NUMERICAL MODELING OF FRAMED DRY STACK MASONRY PANELS

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Abstract

A new masonry system is being developed in the Masonry Research Group at the University of Newcastle. It uses framed dry stack semi interlocking masonry panels. The major objective for developing this new dry stack masonry system is to improve the seismic performance and wind resistance of framed structures with masonry panels. An experimental program is being carried to evaluate the behavior of different framed masonry systems. A reinforced concrete (RC) frame 2.3 m wide and 2.3 m high was used for a series of in-plane cyclic tests. The initial testing included free vibration and cyclic tests on a bare RC frame and cyclic test on the RC frame in-filled with the dry stack concrete brick panel. In parallel with this experimental program, a FE model for this new masonry system was developed using DIANA software and has been verified from the experimental results. This paper reports results of the FE simulation of the initial tests.

Keywords: dry stack, confined, infill, interlocking, masonry panel.

Introduction

Although framed masonry panels are often considered non-structural elements, they are significantly more rigid than RC frame and hence may attract high seismic forces that could be damaging for panels and for frames. This is a typical cause of structural damage in columns repeatedly found after earthquakes. A very recent example that exposed the disadvantages of traditional RC framed masonry panels is Wenchuan earthquake in China [Zhao 2009].

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Most research in this area was concerned with the seismic behavior of traditional confined and infill masonry walls [Mehrabi 1997, Al-Chaar 2008, Tena-Colunga 2009]. Masonry infills are usually considered non-structural elements, their influence on overall structural response and interaction with the bounding frame are deliberately minimized and then ignored. However, in practice the behavior of an in-filled frame is strongly influenced by the interaction of the infill with the frame [Mehrabi 1996]. This interaction is even more critical for the confined masonry system.

It was shown that panels can improve the energy dissipation of the structure. However, most of the energy dissipation in traditional structures was accompanied by the damage to both RC frame and masonry panel such as crushing of bricks or cracking of concrete elements and masonry with the corresponding reduction in the stiffness of structure. In order to increase the energy dissipation (without damage related to the frame/panel interaction) a conceptually new system for framed masonry panel was proposed by Totoev [Lin 2011, Lin 2011]. According to this concept, masonry infills should no longer be considered as non-structural elements. Instead, they should be accepted as "non-gravity-load-bearing" structural elements fully participating in resisting horizontal loads. To achieve this positive contribution from masonry panels to horizontal load resistance, panels should (i) be less rigid in-plane of a wall and (ii) contribute mostly to the energy dissipation. It was proposed to build panels with dry stack masonry units capable of relative sliding in-plane of a wall and interlocked to prevent relative sliding out-of plane of a wall. We call it semi interlocking masonry.

This new system requires comprehensive parametric study. It would be too costly to conduct this study experimentally. Hence, the planned parametric study will be performed numerically using an experimentally verified FE model.

Dry stack masonry was researched and successfully modeled by the research team of Lourenco [Lourenço 2004, Lourenço 2005, Senthivel 2006]. The FE micro modeling approach was adopted in this research. Two different models were developed for the nonlinear behavior of joints: Coulomb friction law [Lourenço 2004] and "Composite Interface model" [Lourenço 2005]. Compared with the experimental results, both of them are adequate to represent the failure of dry masonry joints under moderate stress levels.

A representative FE model should combine both continuum and interface constitutive models for the frame/panel combine structure. A continuum model captures the behavior of the reinforced concrete in the frame and bricks in the masonry panel; an interface model captures the behavior of joints between individual masonry units and between the infill and frame [Al-Chaar 2008].

Because of the highly nonlinear behavior of this structural system, parameters attained from material tests should be adjusted to obtain a better match with the experimental results. Those parameters are mostly concerned with the interface element, such as normal/shear stiffness [Mehrabi 1997], friction factor [Lourenço 2005].

This paper reports a part of ongoing research project at the Centre for Infrastructure Performance and Reliability in the University of Newcastle. The main objective of this project is to investigate the behavior of framed semi interlocking dry stack masonry panels and compare it to that of the traditional masonry panels. The testing program included several tests: the cyclic displacement test on a bare RC frame; the free vibration test on a bare RC frame; the cyclic displacement test on a RC frame in-filled with the dry stack concrete brick panel (dry stack wall, for short); and the cyclic displacement test on a RC frame in-filled with traditional masonry panel (masonry wall, for short). Cyclic displacement tests were performed to investigate the strength, deformation capacity and stiffness degradation. The data obtained in this program was used as a base for the present numerical simulation.

