16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 3864

Registration Code: S-P1464739809

EXPERIMENTAL TESTING AND NUMERICAL MODELING OF A PRE-CAST CONCRETE BLOCK ARCH SYSTEM

A. Martinez[(1)], M. Turek[(2)], C. E. Ventura[(3)]

[(1)] *Graduate student, University of British Columbia (Canada), amaiamar2@gmail.com*
[(2)] *Research Associate, University of British Columbia (Canada), meturek@mail.ubc.ca*
[(3)] *Professor, University of British Columbia (Canada), ventura@civil.ubc.ca*

Abstract

While arches are a well established structural system, with well understood performance under gravity loads, there are known issues under seismic loading. A study was undertaken to assess the seismic performance of a modular pre-cast concrete arch using a combination of experimental testing and numerical modeling. Small scale unreinforced and reinforced arch models were subjected to quasi-static and dynamic testing. For the dynamic testing, shake-table tests using a suite of earthquake records of varying magnitudes, types and locations, were performed. From the results of the shake-table testing on the unreinforced models it was found that the arches tend to collapse by the four-hinge mechanism which is typical for these types of structures. For the reinforced arch testing, a steel band was instrumented to provide information on the loads. The reinforced arch performed well when subjected to the same suite of earthquakes. A numerical distinct element model was developed and calibrated to the quasi-static testing. The response of the numerical model matched the experiments with the arch exhibiting the same four-hinge failure mechanism. From numerical analysis, sensitivity studies were performed on various parameters of the arch.

Keywords: arch; concrete block; seismic assessment; discrete element modeling; shake-table

1. Introduction

While arches are a well established structural system, with well understood performance under gravity loads, there are known issues under seismic loading. A Canadian company has developed a pre-cast concrete structural arch system, intended to be easy to assemble and cost effective. A study was undertaken to assess the the seismic performance of the arch in various configurations and develop methods of reinforcement.

The study included experimental quasi-static and dynamic testing using physical scaled models, and a numerical discrete element model. The phyiscal testing included both unreinforced and externally reinfored models; the results of the experimental test were used to calibrate the numerical model. The numerical model was then subjected to sensitivity analysis to examine key parameters.

This paper describes the Lock-Block arch, the experimental testing (of both unreinforced and reinforced arches), the numerical model and the sensitivity study.

2. Background

2.1. Lock-Block arches

Lock Block Ltd., of Vancouver, Canada, manufactures pre-cast concrete products using either recycled or virgin concrete. Each pre-cast piece has a cross-shape interlocking shear key that allows for assemblage between blocks. More recently, the company has created a system of arch and dome structures. They have developed various types of blocks which fit a range of angles to create a wide variety of shapes and systems.

Fig. 1 – Lock-Block arch structure

The primary objective of these arch systems is to have a structure with a long service life, that it is easy to build and is cost effective. The configuration of the standard arch proposed by Lock-Block features two rows of straight blocks followed by a half circular arch consisting of identical blocks (see Fig.1). The advantage of this configuration is greater interior height and minimizing cost due to repeatability of fabrication.

2.2. Seismic performance of arches

Much research has been done on the seismic performance of masonry arch and dome structures, primarily to study existing historically significant architecture. A significant work was done by Oppenheim [1], which proposed an analytical model for masonry arches. The model assumed fixed hinging points and is based on rigid-body geometry. The arch at collapse is described as a single degree of freedom (SDOF) structure with three links forming a four hinge mechanism (see Fig.2).

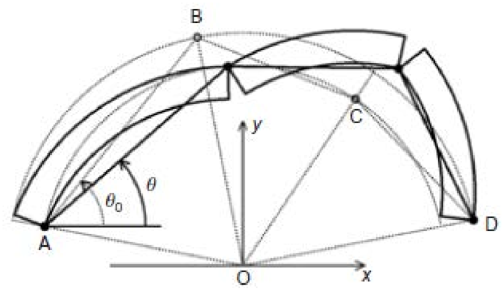


Fig. 2 – 'Four hinge' mechanism [1]

DeJong [2] performed shake-table testing on scaled models of arches, and compared the results to the analytical model presented by Delorenzis [3]. For the experimental program, the excitation was applied as both harmonic motions and earthquake ground motions. The authors chose to deliberately select five very different ground motions to observe a range of behaviours in the arch. It was found that the arch was more vulnerable to impulse-type ground excitations; with the critical failure being on the second half cycle of the main pulse. It was clear in nearly all of the tests that the four-hinge mechanism was observed before collapse.

