13TH CANADIAN MASONRY SYMPOSIUM
HALIFAX, CANADA
JUNE 4TH – JUNE 7TH 2017

INFILL MASONRY INTERACTION WITH A SURROUNDING FRAME UNDER IN-PLANE LOADING

Brodsky, Alex[1]; Rabinovitch, Oded[2] and Yankelevsky, David Z.[3]

ABSTRACT

The interaction of unreinforced masonry infill walls with the surrounding frame is the key mechanism for the composite action of the structural element. This interaction is of importance under all types of loads but it is especially important under extreme loads such as earthquakes, vehicle impact, blast action etc. Due to the complex interaction and the resulting lack of knowledge regarding the composite action of the infill wall and the frame, the masonry infill wall is commonly considered in the structural design through oversimplified methods. Nevertheless, the interaction loads affect the infill wall behaviour and at the same time, they affect the failure mode of the frame. Therefore, it is crucial to characterize, understand, and evaluate this interaction and to establish models that can quantify the composite behaviour and assess the failure mechanism and the capacity of the composite system. Achieving these goals can improve the design tools for new buildings, enhance the assessment methods of existing buildings, and enable the development of advanced computational models. Aiming at these goals, this paper looks into the complex interaction phenomenon. The paper adopts an experimental methodology and an experimental setup that includes a masonry infill wall surrounded by a steel frame is used as the main experimental platform. The new experimental apparatus provides unique parameters of the interaction including the detection of the contact zone between the masonry wall and the frame and the assessment of the magnitude and its distribution of the contact tractions. This paper aims at describing the above and a few of the new findings.

KEYWORDS: *masonry, infill wall, in-plane, interaction, capacity, digital image correlation*

[1] PhD student, Faculty of Civil and Environmental Engineering, Technion Israel Institute of Technology, Haifa 32000, Israel, brod@technion.ac.il

[2] Professor, Abel Wolman Chair in Civil Engineering, Faculty of Civil and Environmental Engineering, Technion Israel Institute of Technology, Haifa 32000, Israel, cvoded@technion.ac.il

[3] Professor Emeritus, Faculty of Civil and Environmental Engineering, Technion Israel Institute of Technology, Haifa 32000, Israel, davidyri@technion.ac.il

INTRODUCTION

Vehicle impact, earthquake or blast action triggers loading condition that may severely damage the supporting columns of a skeletal structure. In such event, the infill wall plays a major role in maintaining the structural system's integrity and reducing the likelihood of a progressive collapse. As such, the contribution of the infill should be incorporated in the structural model. The loss of a supporting column causes a significant increase of the frame downward deflection, which is then restrained by the shear resistance of the masonry infill walls. This composite action is enabled through the development of interaction forces between the infill walls and the surrounding frame. The infill wall acts as a load transfer element, which changes the structural system, affects the loads redistribution, and significantly changes the displacement fields. The infill walls are made of relatively weak and brittle masonry units, and while interacting with the frame under this action they undergo severe cracking and damage and absorb considerable amount of energy. This composite action results in a significant redistribution of internal loads and added resistance to the system, where the effect of the geometry and mechanical properties of the masonry infill wall are of great importance.

The in-plane behaviour of infilled frames was studied extensively with emphasis on the effect of beam/column stiffness ratio [1], frame's aspect ratio [2], type and geometry of the masonry blocks [3], number of stories and bays [4], presence of axial loads [5], opening in the wall [6], etc. Yet, in most cases the investigation focused on the lateral action of the wall. Recently, the contribution of the masonry infill walls in case of removal of a supporting column has started to gain attention. Several experimental studies have been carried out in an attempt to consider the response of infilled frames to vertical loading [7–11]. Correspondingly, several approaches have been developed to represent the infill wall and its interaction with the frame. The equivalent single strut approach is probably the most common simplified model to represent the masonry wall [12]. The properties of the equivalent strut have been widely investigated and the Federal Emergency Management Agency (FEMA) adopted such strut model approach for the design and assessment of infilled frame buildings. However, the use of a single strut connected to the beam-column joints does not allow the evaluation of the surface tractions at the infill wall-frame interface and their evolution along the element and throughout the loading path.