Non-linear finite element analysis using the DIANA program has been carried out to simulate test results. In this numerical simulation interface and plane stress elements have been used.

Summary of Experimental Program

The aim of the performed experiments is to compare and investigate the cyclic behavior of different masonry panels. The test set-up is schematically shown in Figure 1. The cross section of rectangular base beam was 330 × 600 mm; the RC columns were 120 × 200 mm; the top beam was 120 × 300 mm with a 100 × 600 mm slab cast at the top of the top beam. The RC frame has been cast in three batches: (1) base beam; (2) RC columns; (3) top beam and slab. The interval between each batch was seven days.

The yield strengths of the reinforcement (D12: f_y = 400MPa; D10: f_y = 400MPa; D6: f_y = 210MPa) were determined in preliminary tests. For dry stack panel, solid concrete bricks with dimensions of 227×113×80 mm were used. This bricks did not have any out-of-plane interlocking. However, for in-plane behavior they were assumed equivalent to the semi interlocking masonry system.

It was difficult to achieve a tight fit between the panel and the beam. There was approximately 1mm uneven gap left at the top between these two elements.

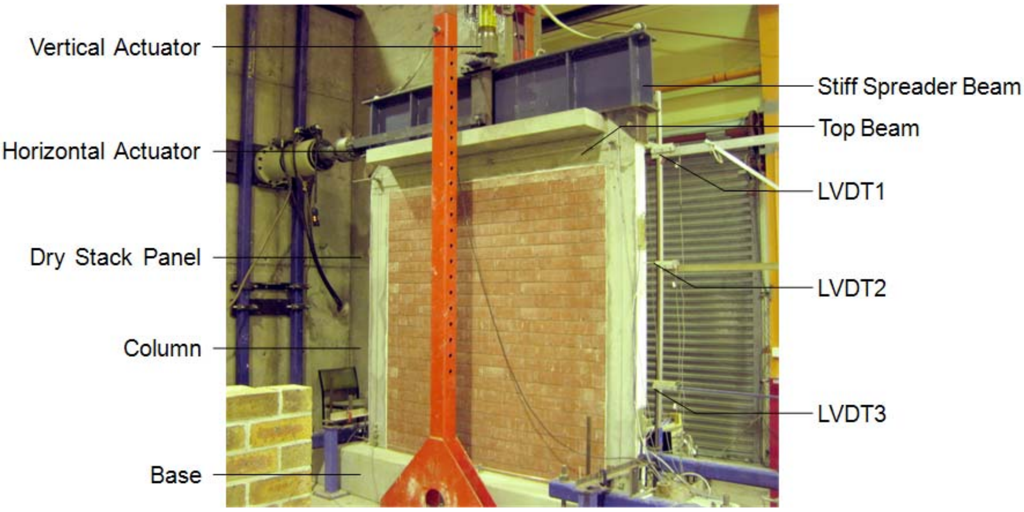


Figure 1. Set up of the Experiment

The base beam was fixed to the strong floor. Vertical compression of 0.3 MPa was applied by the vertical actuator fixed to the reaction frame. A stiff spreader steel beam was used to distribute the vertical load and a set of steel rollers were placed between the top of the beam and the vertical actuator to allow relative horizontal displacement. The cyclic displacement was applied through the horizontal actuator. The incremental static lateral displacement history is shown in Figure 2. The deflections of the specimen were measured by needle type Linearly Variable Differential Transducers (LVDTs). A number of free vibration tests were carried out first before the stiff beam was placed on top of the frame and actuators connected. The typical free vibration history curve (measured by LVDT1) is shown in Figure 3.