3. Methodology

The seismic performance of the described arch system was evaluated by conducting experimental testing and numerical modeling.

The purpose of the experimental testing was to assess the performance of the unreinforced small scale arches under seismic loading. The scale of the models was pre-selected due to the availability of 1/25 and 1/12.5 scale models created by Lock-Block. The experimental program included quasi-static testing and shake-table testing. For the quasi-static testing, an approximation to the maximum ground acceleration that the arch withstands was obtained by monotonically tilting the model until failure. For the dynamic testing, both tri-axial and uniaxial shake-table testing were performed applying different ground motions at increasing intensity levels. In the case that the arch could not survive to the 100% level, reinforcement would be required. In addition, the failure mode and the vulnerability of the arch to different ground shaking was studied. Shake-table testing using the reinforced model was also performed to characterize the forces at the straps caused by the ground shaking.

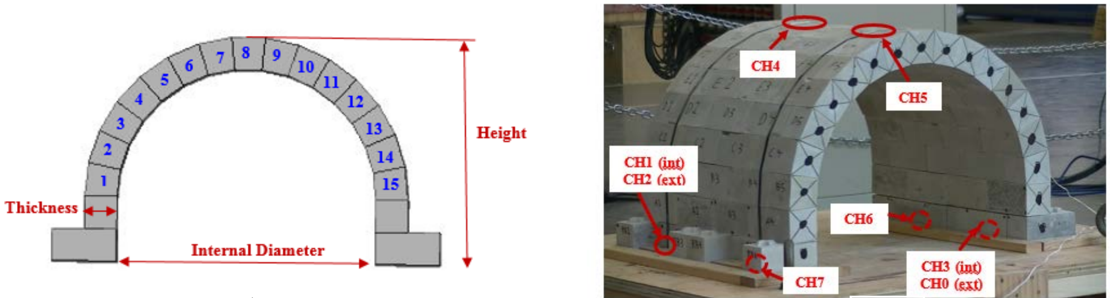
For the numerical modeling, a discrete element model using 3DEC software was developed and calibrated to the quasi-static testing. The model was used to explore the sensitivity of the arch to different parameters and determine possible seismic enhancement solutions.

4. Experimental testing

4.1. Description of the models

Several small scale arches were tested, but the focus of this paper is on the 1/12.5 scale model of a 6m interior diameter arch (see Fig.3). The model, weighs 64kg, is 42cm high, 48cm long, and with an interior diameter of 48 cm. The first course was fixed in place for testing.

When reinforcing the model, two steel straps were placed along the outer perimeter of the arch, which acted to hold it in compression during the lateral loading through tension (see Fig.3b). Steel bands were instrumented with strain gauges in eight differenet channels (CH) to measure the forces during the shaking. The material and dimensions of the reinforcing straps were specifically chosen in order to achieve a measureable strain based on the expected levels of force.



a) b)

Fig. 3 – a) Specifications for height, interior diameter and voissours (block) number for the model with its standard configuration, and b) the tested model with the instrumentation

4.2. Scaling applied in this study

Scaling laws based on dimensional analysis were implemented to account for scale effects between the model and the represented structure. Following the 'Complete Model Type' described by [4] and [5] and using the length scale factor of 1/12.5, the scaling factors were determined as shown in Table 1.