The strut approach has been extended to include off-diagonal struts as well, [13–15]. These models can better represent the interaction forces, but they are still based on arbitrary assumptions regarding the fixed locations of the struts and the distribution of loads among them. These drawbacks prove that the assessment of the physical interaction tractions and their distribution and evaluation are challenges that still have to be faced. The aim of this research is therefore to enhance the understanding of the behavior of the infill masonry walls and its interaction with the surrounding frame when subjected to a vertical loading due to the severe damage to a supporting column underneath.

EXPERIMENT SETUP

The experimental setup shown in Figure 1 is described in detail in [16]; it includes a steel frame in which an infill masonry wall is built, and it is equipped with a loading system and monitoring devices. The steel frame was designed to remain elastic throughout the test. The beam and the columns are connected with pinned joints attempting to avoid any contribution of the steel frame to the composite system resistance and any frame distortion due a downward displacement at the missing column location. In the hinged configuration, the stability of the composite specimen only depends on the infill and on the interaction effects.

A half scale masonry infill wall made of Autoclaved Aerated Concrete (AAC) blocks was built in the frame with dimensions of $2045 \times 1400\ mm^2$. During the infill wall construction process the loaded column was supported at its bottom to prevent any vertical displacement. The masonry blocks were assembled using a 2mm thick special adhesive masonry joints. Attention was given to ensure full and continuous contact of the infill wall with the lower beam and the two side columns. During the construction of the last masonry course, the upper beam was lifted up. Then, adhesive was applied on the upper face of the last course and the beam was lowered down to its location. This procedure assures full contact along all four frame-wall interfaces.

A monotonic load was applied by the hydraulic actuator placed at the top of the left column (the "loaded column"). The frame displacements are monitored by linear variable differential transducers (LVDTs) that are shown in Figure 1 and are placed to measure the release of the upper horizontal support of the right column (the "supported column") and the vertical displacement of the loaded column base. A load cell was located between the loaded column and the loading device. The readings of all sensors were recorded every 5 seconds.

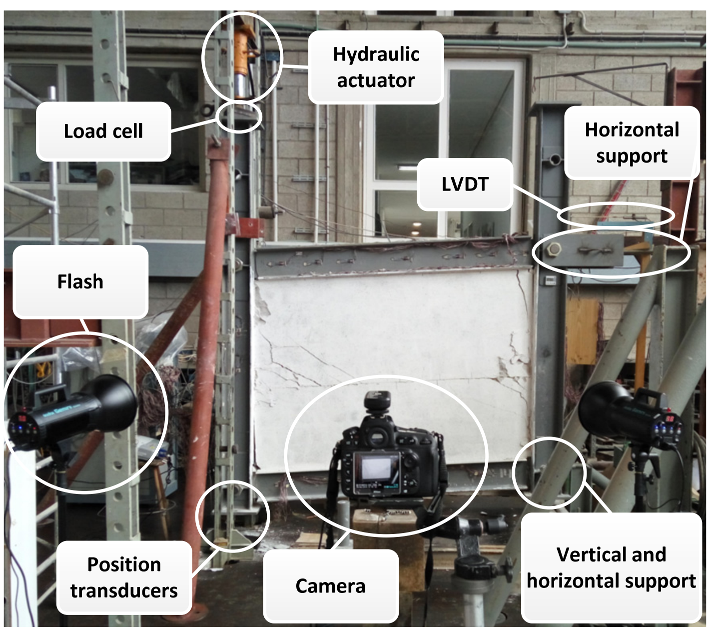

Figure 1: Test setup

LOADING PROCEDURE

Four loading and unloading cycles were performed to examine the effect of stress history. The displacement amplitude was gradually increased at every loading step from about 10mm at the first loading step, to 25mm, 50mm, and 100mm at the following loading steps.

MATERIAL PROPERTIES

The elastic and mechanical properties of the infill wall's blocks and adhesive mortar are given in Table 1. Material tests were conducted on the AAC blocks and the mortar. The mean compressive strength of the AAC block is based on 3 compression tests across its 250x100mm face. The mortar compressive strength is based on 6 compression tests of 40x40x40 mm^3 cubes and the evaluation of the flexural strength is based on 3 individual 40x40x160mm^3 prisms tests according to the relevant European code [17]. The geometrical moment of inertia of the steel elements is $82.9 \cdot 10^6\ mm^4$.

