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Seismic performance of a pre-cast concrete arch system

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ABSTRACT

Lock Block Ltd of Vancouver, Canada produces pre-cast concrete products, including their name-sake retaining wall system which uses recycled materials. More recently they have adapted these products to create a system of easy to assemble dome and arch structures. This study aims to evaluate the behavior of these systems when subjected to seismic loading. A program of experimental shake-table testing was undertaken using a small scale arch models. For the tests, a suite of six earthquake records were chosen, including Tohoku 2011, Loma Prieta 1989 and Kobe 1995. The records were time scaled to increase the applied frequencies to the tested models; the accelerations were applied full-scale. For each model, they were tested with increasing intensity until failure occurred; this determined the failure level for each earthquake. For all the cases, the failure mode exhibited the typical four-hinge mechanism. The failure intensity varied with type of earthquake, with impulses being the dominant factor. The study also explored a method of reinforcing the arches, using a steel band over the structure to withstand the tension force, anchored at both ends of the arch. This method performed well to all applied earthquakes.

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1. Introduction

Lock Block Ltd is the manufacturer of pre-cast concrete products, including their name-sake retaining wall system. They have developed a system of arches and domes using these blocks, using special forms to create angular shapes required for these systems. While arches are a well established structural system for gravity loads, there are potential issues for an unreinforced arch subjected to seismic loads. This project attempts to define the seismic response of the arch by means of shake table testing of scale models and looks at effective methods of reinforcement.

Lock Block creates scale models of their products, which allows them to experiment with new geometric configurations. The models are cast using grout at 1/25th scale. A series of shake-table tests were performed on scale model 6m arches. The weight of the blocks is proportionate to their size and this allows for useful response of the models the shaking. The test time histories were chosen to represent the current design in BC, and also choosing a selection of significant earthquakes from around the world. For each test, the record is applied at a reduced intensity, and then incrementally increased until failure. This establishes the failure level for each model to each applied earthquake.

For the external reinforcement, a steel band is attached along the outer edge of the arch. The band was instrumented with strain gauges and tested on the shake table to determine the forces in the band due to the same records.

This paper presents the background to this project, results of the unreinforced system and preliminary results with the reinforced system.

2. Background

The Lock Block (TM) is a pre-cast concrete unit designed for use in retaining wall systems. It is made by Lock Block Ltd., of Vancouver, BC, in their material recycling plant located in the Lower Mainland. The recycling plant reclaims material to make new concrete,

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which can obtain strengths of 20MPa. Over the last several years they have been experimenting with various shapes of forms to create arch and dome structures. Several demonstration structures have been built, including 3m and 6m arches. The arches can be built in relatively short time using chains and a few extra blocks, and a single excavator. Once all the blocks are in place the keystone is placed and the chains are loosened to bring the structure into place.

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 DeLorenzis et al (2007) which proposed an analytical model for masonry arches. The model assumed fixed hinging points and is based on rigid-body geometry. It describes the collapse of the arch based on the ‘four-link' mechanism. The arrangement of the four-link mechanism is shown in Fig. 1; this mechanism requires the formation of three hinges which precedes collapse.

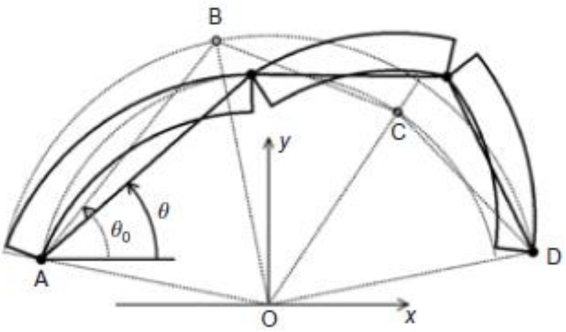

Fig. 1. ‘Four-link' mechanism described by DeLorenzis et al. (2007).