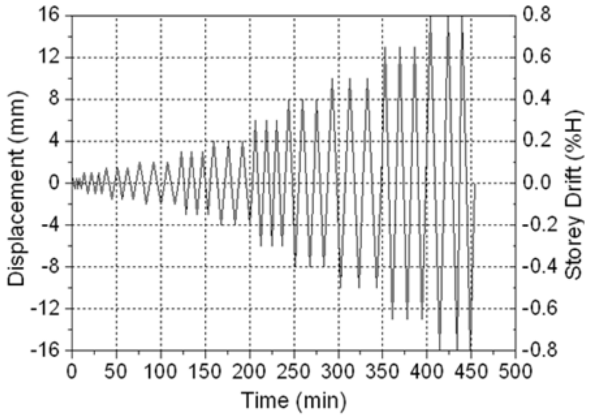


Figure 2. Applied Displacement History

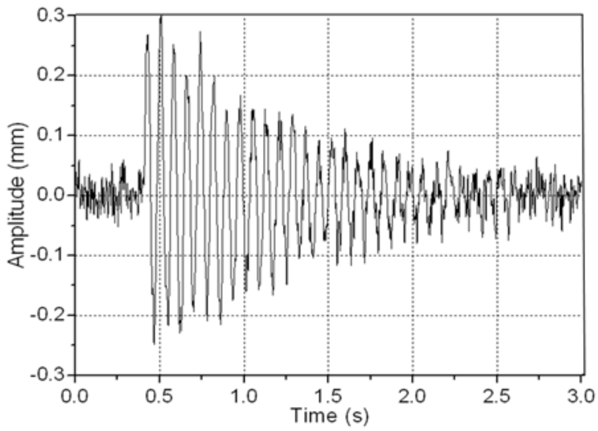


Figure 3. Typical Free Vibration Test Results

The induced horizontal force and displacement measured by LVDT positioned at the top of RC frame were recorded. The storey drift was calculated by dividing the measured displacement of top beam by the story height of 2 m. The cyclic test results for the bare frame and the frame in-filled with dry stack panel are shown in Figure 4 and Figure 5 respectively.

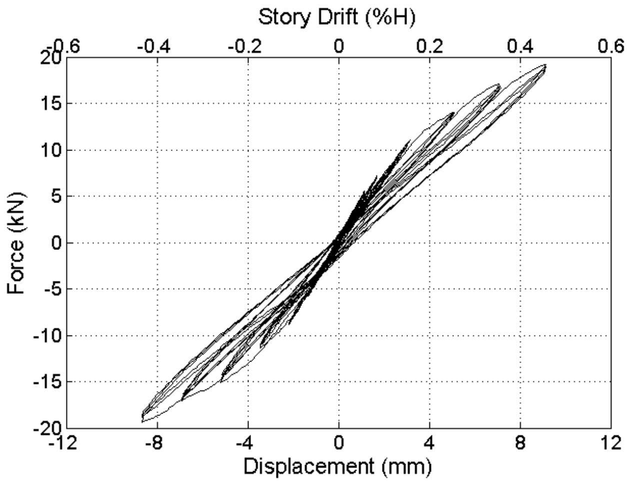


Figure 4. Cyclic Test of Bare Frame

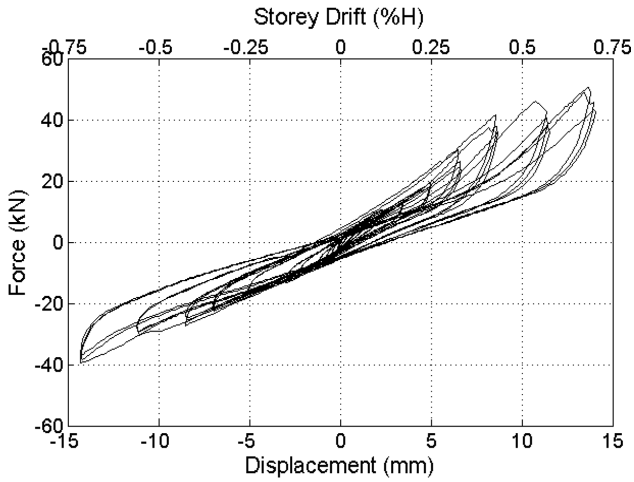


Figure 5. Cyclic Test of Frame with Dry Stack Panel

Finite Element Modeling

The experimental results by Lin [Lin 2011] have been used as a base for comparison in the present numerical analysis. A 2D non-linear finite element analysis has been carried out using the DIANA (version 9.2) software.

As discussed previously, both continuum and interface constitutive element were used in the model. For the concrete frame and bricks, an eight node continuum plane stress element has been chosen. This element is based on quadratic interpolation and Gauss integration. Both the joints between individual masonry units and joints between the infill and the frame are simulated using a six node zero thickness line interface element. A bar reinforcement element was embedded in the plane stress element to simulate the effect of reinforcement bars. The detailed parameters are presented below.

RC Frame

In this model, a perfect bond has been assumed between the concrete and the reinforcement bars. The Drucker-Prager yield criterion based on the multi-directed fixed crack theory is used to define the non-linear behavior of concrete where the ultimate tensile strain 0.0002 is achieved [Béton 1990]. The Von-Mises ideal plasticity material model is used for the steel reinforcement bars with a yield stress attained from the preliminary material tests. Both the friction and dilatancy angle are selected as the suggested value in accordance with DIANA manual [Witte 2002]. The material parameters used for the reinforced concrete frame are listed in Table 1.