Table 1: Material properties

	Dimensions [mm]	Mean compressive strength [MPa]	Flexural strength [MPa]	Modulus of elasticity [GPa]	Passion's ratio
AAC blocks	250 x 150 x 100	3.1	-	1.35	-
Mortar	t=2	7.67	2.54	-	-
Steel Frame	-	-	-	200	0.3

TEST RESULTS

Figure 2 shows the load-displacement curve during the experiment. The key characterizing parameters, which include the stiffnesses and the residual displacements, are given in Table 2. In this table K_a and K_b are the stiffnesses at each loading as shown in Figure 2, v_r is the residual displacement at the end of the unloading phase, and Δv_r is the incremental residual displacement at the current loading step

$$\Delta v_{r_i} = v_{r_i} - v_{r_{i-1}} \tag{1}$$

Table 2: Test results

Loading	$K_a\ [kN/mm]$	$K_b\ [kN/mm]$	$v_r\ [mm]$	$\Delta v_r\ [mm]$
1st	2.080	1.437	4.66	4.66
2nd	2.553	0.895	18.28	13.62
3rd	2.718	1.127	41.37	23.09
4th	2.362	0.332	90.68	49.31

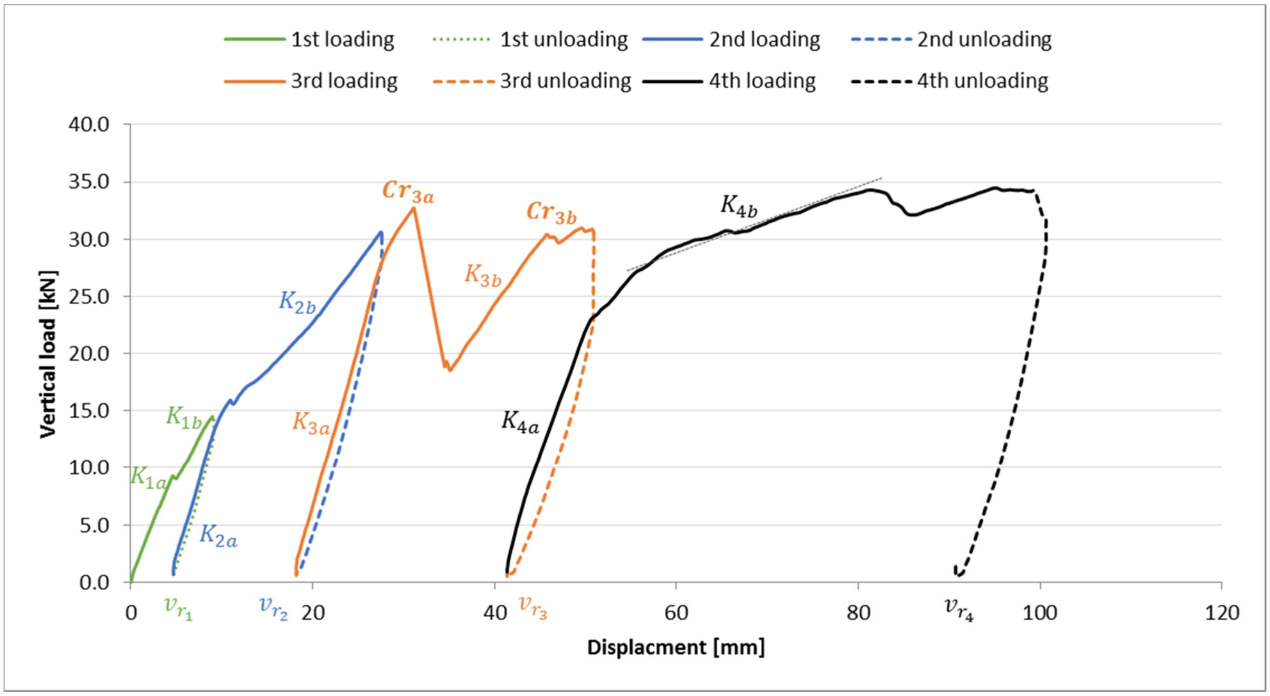

Figure 2: Load-displacement curve

The initial stiffness K_a is very similar in all four loading cycles. However, the following stiffness K_b is decreasing from a relatively large value ($1.437 kN/mm$) for K_{1b} at the first loading cycle to about 23% of that value ($0.332\ kN/mm$) at the fourth loading cycle K_{4b}. This trend indicates an accumulated damage with increasing displacements and different mechanical properties of the damaged infill walls. Even when the damage is invisible, as can be seen after the first loading cycle where no infill cracks are detected, change in the stiffness is indicated and a 38% reduction of the second stiffness K_b was recorded in the second loading cycle. The only exception is the stiffness of the third phase K_{3b} which was higher (+25%) than the stiffness at the previous loading (K_{2b}). This is due to the infill cracking (Cr_{3a} in Figure 2), that defines the starting point of the K_{2b} stiffness, as shown in Figure 2. The additions residual displacement Δv_r increases in every loading cycle. This indicates that the infill wall accumulates damage along the loading process.

CONTACT REGIONS

Figure 3 shows pictures of the loaded column and the infill interaction zone at 5 different points along the experiment. The contact region is marked by a horizontal dashed line. In Figure 4, the infill damage pattern that is related to each of the 5 points is shown. Straight lines represent infill cracks and the hatched patterns represent the infill spalling.

At the beginning of the experiment, full contact exists due to the mortar layer placed between the columns and the infill blocks (Figure 3A). The contact region is shortening with the increase of the vertical displacement as can be seen in Figure 3B and Figure 3C that were taken after the beginning of the second and the third loading cycles. However, the infill cracking changes this trend and the contact region increases instantly as a result of the infill wall cracking (Cr_{3a} in Figure 2) as shown in Figure 3D. The contact region increases more as the infill wall is further damaged, as shown in Figure 3E that was taken at the beginning of the fourth loading cycle.