A complimentary work by DeJong et al (2008,2010) performs shake-table testing on scale models of arches, while applying the analytical model to each tested arch. For the experimental program, the excitation was applied as (a) harmonic motions and (b) as one of five 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 sensitive to the first large impulse in each record; some of the records would fail the arch on the first half cycle of the impulse but many failed the arch on the second half cycle. It was clear in nearly all of the tests that the four-link mechanism was observed before collapse. The important results that came from this work included

- rocking-type failure based on the four-link mechanism governs
- elastic resonance does not occur due to its high frequency (>300Hz) relative to the earthquake input motions
- the analytical model provided accurate failure prediction when using the ‘primary' impulse from the earthquake record
- the arches are also more vulnerable to impulse-type ground excitations v) a suite of failure curves was created to identify the failure acceleration for a variety of arch geometries (which was part of the development of an assessment criterion to evaluate safety).

3. Methodology

The methodology adopted for this study has two main parts: first, to characterize the behaviour of an unreinforced arch, and second, to explore options for reinforcing the arch and develop a design guideline for that reinforcement. To achieve the objective of creating the guideline, both experimental and analytical studies will be undertaken; this paper focuses on the first phase which includes shake-table testing of scale models of the arches.

The scale of the models is pre-selected due to the availability of 1/25 scale models created by Lock-Block. Several models were tested, including a 3m and 6m arch, a 6m and 12m dome. This paper deals with the 6m arch. A suite of earthquake records was developed with three criteria:

- to match those used in DeJong et al (2008) for direct comparison,
- from the suite of records used for the BC Seismic Retrofit Guidelines by Pina et al (2013) and
- a selection of worldwide significant events. The records were appropriately scaled for the models used.

The testing is done uni-directionally in the weak direction of the arch. The objective is to identify which parameters they are sensitive to, including but not limited to frequency, displacement, impulses, directionality etc. Each model is tested with each earthquake, at varying levels of intensity until failure is observed. At the failure level the test is repeated at least 3 times to ensure consistency.

A method of externally reinforcing the arch is applied using a tension member. This member is placed along the outer perimeter of the arch, which acts to hold it together during the lateral loading through tension. For these tests, a steel band is used, anchored at either end. The band is instrumented with strain gauges to measure the forces during the shaking. The earthquakes are reapplied to the reinforced model at the previously determined failure level. The recorded force is then said to be proportional to the inertial load that causes the collapse of the unreinforced arch when subjected to the given earthquake. This force can then be used for design by stating it as a fraction of the weight of the arch.

4. Shake-Table Testing

Shake-table tests were performed using a long stroke electrodynamic APS shaker, with a plywood platform attached to the top used as the base for the models. The first course of blocks in the model was fixed at the base. The shaking was in the weak direction of the arch. A high speed camera was used with targets on the model.

4.1. Models

The models are made from 1/25 scale blocks (see Fig. 2). Each block is 6x3x3cm and weighs 85 g, made from Rockite Cement, which is used for patching and is very strong. The advantage of this type of material is that it has a similar density to real concrete, which makes it useful for seismic testing. The Lock-Block products have a cross-shaped shear key at the top of each block, that fits into the bottom of the above block as seen in the figure.

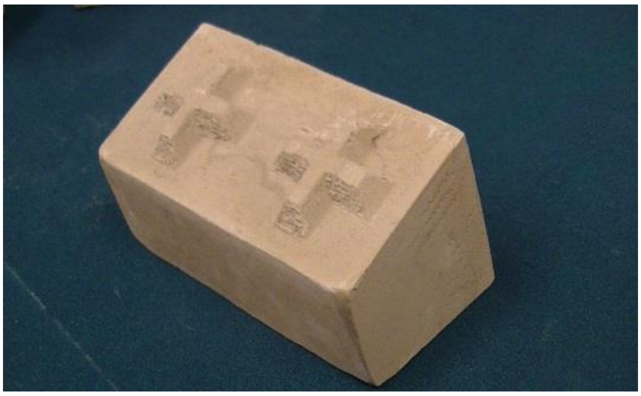

Fig. 2. Small-scale lock block used for the model.

Several models were tested, but the focus of this paper is on the 6m arch, shown in Fig. 3. This model weighs 7kg, is 18cm high and 12cm deep (which uses four full blocks). The interior diameter is 24cm. The first course of blocks was oriented at 90 degrees to the rest of the courses; it was found that this gave the most stable base and allowed for easier assembly of the arch. The first course was held in place on either side by a piece of wood attached to the plywood base.