Table 1. Parameters for Bare Frame

	Linear Behavior Parameters				Drucker-Prager Plastic Param.		
	Density (kg/mm^3)	Poisson's Ratio	Elastic Modulus (MPa)	Compressive Strength (MPa)	Tensile Stress (MPa)	Ultimate Strain	Cohesion (MPa)
Base	2366	0.2	32000	21.8	2.93	0.0002	9.156
Column	2281	0.2	25000	22.7	2.34	0.0002	9.534
Connection	2281	0.2	2500	22.7	2.34	0.0002	9.534
Top-Beam	2350	0.2	33000	23.4	3.3	0.0002	9.828

Because the RC frame was cast in three batches, the connections between different batches were planes of weakness in the structure. The frame also was transported in the laboratory by the crane with the slings attached to the top beam. This subjected those connections to the tension further weakening them. To account for this, four layers named "Connection" has been introduced near the top and bottom sections of both columns as shown in Figure 6. Their elastic modulus has been reduced to 10 percents of the column modulus, as listed in Table 1.

A thin layer of rubber like material has been introduced between the spreader stiff beam and the RC frame to account for the free play in the horizontal loading system during load reversals. The materials properties of this “rubber” are selected by trial and error to match the displacement of the column (LVDT 1-3, shown in Figure 1).

Dry Stack Masonry Panel

The bricks were modeled using an eight node continuum plane stress elements with Gauss integration. Joints between bricks and between the frame and the infill panel were modeled using six node and zero thickness line interface elements. Eight elements were used for each masonry unit.

For joints between individual bricks and between the infill and the frame, a Mohr-Coulomb criterion was used. For the shear behavior of the dry stack masonry joints, a value of 0.57 was determined experimentally for tan ϕ; and a value of zero was assumed for tanψ after [Lourenço 2005]. The normal stiffness and shear stiffness of the joint have been also taken from the literature [Lourenço 2005, Petersen 2009]. However, to achieve a better match with the experimental results, the shear stiffness of interface element has been reduced to one third in our model. It appears to be reasonable assumption because perfect surface to surface connection between bricks is difficult to achieve in practice. To avoid the singularity of matrix, a small value has been used instead of zero for tensile strength, cohesion and tanψ. The parameters used in the model are listed in Table 2.

Table 2. Material Parameters for Dry Stack Masonry Panel

	Density (kg/m^3)	Poisson’s Ratio	Elastic Modulus (MPa)	Friction Factor	Normal Stiffness (N/mm^3)	Shear Stiffness (N/mm^3)	Tension Strength (MPa)	Tension Energy (N/mm)
Brick	2250	0.2	27600	/	/	/	/	/
Joint	/	/	/	0.57	8.08	1.12	/	/
Crack	/	/	/	0.57	8.08	1.12	2.38	0.025