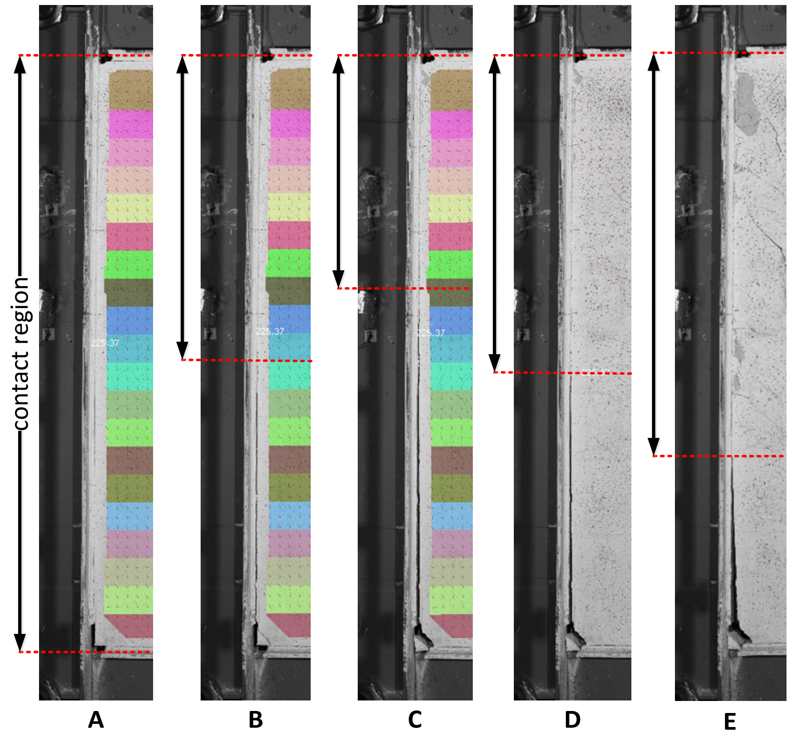

Figure 3 : Contact regions along the loaded column

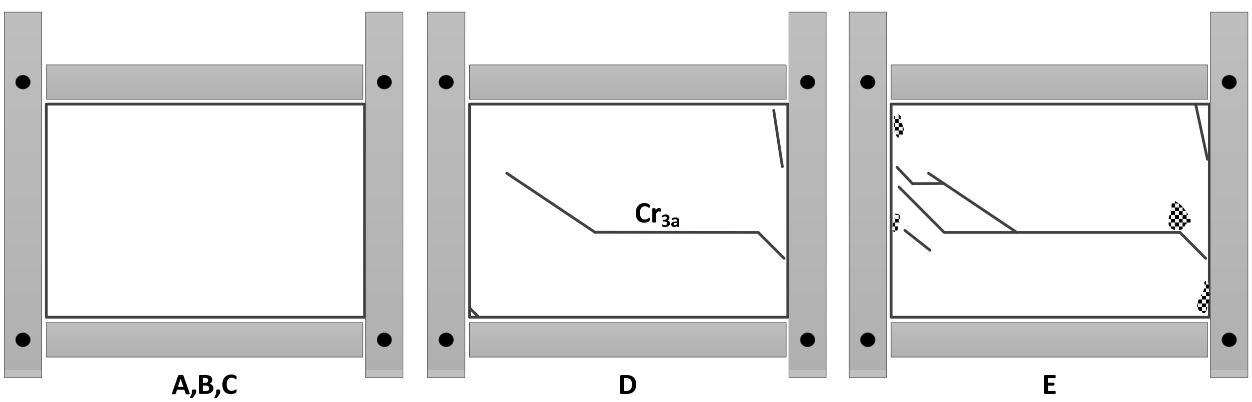

Figure 4: Cracking patterns in different time steps

The infill wall-frame contact region is an important parameter representing the composite system behaviour. The above demonstrates the complexity of this contact state, and its tendency to change along the loading process. It is a key parameter that determines the infill wall-frame interaction stresses. The simplified models that are commonly used to represent the infill wall interaction with the frame, assume either no contact or constant regions of contact whereas the real situation is much more complex. The ultimate resistance is not dictated by the infill cracking, and after this cracking the resistance gradually increases. Therefore, the change of the contact state accompanied by the infill cracking is important in evaluation of the system ultimate resistance.

FINITE ELEMENT ANALYSIS

A finite element analysis (FEA) was carried out to represent the infill wall behaviour and its contact regions with the surrounding steel frame at the linear elastic range of the loading process. In this analysis, the focus is on the nonlinear evaluation of the contact region rather than the infill wall nonlinear cracking patterns that develop at a later stage. A 3D analysis was carried out using commercial software (ANSYS Version 17.1). The infill wall was modeled as an elastic isotropic