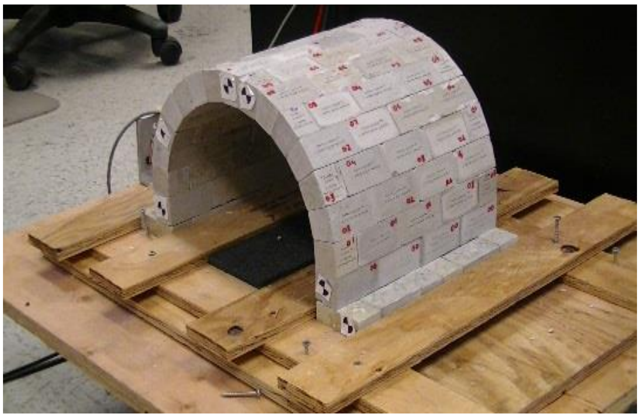

Fig. 3. Shake table testing set up.

4.2. Selected time histories

The total suite of records was approximately 20, which included the study done by DeJong et al (2008), the seismic retrofit guideline records and others. For this first phase 6 records were used. One governing factor in selection of the records was in the physical limitations of the shaker used, particularly with displacements.

Crustal, subcrustal and subduction earthquakes were considered for the selection. Several records, with a considerable difference in their frequency content, maximum acceleration amplitude, maximum displacement amplitude and impulses, are chosen from Pina et al (2013) and PEER Strong Motion database. Table 1 lists the records used. Included is the name, location, year, station name and peak acceleration from that station.

4.3. Scaling of time histories

Time scaling of the records was implemented to account for scale effects between the model and the represented structure. The scaling of this ground motions, as well as, the rest of dimensions involved in this small-scale testing, are based on dimensional analysis described in several studies : Jha (2004), Noam et al (2010), Stojadinovic (2012) and Petry et al. (2012). Following that approach and using the length scale factor of 1/25, the scaling factors are determined as shown in Table 2.

A time scale factor of 1/5 was applied, reducing the duration of the time histories to one fifth of the original durations and increasing the frequencies five times. The accelerations are unscaled.

4.4. Testing procedure

A range of six selected scaled ground motions, calibrated for different intensity levels, are applied to the model in one horizontal direction. The records were repeatedly applied at increasing levels, as a fraction of the record full-scale (referred to in this paper as "Test Level") starting from 40%. Once a failure of the model was observed, the test was repeated three times at the same test level. This was done to check for repeatability.

A total of 80 tests for the unreinforced and reinforced models were run. All tests were recorded with a high-speed video camera at 400 frames per second. A set of targets are attached to the model which allows for the tracking of displacements with the camera software.

4.5. Unreinforced model results

Table 3 summarizes the results of the shake table tests on the unreinforced model. The table shows each applied earthquake and test level; an "O" represents a test where the arch did not collapse, whereas the "X" shows the cases in which collapse occurred. For Tokachi-Oki, Loma Prieta and Tohoku earthquakes tests beyond the failure level were performed.

These tests establish the TL at failure for each earthquake. A study of several relevant parameters was made in an effort to identify the sensitivities of the arch to the different earthquakes. These included peak ground acceleration, velocity and displacement; intensity and duration among others. It was found that in most cases there was not direct correlation or trend to the failures and these parameters. The most consistent result agrees with the work done by DeJong et al (2008, 2010) in that the impulse-type ground motion has the strongest effect; this was observed with the least impulse-like record (Nisqually) having the least effect on the arch.

The rocking type failure based on the four-link mechanism typical of arch structure, as described in (Anshuman, 2004), was seen in all of the tests. A typical collapse of the arch taken from the high speed camera footage is shown in Fig. 4. The hinges were created at the same points for all the earthquakes with the only variation of the collapse direction. One interesting observation from analysis of the collapse videos is that the arch tends to behave in a base-isolated manner with the ground moving much faster than the arch itself; the collapse occurs in a much slower rate once the critical displacement is reached.