Table 1 – Scaled factors based on 'Complete Model' for the 1/12.5 scale model

Dimension	Scale Factor	1/12.5 scale model
Length	S_L	1/12.5
Density	S_ρ	1
Acceleration	S_a	1
Time	$S_t = \sqrt{S_L}$	$1/\sqrt{12.5}$
Frequency	$S_f = \sqrt{1/S_L}$	$\sqrt{12.5}$

The length and density scale factors were determined values given by the size and material availability of the physical models provided from Lock-Block. With the assumption of 1:1 acceleration scaling, time is scaled based on the square root of the length scale factor. This results in the records of the ground motions being shorter with the displacements being 12.5 times smaller than the displacements of the original records, while keeping the same acceleration.

4.3. Tilt testing

Tilt testing provides an approximation of the minimum horizontal ground acceleration to collapse the arch by tilting the structure until it collapses. When the structure is tilted one component of gravity acts normal to the tilted surface and the second component acts parallel to the surface. The approximate collapse acceleration from tilt test (α) is defined as:

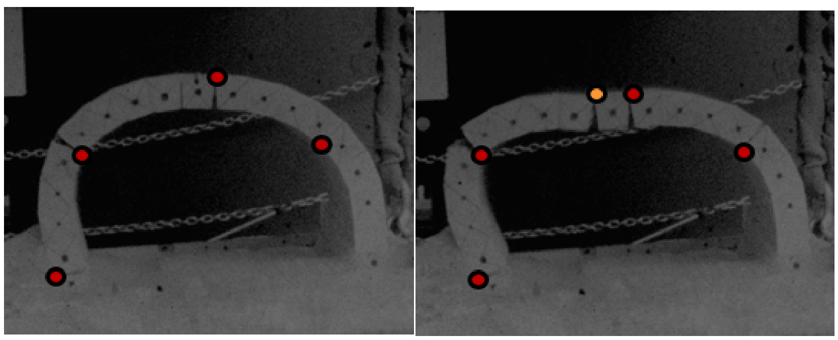
$$\alpha = tan\,(\gamma) * g \tag{1}$$

where g is acceleration due to gravity and γ is the tilt angle.

The model was placed on a tilting platform with the length of the bottom rows parallel to the axis of rotation. As one of the end of the platform was raised using an overhead crane, a digital inclinometer recorded the maximum angle of tilt before collapse.

The model, which has a thickness of the blocks to radius ratio (b/R) of 0.25, was observed to collapse at 5.5 degrees of tilt angle, which corresponds to an **α** value of 0.1g. Tilt testing performed in arches with higher b/R ratio were found to collapse for higher **α** values.

For all of the tilt tests performed, the four-hinge collapse mechanism described previously in Fig.2 was observed (see Fig.4). The failure mechanism of the arch was initiated by the opening of the four hinges highlighted in red in Fig. 4a. As the collapse progressed, a fifth additional hinge, highlighted in orange in Fig. 4b, was developed. When observing the failure mode along the longitudinal axis of the arch, the hinges were seen as a straight line across the entire model (see Fig.5)**.**



a) b)

Fig. 4 – Failure mechanism recorded with the high speed camera a) as the collapse was initiated and b) as the collapse progressed

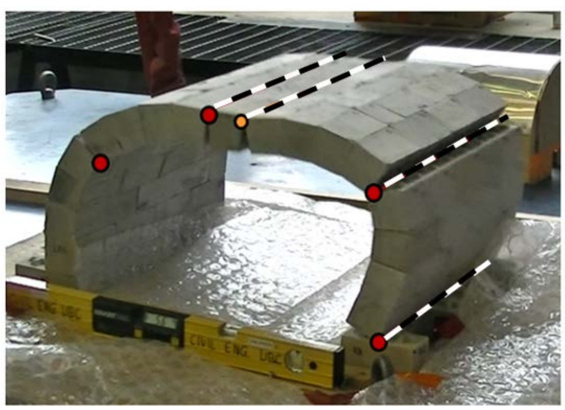


Fig.5 - Collapse mechanism of the arch when tilting the structure

4.4. Shake table testing

For the shake-table testing, a suite of earthquake records was selected from Pina et al [6] and PEER [7]. Crustal, subcrustal and subduction earthquakes with varying frequency content, maximum acceleration amplitude, maximum displacement amplitude and impulses, were chosen. For the 1/12.5 scale model, the Loma Prieta, Northridge and Parkfield earthquake records were used, each with three directions of motion. The component with highest peak acceleration was applied in the transversal direction of the arch. These three time scaled records and their parameters are shown in the following table.