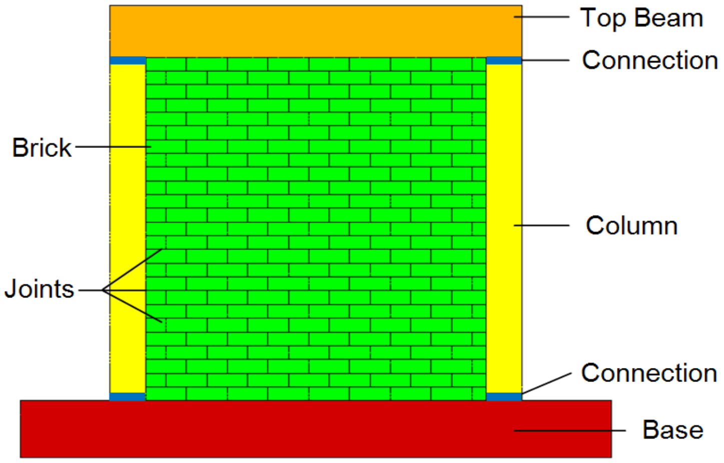


Figure 6. Finite Element Model for Frame with Dry Stack Panel

Loading Sequence

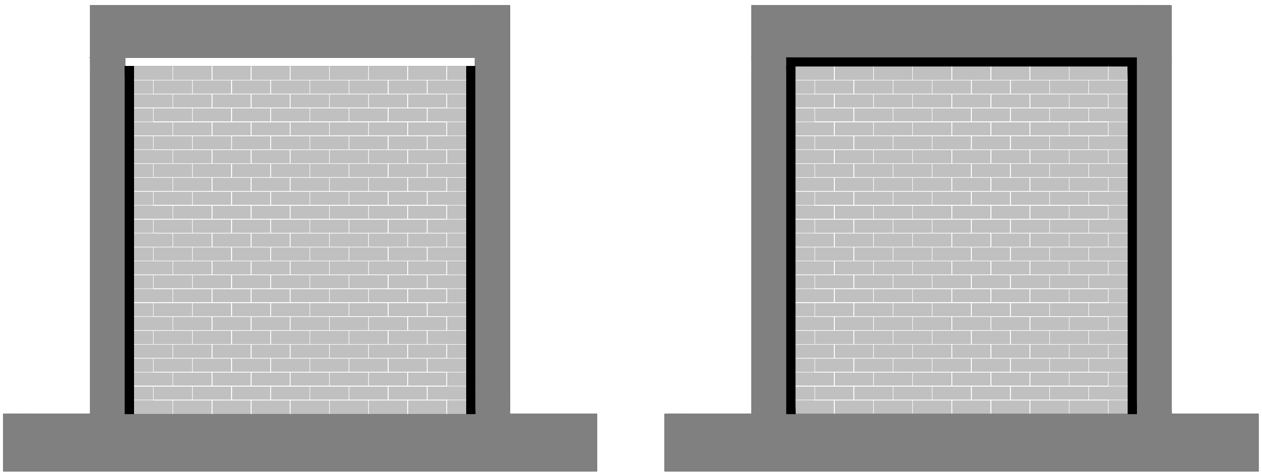
First, the gravity load for both masonry and frame was applied. After that the vertical load was applied at the top middle point and was kept constant, finally the lateral displacement was applied as shown in Figure 2. The finite element model of dry stack masonry infilled system is shown in Figure 6.

Frame/Panel Interaction

The results in Figure 5 are not perfectly symmetric because of the uneven gap at the top of the panel. This gap between the top of the panel and the frame has been very difficult to simulate. It is important to account for this gap because it significantly influences the overall behavior of the frame as described elsewhere [Lin 2011]. It was decided to simulate the "positive" branch of the curve as having more pronounced effect of the dry stack panel.

The interaction between the RC frame and the masonry panel is a continuum process. Ideally, the model should simulate this process with the gap closing and opening according to the combination of imposed loads and developed reactions. However, due to the limited number of available element types, this process has been divided into two stages: (i) gap is open and (ii) gap is closed. Two separate models have been used for simulation of each stage and the results have been combined. The only difference between these two models is the connection or disconnection between the RC frame and the top of dry stack masonry panel, as shown in Figure 7.

The moment of contact (applied horizontal displacement) is confirmed from the experimental results. When simulating the behavior, before contact, the model shown in Figure 7 (a) was used; after the contact, the model shown in Figure 7 (b) was used.



(a) Before Contact (b) After Contact

Figure 7. Models with and without the Gap at the Top of the Panel

Results

Several numerical simulations have been carried out to verify the developed FE model. These simulations included:

1. Natural frequencies and mode shapes analysis for the bare frame;
2. Non-linear analysis of the bare frame under constant vertical load and monotonic horizontal displacement;
3. Non-linear analysis of the frame with the dry stack panel under constant vertical load and monotonic horizontal displacement.

Most of the parameters for the non-linear models have been confirm from preliminary material tests. A limited number of parameters is taken as recommended by the DIANA software manual or from the literature. The numerical results were compared to the experimental results and some parameters have been adjusted to achieve reasonable matches to experiments.

Bare Frame Natural Frequency Analysis

Natural frequencies and mode shapes analysis for the bare frame was performed. The fundamental frequency of 15.1 Hz has been calculated. The corresponding mode shape is shown in Figure 8. The damped frequency of approximately 14 Hz and the damping of about 1.5% have been estimated from the free vibration test. These correspond to the fundamental frequency of a bit more than 14 Hz. The difference of about 7% was assumed acceptable for the dynamic test. The recorded mode shape was also similar to the calculated one.