material. The steel frame was also modeled as an elastic isotropic material. The infill-frame interface, which is at the focus of the analysis, was modeled by “Frictional contact” elements. The Augmented Lagrange formulation was chosen because it is less sensitive to the selection of normal contact stiffness. The contact and the infill material properties are given in Table 3.

Table 3 : FEA material properties

Contact [18]	Type	Frictional
	Formulation	Augmented Lagrange
	Friction Coefficient	0.1
	Normal Stiffness Factor	0.01
Infill wall [11]	Young's Modulus [GPa]	1.35
	Poisson's Ratio	0.01
	Bulk Modulus [GPa]	0.46
	Shear Modulus [GPa]	0.67

Figure 5 shows the deformed shape detected by the model and the minimum principal stress after applying a vertical load that equals to the maximum load at the first loading step (14kN, Figure 2). The FEA results of the contact and no-contact regions along the loaded column are shown in Figure 6. The loaded column is presented in a 90° rotated position for convenience. The contact region is 650mm, which is about 46% of the infill wall height.

The comparison of the experimental and the FEA results of the contact region are shown in Figure 7. The results show good agreement with the experimental results at the linear elastic range, before the infill wall cracking (Figure 7B and Figure 7C).

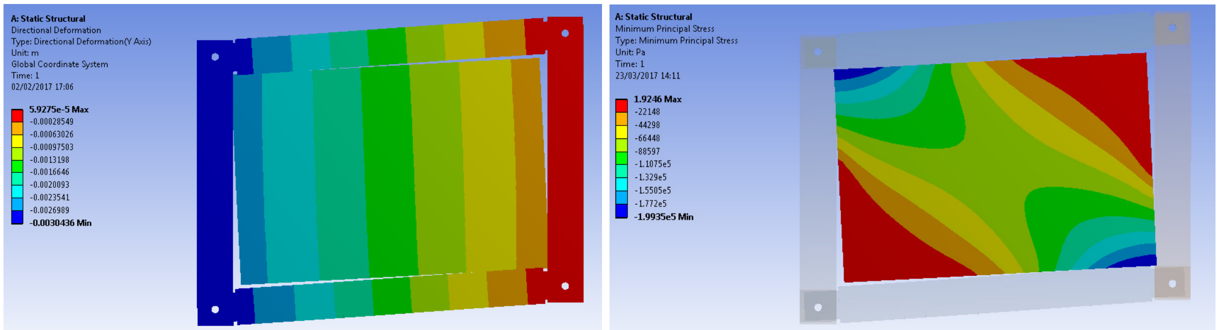

Figure 5: Results of FEA (P=14kN): vertical displacment (left) and minimum principal stress (right)