Table 2 – Parameters of the applied time scaled earthquakes for the 1/12.5 scale model

EQ	Direction	PGA (g)	PGD (cm)	PGV (cm/sec)	Duration (sec)
Loma Prieta	x	0.64	0.87	15.6	11.3
	y	0.48	0.90	12.77	
	z	0.46	0.57	5	
Northridge	x	0.83	2.37	45.29	5.63
	y	0.49	2.16	21.08	
	z	0.83	0.80	12.31	
Parkfield	x	0.44	0.41	6.97	12.42
	y	0.37	0.31	6.16	
	z	0.14	0.21	1.93	

The MAST (Multi-Axis Shake-table) system, with six degree of freedom, was used for testing the 1/12.5 scale model. A photo of the shake-table (Fig. 6) with the defined test directions are specified as follows: x-axis as the transversal direction, y-axis as the longitudinal direction and z-axis as the vertical direction.

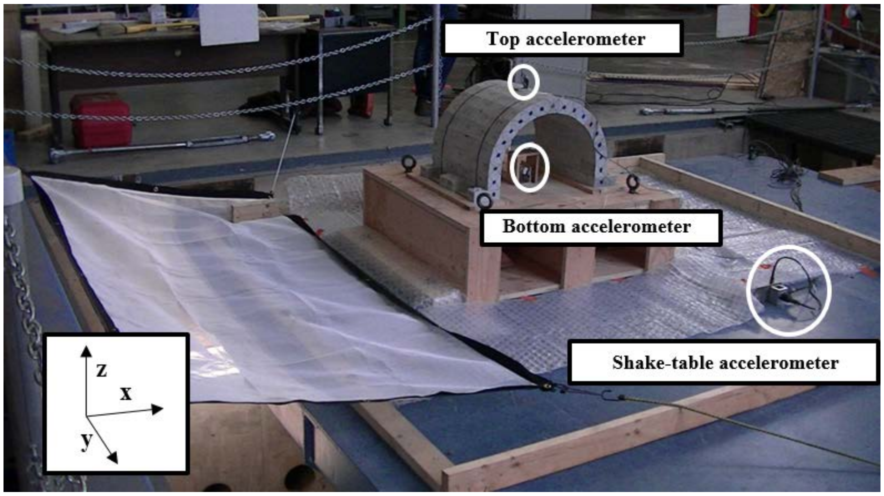


Fig. 6 – MAST with the 1/12.5 scale model on top

4.4.1. Testing using the unreinforced model

The selected records were applied repeatedly at increasing levels, as a fraction of the original record (referred as "Test Level (TL)") starting from 20%. Once a failure of the model was observed, the test was repeated three times at the same test level. This was done to ensure repeatability.

Table 3 summarizes the results of the shake-table tests on the unreinforced small scale models. Each applied earthquake and test level are shown; an "O" represents a test where the arch did not collapse, whereas the "X" shows the cases in which collapse occurred. Collapse was recorded for 80% of the Loma Prieta and 25-30% of the Northridge earthquakes. However, the model survived the Parkfield earthquake. For Northridge at 25% de model collapsed in some but not all of the three repeated tests.

Table 3 – Summary of shake-table tests on the unreinforced 1/12.5 scale model

EARTHQUAKE	TEST LEVEL (TL)							
	20%	25%	30%	40%	60%	65%	80%	100%
PARKFIELD		O		O		O		O
LOMA PRIETA		O			O		X	
NORTHRIDGE	O	X	X					

A study on the sensitivity of the arches to different parameters of the earthquakes was conducted. The most consistent result agreed with the work done by [2] in that the impulse-type ground motion has the strongest effect; peak acceleration and duration of the impulse being the governing factors.

