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Division V

VeRCoRs Experience: Predicting Containment Ageing, from the Mockup to the Digital Twin: Experimental Characterization of Airflow through Concrete Cracks and its Application to VeRCoRs Benchmark Containment Structure

Xu Huang[1], Julia Bruce[2], Evan Bentz[3] and Oh-Sung Kwon[4]

[1] Ph.D., Research Associate, University of Toronto, Canada (xu.huang@mail.utoronto.ca)
[2] Structural Engineer, HNTB Corporation, Kansas City, MO, USA (jabruce@hntb.com)
[3] Professor, Civil and Mineral Engineering, University of Toronto, Canada (bentz@civ.utoronto.ca)
[4] Associate Professor, Civil and Mineral Engineering, Univ. of Toronto, Canada (os.kwon@utoronto.ca)

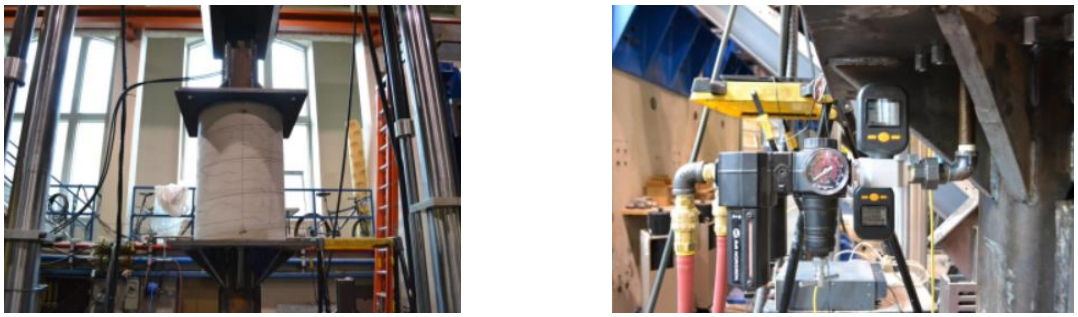
ABSTRACT

This paper discusses the experimental procedure developed at the University of Toronto to analyse air flow through concrete cracks due to internal pressurization of a hollow concrete structure. A three-dimensional finite element model was also built using VecTor4 to evaluate strain evolution during the VeRCoRs pressurization tests. Data from the experimental tests were used in conjunction with the model to predict air leakage during the pressurization tests.

EXPERIMENTAL PROCEDURES

A test program was developed at the University of Toronto (Dury, 2018) to investigate the flow of air through cracks in concrete. Two hollow, cylindrical pilot specimens were cast to determine the capabilities of the experimental setup. Both specimens were reinforced in the longitudinal direction only. The reinforcing bars were threaded on the ends in order to allow placement of nuts, which were used to secure 1-in. thick steel plates to the top and bottom surfaces of the specimens. Silicone was placed between the steel plates and the concrete to create a flexible, airtight seal.

The specimens, shown in Figure 1(a), were loaded in tension using a displacement-controlled testing protocol in a manner similar to tests by Rizkalla (1984) and others. At each selected axial tension force (load stage) the pressure regulator shown in Figure 1(b) applied steps of air pressure in increments of 0.137 bar up to a maximum internal pressure of 1.03 bar and the flow was measured in the steady-state condition.

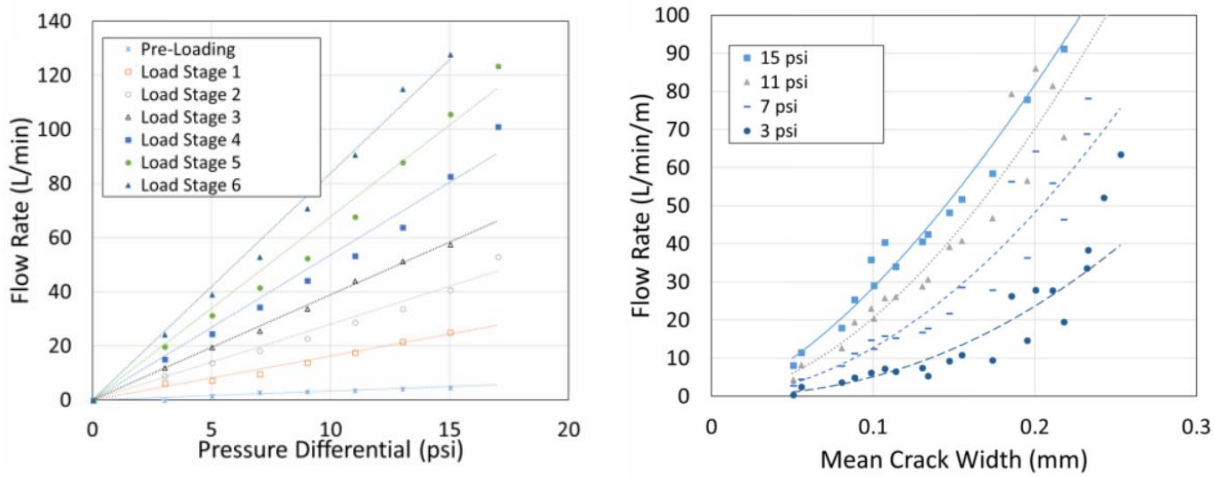


(a) (b)

Figure 1: (a) Leak Rate Specimen during Testing; (b) Pressure Regulating and Monitoring Equipment

Results

Specimen LRT01 was loaded through 14 load stages up to a maximum crosshead displacement of 1.30 mm and specimen LRT02 was loaded through 26 load stages up to a maximum crosshead displacement of 3.00 mm. Both specimens developed cracks of varying widths. The flow rates were measured at each load stage as previously described and the relationship between pressure increase and flow rate at each load stage followed a linear trend, as shown in Figure 2(a). Crack lengths were also measured for each load stage and the average crack width was determined using data from four LVDTs which were attached to the specimens. This allowed for the measured flow rates to be normalized by crack length. The relationship between the mean crack width and the normalized flow rate at varying pressure differentials is shown in Figure 2(b).