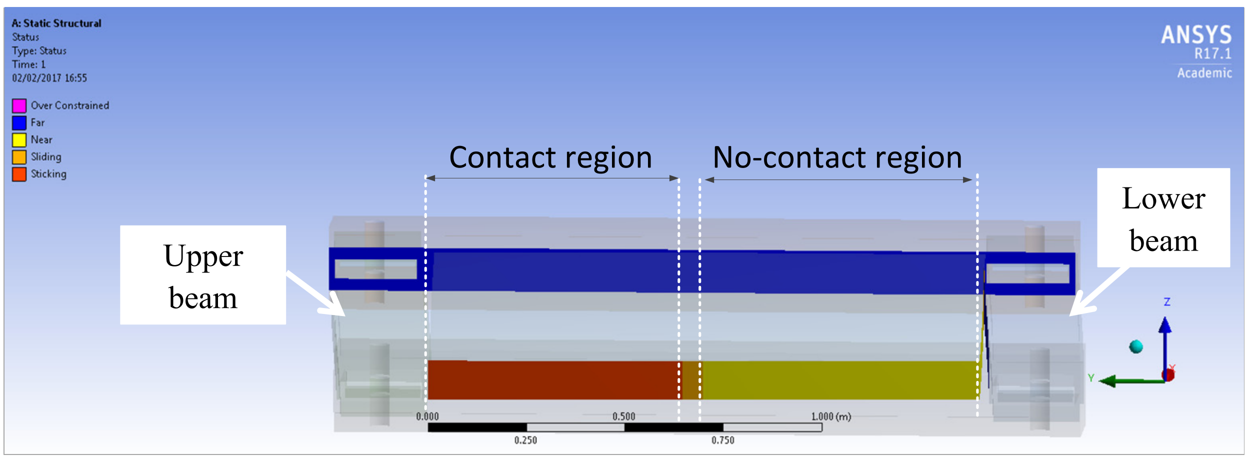

Figure 6: Contact region along the loaded column based on FEA

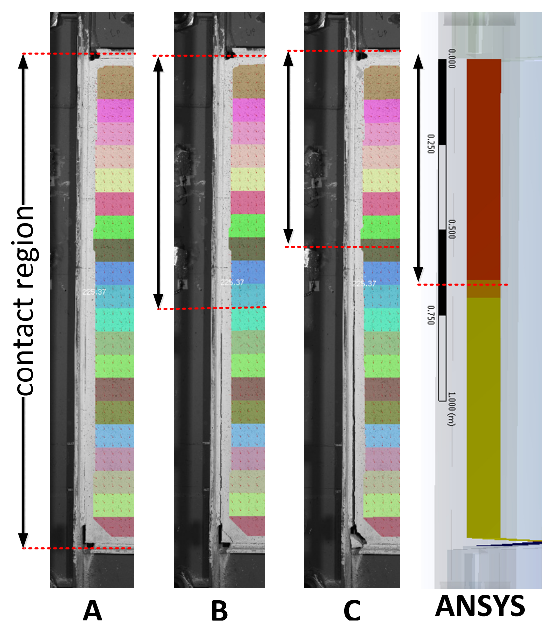

Figure 7: A comparison of the contact regions based on FEA and experimental results

CONCLUSIONS

This article presents the results of an experimental and a numerical study on the behaviour of infill walls subjected to vertical loading triggered by the loss of a supporting column. The main conclusions of this study are:

1. The infill wall changes it properties along the loading process, even when the damage is not visible. The loading history of the infill wall is important in defining its material properties and the current state of the wall-frame assembly
2. The contact zone between the masonry infill wall and the frame varies during the loading/displacement process.
3. When cracking of the masonry infill occurs, it drastically changes the contact conditions. In the case of lateral loading and lateral displacements, the infill cracking determines the ultimate resistance of the composite system. However, in vertical displacements, the diagonal cracking does not necessarily determine the ultimate resistance as it was observed in the experiment. In this scenario, the post cracking behaviour is of great importance.