It was observed that the arches always collapsed at higher ground accelerations than the **α** value obtained from tilting of the structure. Additionally, the acceleration required to collapse the arch was found to increase as the dominant frequency of the main pulse increased.

For all of the shake-table tests performed, the same collapse mechanism described for the tilt testing was observed. When the shaking was not strong enough to let the hinges open to a critical displacement, they were closed due to the reversing motion that stabilized the arch. In all of the performed shake-table tests, the hinges were created at the same locations for all the earthquakes with the only variation being the collapse direction.

4.4.2 Testing using the reinforced model

For the shake-table testing using the reinforced models, the forces recorded at the strain gauges were used for calculation of the ratio F_{nW}. This ratio is a non-dimensional expression of the peak dynamic forces as a percentage of the total weight of the model.

$$F_{nW}(\%) = \frac{F_{peak}}{W} * 100 \tag{2}$$

where F_{peak} is the average peak force (without accounting for the pretension) of all the channels calculated from the recorded strains, and W is the total weight of the model.

The purpose of the reinforced experimental testing was to obtain the dynamic forces created by different earthquakes in the 1/12.5 scale model. A total of 13 tri-axial shake-table tests were performed varying the intensity level applied to each earthquake (50, 65, 80, 100 and 120%). The reinforcing was found to prevent collapse for all of the cases. Fig.7 summarizes the results obtained using the Loma Prieta, Northridge and Parkfield earthquakes.

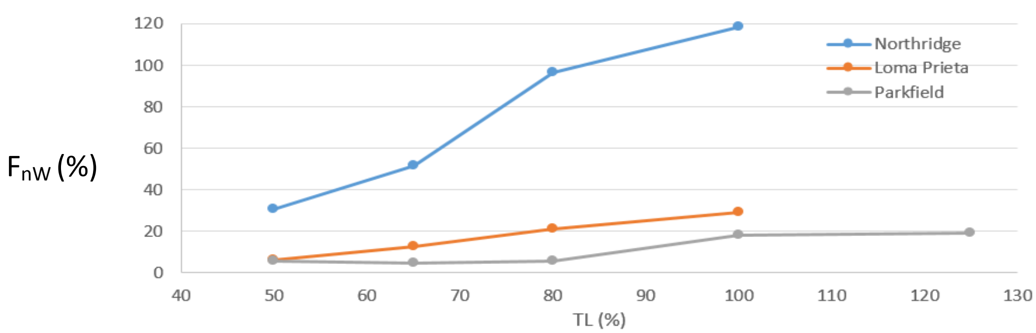


Fig. 7 – F_{nW} ratio for different test levels of the Loma Prieta, Northridge and Parkfield earthquakes

It can be observed from the figure above that as the intensity increased, the F_{nW} ratio also increased for all the earthquakes. At the 100% TL, the F_{nW} value for Loma Prieta (29%) and Parkfield (18.2%) were similar while Northridge (118.5%) was much higher. This is most likely due to significant higher horizontal velocities and displacements.

Slight separation between the blocks could be observed at the same locations as the hinges on the unreinforced model (see Fig. 8); however these were small and the arch did not collapse neither cracking in any block was observed. Therefore, it is considered that properly dimensioned reinforcement could enhance the seismic performance of the structure.

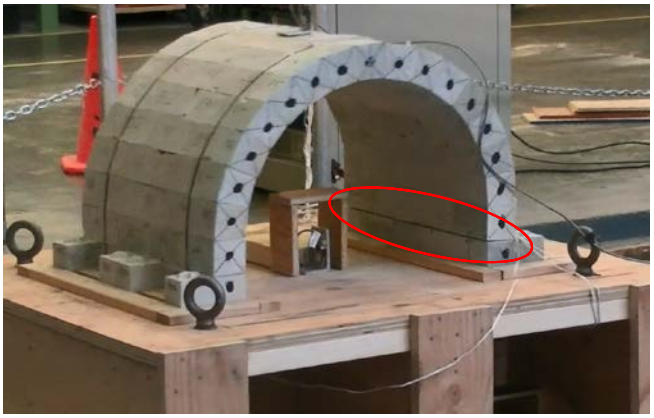


Fig. 8 – Reinforced arch showing slight openings (red circle)

5. Numerical Analysis

5.1 Description of the modeling

Based on the behavior of arches, discrete element modeling was chosen to create the numerical model due to its ability for allowing large displacements during dynamic analysis and adequately dealing with the discontinuities between the blocks. A discrete element model using 3DEC software was developed and calibrated to the quasi-static experimental testing.