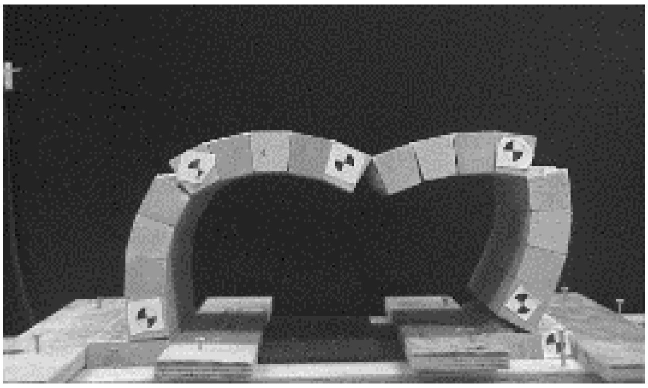

Fig. 4. Typical four-link failure mechanism taken from the high-speed camera footage.

Table 1. Suite of time history records used for the shake table testing.

EARTHQUAKE NAME	LOCATION	YEAR	STATION NAME	PEAK ACC (g)
NISQUALLY	Washington	2001	Seattle (BHD) Z	0.16
TOKACHI-OKI	Japan	2003	Noya (HKD107) EW	0.48
LOMA PRIETA	California	1989	CDMG 57007 Corralitos	0.64
KOBE	Japan	1995	CUE 99999 Nishi-Akashi	0.51
TOHOKU	Japan	2011	TH2011_FKS031_NS	0.42
PARKFIELD	California	1966	CDMG STATION 1014	0.44

Table 2. Scale factors based on dimensional analysis.

	LENGTH SL	TIME St	FREQUENCY Sf	ACCELERATION Sa
Dimension	L	T	T-1	LT-2
Relation to length factor	N/A	$\sqrt{1/S_L}$	$\sqrt{S_L}$	$S_L * \left(\sqrt{1/S_L}\right)^2$
Value	1/25	1/5	5	1

Table 3. Summary of performed shake-table tests on unreinforced model.

EARTHQUAKE	TEST LEVEL (TL)							
	40%	50%	60%	70%	80%	90%	100%	120%
NISQUALLY			O	O	O	O	O	X
TOKACHI-OKI	O	O	O		O	X	X	
LOMA PRIETA	X	X	X					
KOBE	X							
TOHOKU	X		X					
PARKFIELD	O		O	O	X			

5. Externally Reinforced Model

From the tests on the unreinforced model, it was clear that the model would not survive most earthquakes. There was however, significant variability in the failure level, from very low, to almost 100% of the design level. There are many possible ways to stabilize the model, but the simplest and most reliable is add an external tension reinforcement around the arch.

From the unreinforced tests, it was apparent that the arch tends to fail in the same location each test, with three hinges opening in the arch (plus two at the base). The collapse occurs once the hinges open to a critical displacement level. It then leads that preventing the hinge from opening will prevent the collapse; this can be done is several ways:

- Application of epoxy between the blocks – this would likely present a failure in tension of the concrete since the epoxy strength is quite high.
- Use an externally bonded type reinforcement (such as FRP's) that can be placed at each of the hinge locations – care must be taken to select locations in order to prevent other hinges from opening.
- Use a continuos non-bonded tension reinforcement anchored at the ends.

The second is possibly the most effective, since it allows reinforcement at the hinge locations directly, however the third is the simplest to apply and was used in this study.

For these tests, a steel strap was added to the outside of the arch, anchored at each end (which capability to tighten at one end) and positioned at the midpoint of the depth of the arch. In the full scale application, a variety of materials, dimensions and arrangements can be used. For the scale model tests, the material and dimensions were specifically chosen in order to achieve a measureable strain based on the expected levels of force.

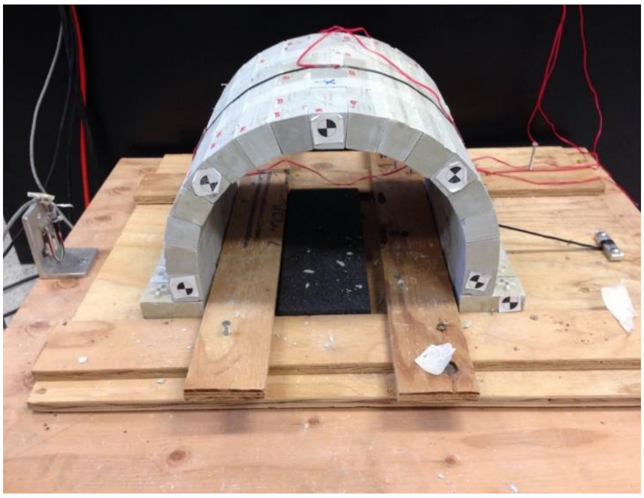

Fig. 5. Instrumented steel band reinforcing the arch model.