ACKNOWLEDGEMENTS

The research for this paper was financially by The Israeli Ministry of Science, Space and Technology (MOST), grant no. 2021954.

Our late colleague and friend Stephan Schwarz was involved in the early stages of the concept development of the experimental facility. His contributions are highly appreciated and remembered.

REFERENCES

[1] Schwarz S, Hanaor A, Yankelevsky DZ. Experimental Response of Reinforced Concrete Frames With AAC Masonry Infill Walls to In-plane Cyclic Loading. Structures 2015;3:306–19. doi:10.1016/j.istruc.2015.06.005.

[2] Mehrabi BA, Shing PB, Schuller PM, Noland LJ. Experimental Evaluation of Masonry-Infilled RC Frames. J Struct Eng 1996.

[3] Amato G, Fossetti M, Cavaleri L, Papia M. An updated model of equivalent diagonal strut for infill panels. Proc Eurocode 2009:119–28.

[4] Fiorato AE, Sozen MA, Gamble WL. An Investigation of the Interaction of Reinforced Concrete Frames with Masonry Filler Walls. Illinois Univ Urbana Dept of Civil Engineering: 1970.

[5] Liu Y, Manesh P. Concrete masonry infilled steel frames subjected to combined in-plane lateral and axial loading – An experimental study. Eng Struct 2013;52:331–9. doi:http://dx.doi.org/10.1016/j.engstruct.2013.02.038.

[6] Anil Ö, Altin S. An experimental study on reinforced concrete partially infilled frames. Eng Struct 2007;29:449–60. doi:10.1016/j.engstruct.2006.05.011.

[7] Shan S, Li S, Xu S, Xie L. Experimental study on the progressive collapse performance of RC frames with infill walls. Eng Struct 2016;111:80–92. doi:10.1016/j.engstruct.2015.12.010.

[8] Stinger SM, Orton SL. Experimental evaluation of disproportionate collapse resistance in reinforced concrete frames. ACI Struct J 2013;110:521–9. doi:10.14359/51685609.
[9] Li S, Shan S, Zhai C, Xie L. Experimental and numerical study on progressive collapse process of RC frames with full-height infill walls. Eng Fail Anal 2016;59:57–68. doi:10.1016/j.engfailanal.2015.11.020.
[10] Brodsky A, Yankelevsky DZ. Resistance of Reinforced Concrete Frames with Masonry Infill Walls to In-Plane Vertical Loading. Key Eng Mater 2016;711:982–8. doi:10.4028/www.scientific.net/KEM.711.982.
[11] Brodsky A, Yankelevsky DZ. Resistance of Reinforced Concrete Frames with Masonry Infill Walls to In-Plane Gravity Loading Due to Loss of a Supporting Column. Eng Struct 2017;140:134–50. doi:10.1016/j.engstruct.2017.02.061.
[12] Shing PB, Mehrabi AB. Behaviour and analysis of masonry-infilled frames. Prog Struct Eng Mater 2002;4:320–31. doi:10.1002/pse.122.
[13] DesRoches J-SJJ-HPR. Seismic fragility of lightly reinforced concrete frames with masonry infill. Earthq Eng Struct Dyn 2015;41:1549–68. doi:10.1002/eqe.
[14] Crisafulli FJ, Carr AJ. Proposed macro-model for the analysis of infilled frame structures. Bull New Zeal Soc Earthq Eng 2007;40:69–77.
[15] El-Dakhakhni WW, Elgaaly M, Hamid A a. Three-Strut Model for Concrete Masonry-Infilled Steel Frames. J Struct Eng 2003;129:177–85. doi:10.1061/(ASCE)0733-9445(2003)129:2(177).
[16] Brodsky A, Rabinovitch O, Yankelevsky DZ. Experimental Evaluation of the Interaction between an Infill Wall and the Surrounding Frame 2017.
[17] BS EN 196-1: “Methods of testing cement. Determination of strength” 2005.
[18] ANSYS Inc. ANSYS Mechanical User’s Guide. ANSYS Man 2014;15317:724–46.