The geometry of the structure and density of the blocks was obtained from the 1/12.5 small scale arch model, which was used to perform experimental testing. Fig.9 shows the geometry of the 3DEC numerical model based on the tested physical arch.

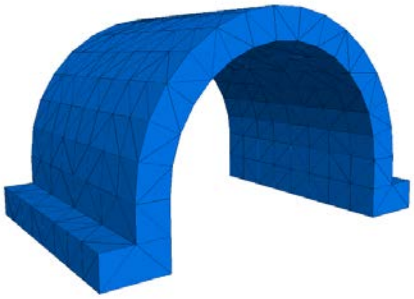


Fig. 9 – Numerical model of the 1/12.5 small scale arch using 3DEC software

It has been shown experimentally [8] and proved analytically in past studies [1, 2, 3], that this type of arch structure collapses due to the rocking or opening between the blocks. During the performed experiments, no damage was found in the blocks (cracks were not generated). This suggested that material strength does not affect the failure of the structure; thus, the blocks could be assumed rigid. The cross-shape shear keys, used for assemblage of the blocks, were modeled as simple face interfaces with extra shear stiffness assigned to the joints of the numerical model. Table 4 shows the properties considered for both the blocks and the interfaces of the numerical model.

Table 4 – Properties of the blocks and interfaces between blocks used in 3DEC

Block Properties	Density (kg/m^3)	1715
Joint Properties	Normal stiffness (GPa)	20
	Shear stiffness (GPa)	10 (with shear keys) 0.1(with no shear keys)
	Friction Angle (degrees)	35
	Cohesive strength (GPa)	0
	Tensile strength (GPa)	0
	Dilation Angle (degrees)	0

5.2 Performed analysis

In order to validate the numerical model with the experimental results, an equivalent tilt test using the 3DEC model was conducted. For this purpose, the tilt angle was increased until failure of the structure occurred. The loading was applied as gravity, divided in its corresponding vertical (in red) and horizontal (in blue) components, in the middle of each of the blocks, as shown in Fig.10.

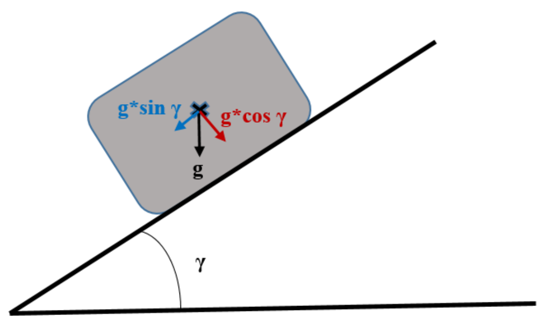


Fig.10 – Vertical and horizontal components of the gravity when tilting a block

5.3 Results from the numerical analysis

The results obtained from a sensitivity analysis for the modeling parameters showed that the arch is more sensitive to the thickness of the blocks and boundary conditions.

The initial numerical model collapsed at 9.7 degrees of inclination, which is equal to an **α** value of 0.16g. However, past studies [2] found that an 80% of the thickness should be considered in the analytical model to account for the irregularities of the blocks and the instability of the model. A new numerical model was created using blocks with that reduced thickness. For that case, the arch collapses at a lower angle (3.7degrees), which corresponds to 0.07g. Table 5 shows the obtained results and compares them to the experimental data.