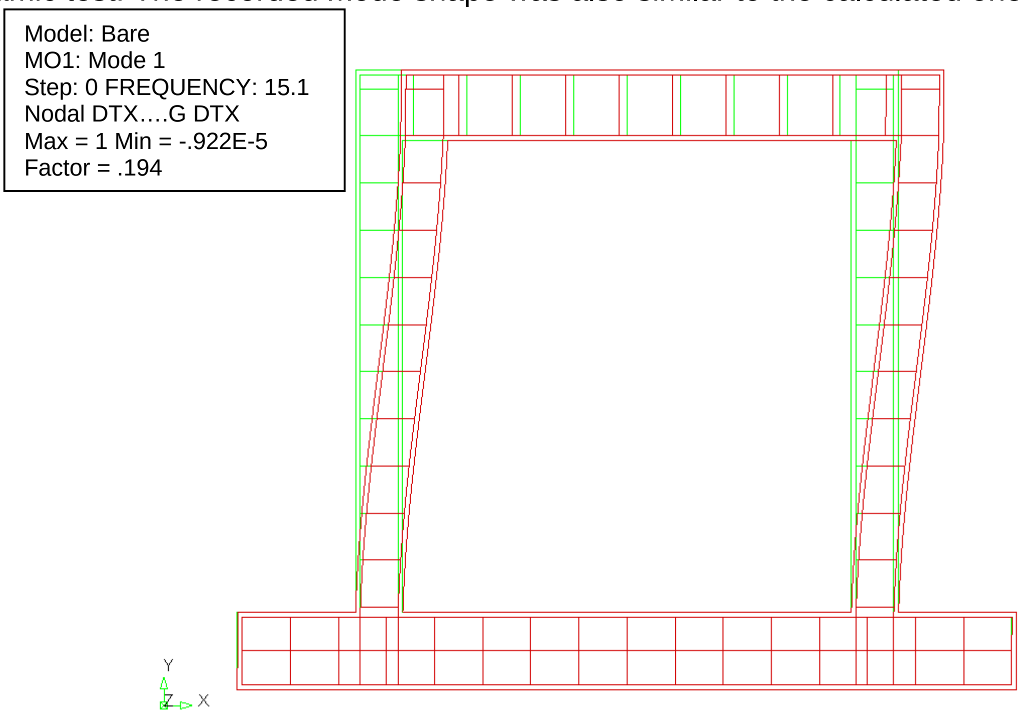


Figure 8. First Mode Shape for the Bare Frame

Bare Frame Non-Linear Analysis

The displacements are some of the most important verifiable targets for the modeling. The recorded displacements of three points have been used to make a comparison with the numerical simulation to confirm the parameters of the bare frame model. The comparison is presented in Table 3.

Table 3. Displacements of the Bare Frame (mm)

Imposed Horizontal Displacement (mm)		0.50	1.00	1.50	2.00	3.00	4.00	6.00	8.00	10.00	Average Difference (%)
LVDT1	Experiment	0.41	0.84	1.17	1.70	2.63	3.17	5.07	7.09	9.13	3.74
	FEM	0.41	0.83	1.26	1.70	2.60	3.50	5.37	7.30	9.24	
	Diff.(%)	1.72	-1.66	8.15	0.35	-1.07	10.62	6.00	2.93	1.19	
LVDT2	Experiment	0.30	0.61	0.84	1.24	1.89	2.26	3.64	5.15	6.54	3.52
	FEM	0.30	0.60	0.89	1.21	1.86	2.52	3.83	5.17	6.47	
	Diff.(%)	-1.33	-1.81	6.57	-2.26	-1.48	11.40	5.25	0.51	-1.09	
LVDT3	Experiment	0.13	0.26	0.36	0.55	0.85	1.00	1.64	2.30	2.92	7.29
	FEM	0.12	0.24	0.35	0.49	0.76	1.04	1.59	2.15	2.68	
	Diff.(%)	-8.40	-9.13	-4.12	-11.41	-10.14	4.72	-2.93	-6.48	-8.24	

The developed FE model for the bare RC frame has been used for two different numerical simulations (the natural frequency and the non-linear displacement). Numerical results have been compared to the experimental results and found acceptably accurate. It was concluded that the FE model of the bare frame is verified and representative.

Non-Linear Analysis of the Frame with the Dry stack Panel

Figure 9 shows the comparison between the horizontal load-displacement curves obtained from the non-linear finite element analysis and the experimental results. The experimental curves are the envelope curves for the hysteretic curves shown in Figures 4 and 5. As mentioned before, the numerical results for dry stack panel are the combination of two separate simulations. It can be seen from the figure, the finite element model is reasonably accurate. It captures all three different stages of structural response:

1. First stage – constant friction response. RC frame is interacting with dry stack panel compressed by its own weight only. The frame is not in contact with the top of the panel because of the gap between them. Frictional forces between bricks are therefore relatively small and constant. At this stage, the envelope response curve for the structure closely follows the response curve of the bare frame. The RC frame resists most of the applied horizontal force with the friction between bricks contributing approximately 2 kN to the strength of the structure;
2. Second stage – Mohr-Coulomb response. RC frame is now in contact with the top of the panel. This has two significant effects: (i) the friction between bricks is increasing due to increasing compression of the panel by the frame and (ii) a type of compressive

strut is formed within the panel similar to the traditional in-filled masonry panel. Comparing with the first stage, the stiffness of the structure has increased. At the end of this stage (about 8.5 mm displacement), the dry stack panel contributes more than half of the strength of the structure;

3. Third stage – plastic response. The RC frame is cracking and exhibits plastic behavior. Compared with second stage, the stiffness of the assembly has decreased to about the same as in the first stage. The damage to RC frame is assumed to be the reason. At this stage, the cracks are developing at column/beam connections, as shown in Figure 11. Cracks in these locations were also observed during the test. This stage cannot be compared to bare frame because bare frame test had been stopped at 10mm jack travel to avoid damaging frame.

However, the key parameter for this numerical simulation - the point at which the frame comes in contact with the panel has to be estimated with good accuracy.

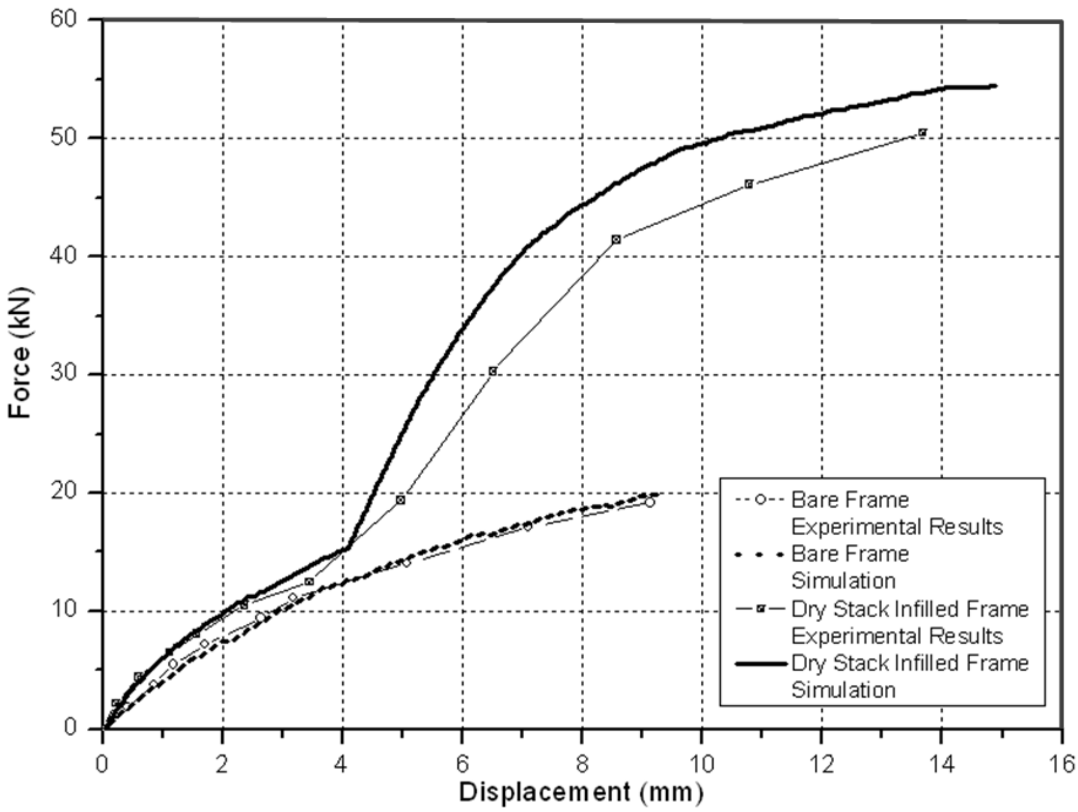


Figure 9. Load-Displacement Curves for Bare Frame and Frame with Infill

Figure 10 presents the deformation and the first principal stress at the end of numerical simulation. Slip between individual bricks can be seen as well as diagonal stress behavior indicative of the development of a compressive strut in the panel.