The material for the reinforcement was a 1095 spring steel strap, 6.35mm wide and 0.127mm thick. These dimensions provided the smallest cross sectional area for the strap out of the available materials. The strain gauges had the ability to register changes in strain of 1με and the estimated applied force of the model was 1-2lbs. Material calibration was performed by adding 1kg masses to the steel strap which was oriented in a vertical position. Additional 1kg masses were attached to increase the applied strain linearly. Approximate strain due to 1kg was 66με. The elastic modulus of the material was calculated to be approximately 212.2Mpa.

5.1. Reinforced arch model results

From a qualitative point of view, the steel band reinforcement prevented failure in any of the applied tests. This is expected and in itself is not conclusive since a single band may not perform as well with multi-directional shaking; however, it does prove the concept in principle. The applied tests are shown in Table 4.

Two main observations can be made from the results of the reinforced arch tests. First, hinges can be observed by a slight separation between the blocks at the same location as the unreinforced model. This effect is shown in Fig. 6 with the circles showing the hinges. It is worth noting that the appearance of the hinge on the outer edge is dependent on the tension of the band (ie. the more tension the smaller the hinge) and that the inner hinge cannot be easily controlled by the tension band, which brings into consideration the earlier point of using bonded reinforcement at the location of the hinges.

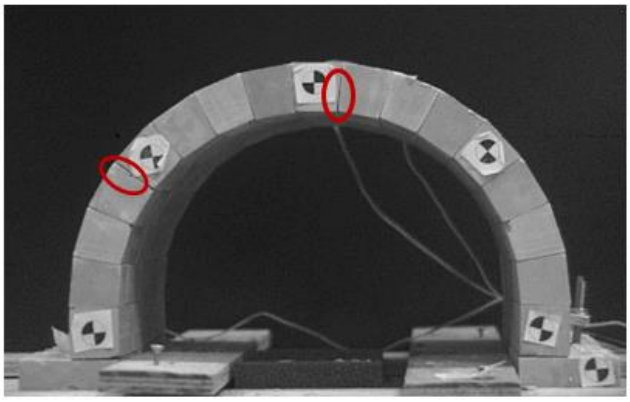

Fig. 6. Reinforced arch with hinges shown taken from the high speed camera footage.

The second observation was that the recorded forces appeared to be consistently lower than what was expected, by as much as 50% (approximately 1lb maximum). It was expected that the tension band would take a majority of the inertial force that results in the collapse of the arch. One possible explanation is that by holding the arch together during shaking, the arch maintains much of its primary load paths in compression for the additional lateral load. Additional shake table tests will be done including multi-directional; and an analytical model will be created to further study the load paths and their effects.

6. Conclusions

Lock Block Ltd. has created arch and dome structures based on their patented interlocking block system. This study examines the seismic performance of the arch structures by shake-table testing of scale models of the arches.

A suite of six time-scaled records was used and applied to a scaled 6m arch. The records were applied at increasing levels of intensity until collapse occurred. It was seen that the collapse followed the typical four-link mechanism with the hinges opening at the same location in each case.

A steel band was attached to the model to act as external tension reinforcement. The band was instrumented with three strain gauges. All of the tests applied to the unreinforced model were applied at the failure level were applied to the reinforced model; in each case the model survived.

Small openings between blocks were observed in the reinforced model which indicated that the same hinges were formed and that the arch maintained the four-link mechanism even without failure. The tension forces in the band were very low and typically about half of what was expected.

Further studies will be done, including using larger models, expanding the suite of records used, and creation of an analytical model to study the load paths in detail and to examine various factors including multi-directional loading and boundary conditions.

Table 4. Summary of performed shake-table tests with reinforced model.

EARTHQUAKE	TEST LEVEL (TL)							
	40%	50%	60%	70%	80%	90%	100%	120%
NISQUALLY							O	O
TOKACHI-OKI					O	O		
LOMA PRIETA	O							
KOBE	O							
TOHOKU	O							
PARKFIELD					O			

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