It can be concluded that the irregularities of the blocks need to be taken into account reducing the thickness of the blocks, but not as much as 80%. In order to calibrate the model to the experimental data, a sensitivity analysis of the thickness of the blocks was conducted and the results are shown in Fig. 13 a. From this plot, the **α** is decreased as the thickness of the blocks is reduced. When reducing the effective thickness from 100% to 60%, the **α** decreases from 0.16g to complete collapse for the original model. An effective thickness of the blocks of 92% should be considered to calibrate the model to the experiments.

Table 5 – Comparison of collapse tilt angle and corresponding **α** between numerical and experimental results

	Experimental	**Numerical**		
		Initial model (100%thickness)	[2] model (80%thickness)	Calibrated model (92%thickness)
Collapse Tilt Angle (degrees)	5.5	9.7	3.7	5.5
α (g)	0.1	0.16	0.07	0.1

According to Heyman [9] and Oschendorf [10], the minimun required thickness to collapse a 180 degrees inclusion angle arch should be 33% and 50% respectively. The arch was found to be unstable for 60% of thickness as shown in Fig.11a. This is due to the fact that the half circular arch is supported on top of two rows of vertical blocks, making it more difficult to maintain the thrust line within the thickness of the arch. In order to prove this, a quasi-static analysis was conducted in the same arch but fixing also the second row of blocks. The obtained results are plotted in Fig.11b. The **α** increases significantly when an additional row of blocks was fixed. For 100% of effective thickness, the **α** was doubled (from 0.16g to 0.34g) when fixing the second row of blocks.

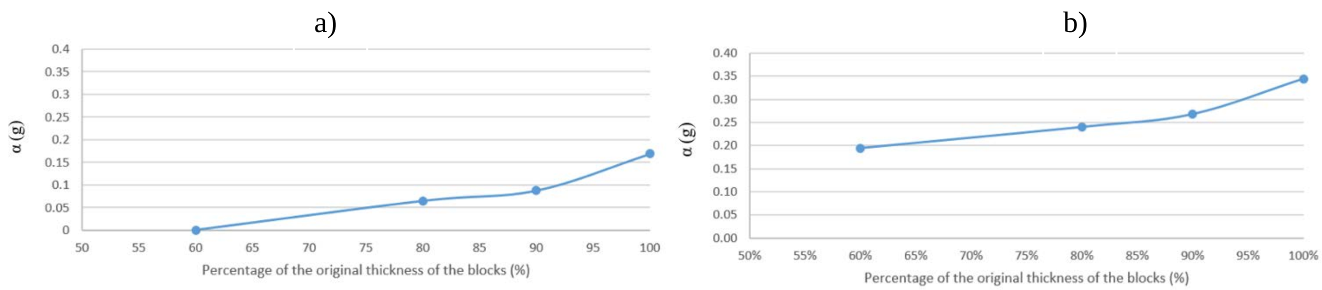


Fig.11 –Thickness of the blocks versus collapse **α** obtained from the quasi-static analysis for the model with a) the first row fixed, and b) the first two rows fixed

The numerical model collapsed following the four-hinge mechanism observed in the experimental testing. Fig.10 shows the failure mode of the computer model when the collapse was initiated (a) and as it progressed (b).

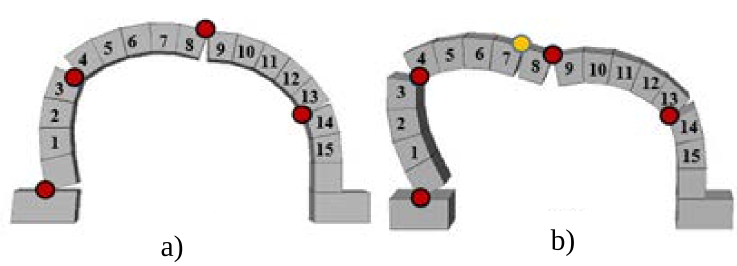


Fig. 12 – Collapse mechanism during quasi-static analysis (structure tilted from the left side) as the collapse a) was initiated and b) as it progressed

Most of the hinges occurred at the same locations for the experimental and numerical model, including the secondary hinge (orange color hinge in b). However, hinging at the left side of the arch was observed between block number #12 and #13 in the experiments instead of between #13 and #14 (Fig. 12). Although, in general, the predicted failure mechanism by 3DEC agreed qualitatively with the hinging behavior shown in the laboratory, the exact location of all the hinges could not be forecasted.

