrector factors, derived from the base panel are summarised in Table 6. Figure 11 shows a comparison of experimental and predicted load deflection curves at the location of maximum deflection. From Figure 11 it is clear that there is a good agreement between experimental and predicted results, which demonstrates the generality of the proposed method.

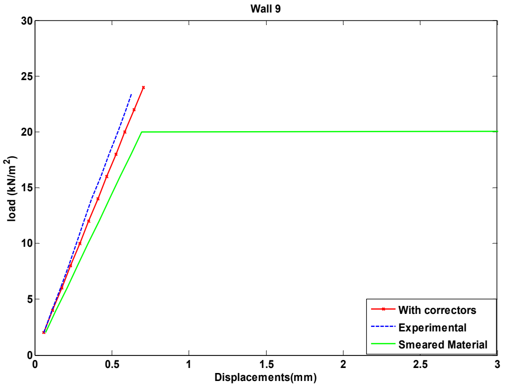

Figure 11. Load deflection relationships of Wall 9 using correctors.

5 CONCLUSION

The research presented in this paper introduces a novel approach using a numerical model updating technique supported by AI for predicting the behaviour of masonry wall panels much better than any other analytical model used so far. This method has the potential to be extended beyond masonry brick walls and could also be used with other materials to reduce the degree of uncertainty in analytical models and analytical results. The simplicity of the model is that once corrector factors for a representative base panel are determined it would be easy to use these factors for any panels using zone similarity techniques.

In this research, corrector factors from a single panel tested in the laboratory were used for a number of unseen panels with different boundary types, size and configurations. The results produced a more accurate prediction of the behaviour of the laterally loaded masonry wall panels.

Incorrect modelling of boundary types produces incorrect analytical results. Using corrector factors minimises this error and corrects the error in modelling to a great extent.

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