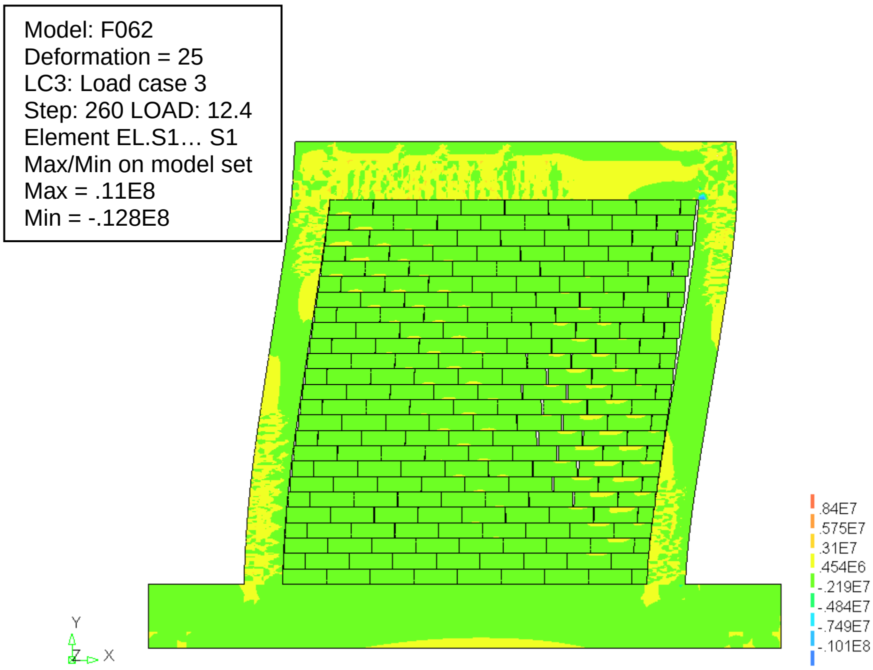


Figure 10. Deformations and the First Principal Stresses

Figure 11 presents the plastic cracks in the columns at the maximum applied horizontal displacement. From this figure, we can see the cracks concerned at the corner of the RC frame which is quite similar to the actual damage of the specimens.

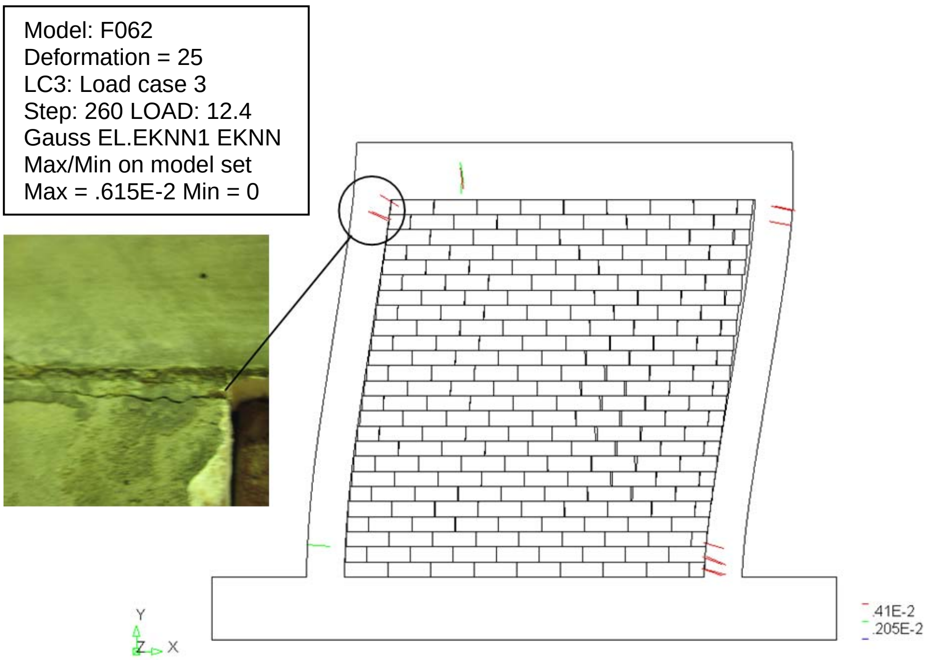


Figure 11. Damage of the Frame at 16 mm Displacement

Conclusions

- A new masonry system is being developed at the University of Newcastle. It uses framed dry stack semi interlocking masonry panels. The finite element model for this new system has been developed with the DIANA program;
- Parameters in the model have been adjusted to match the global behavior of test specimens. The model has been verified by comparing numerical simulations to the experimental results. Comparison included dynamic and non-linear static behavior;
- Modeling gap between the panel and the frame is the key to successful model;
- The developed model is capable of capturing complex structural response with good accuracy and is suitable for further numerical parametric study of the new masonry system.

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