6. Conclusions

The main goal of this study was to assess the seismic performance of an unreinforced arch system and to develop concepts of strengthening if necessary. This was achieved by a program of experimental testing using small scale arches and numerical modelling of the arch. It was found that the unreinforced and unconfined arches in the studied configuration were vulnerable to collapse due to strong shaking and a possible reinforcement was explored.

Several shake-table tests were performed using a variety of earthquakes, test levels and directions (including vertical). The most significant parameter on the response of the arch was the impulse-type motion. Based on the results from the experimental testing and the numerical modelling, it was observed that the scale model arches collapsed following the four-hinge mechanism, which is a rocking-type failure and agrees with what is found in the literature. A simple external reinforcing system was implemented for the experimental tests. It was found that the reinforcing prevented collapse for all tests, and typically had loads of 30% of the weight of the arch for most earthquakes, while in some cases loads in excess of 100% of the weight of the arch.

A numerical model was created and calibrated to the experimental testing with the 3DEC discrete element software. A sensitivity analysis was performed which showed that restraining multiple rows at the bottom of the arch and increasing the thickness of the blocks increased its seismic resistance.

Based on the results of the experimental test, it was found that addition of external reinforcement to prevent hinge opening could reduce the risk of collapse. From the numerical model sensitivity study, it was found that fixing multiple rows of blocks increases the stability of the arch.

7. Acknowledgements

Funding for this study was provided by Lock-Block Ltd. and by Natural Science and Engineering Research Council (NSERC) of Canada.

The authors would like to thank the contribution of Mr. Scott Jackson, Mr. Jermin Dela Cruz, Mr. Garrilo lazio and Mr. Simon Lee of UBC for setup and running the shake-table tests. The authors would also like to thank Mr. Jay Drew, Mr. Brent Wallace and Mr. Arley Drew from Lock-Block Ltd for their assistance with the project.

8. References

[1] Oppenheim, I. (1992). The Masonry Arch as a Four-Link Mechanism Under Base Motion. *Earthquake Engineering in Structural Dynamics*, 1005-1017.

[2] Dejong, M. J. (2009). *Seismic Assessment Strategies for Masonry Structures.* Massachusetts: Institude of Technology.

[3] Delorenzis, L., Dejong, M., & Ochsendorf, J. (2007). Failure of Masonry Under Impulse Base Motion. *Earthquake Engineering Struct. Dyn. 36*, 2119-2136.

[4] Krawinkler, H. (1979). Possibilities and Limitations of Scale-Model Testing in Earthquake Engineering. *Proc. of the Second US National Conference on Earthquake Engineering*, (pp. 283-292). Standford (California).

[5] Tomazevic, M., & Velechovsky, T. (1992). Some Aspects of Testing Small-Scale Masonry Building Models on Simple Earthquake Simulators. *Earthquake Engineering and Structural Dynamics 21*, (pp. 945-963).

[6] Pina, F., Ventura, C., Taylor, G., & Liam Finn, W. (2013). Selection of Ground Motions for the Seismic Risk Assessment of Low-Rise School Buildings in South-Western British Columbia. Manual Volume #5, Appendix F.

[7] PEER *Pacific Earthquake Engineering Research Center*. (2016) Retrieved from http://peer.berkeley.edu

[8] Martinez, A., Turek, M., Ventura, C. & Drew, J. (2015). Seismic Performance of a Pre-Cast Concrete Arch System. *The 11th Canadian Conference on Earthquake Engineering*

[9] Heyman, J. (1972). Coulomb's memoir in Statics: An Essay in the History of Civil Engineering. Cambridge University.

[10] Ochsendorf, J. (2002). *Collapse of Masonry Structures.* Cambridge (UK): PhD dissertation