(a) (b)

Figure 2: (a) Relationship Between Pressure and Flow Rate for Specimen LRT02; (b) Relationship Between Mean Crack Width and Flow Rate at Varying Pressure Differentials

Prediction

A prediction based on data from the experiments determined the flow rate through cracks in the cylinder portion of the VeRCoRs mockup to be 0.18 m^3/hr/meter of crack. Due to limitations in size and pressure of the laboratory experiments, the data was extrapolated to adjust for the increased wall thickness and pressure differential of the VeRCoRs tests. Additionally, using data from previous pressurization tests, a theoretical crack length was predict the total flow rate for each area of the structure. Flow rate predictions and results, in normalized cubic meters per hour, for the pressurization test are shown in Table 1.

Table 1: Predicted Flow Rates

Area	Flow Rate (Nm^3/hr/meter of crack)	Theoretical Crack Length (m)	Predicted Flow Rate (Nm^3/hr)	Measured Flow Rate (Nm^3/hr)
Gusset	0.18	21.7	3.9	23.95
Hatch	0.18	6.1	1.1	0.812
Cylinder	0.18	10.0	1.8	2.955
Dome	0.14	1.5	0.2	0.828

While the predicted values underestimate the measured flow rates, the area contributions were predicted in the correct order – with the gusset contributing the largest volume of leakage and the dome contributing the smallest. The discrepancy between the predicted and measured flow rate values is due to the difference in predicted and measured crack lengths.

NUMERICAL MODEL

A numerical model was built in VecTor4 which represents the containment structure in a quarter model, assuming the structure to be axisymmetric, to predict the mechanical behaviour of the containment structure during pressurization. The model was developed using the following assumptions:

- Reinforcement was modelled as continuous and regular. Irregularities in reinforcing bars and tendons due to opening and support bracket were ignored.
- Mesh transitions were developed to be smooth at sharp geometric changes, such as at the ring beam and the gusset, shown in Figure 3(a), and the perimeter wall was prismatically modelled.
- Truss elements were used to connect nodes at the bottom of the perimeter wall to the axis of symmetry to consider the deformation of the foundation due to shrinkage as well as forces transmitted from the perimeter wall.

The following improvements were made to the numerical model used for the first benchmark (Huang, et. al. 2016) based on the received results:

- The mesh at the top of the dome, shown in Figure 3(b), was arranged to eliminate the hole which was present in the previous model.
- Temperature and relative humidity used for model predictions were updated based on data provided by the benchmark committee, which more closely resemble the actual conditions at the site.
- The CEB/FIP MC2010 model code was used for modelling creep and two models were used to model the concrete shrinkage. At the dome, the ACI 209R-08 model was used, while at the ring beam and the perimeter wall, the MC2010 model was used.

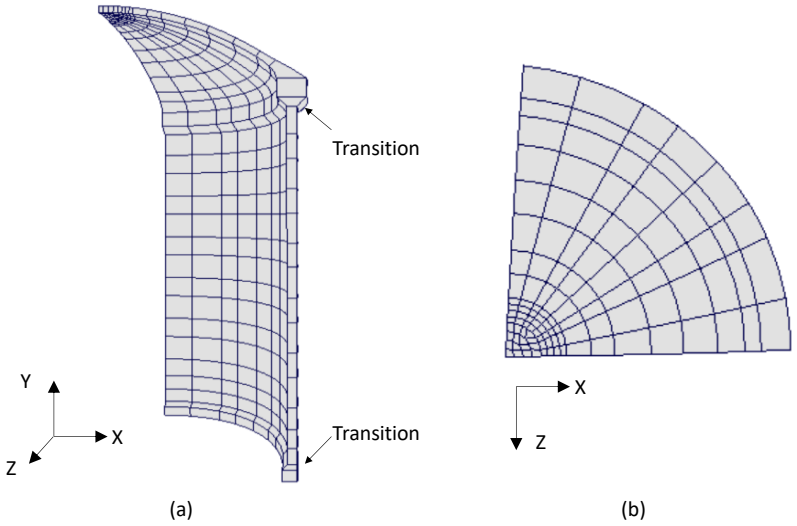


Figure 3: Mesh Scheme

Prediction

Predicted strain changes due to increase in internal pressure, shown in Table 2, were in good agreement with the measured results for the perimeter wall. For the gusset, however, the strains were not as accurately predicted due to the simplified boundary condition between the ring beam and the gusset in the model. Likewise, the assumptions previously noted, which simplified the model at the transition between the dome and the ring beam, led to inaccurate predictions of strain change in the gusset.

Table 2: Predicted Strain Changes During Pressurization Tests (units microstrain)

Zone	Strain gauge	Direction	VD1 Prediction	VD1 Measurement
Perimeter wall	P1	Vertical	88	73
	P1	Horizontal	218	216
	P2	Vertical	86	88
	P2	Horizontal	229	234
	H1	Vertical	77	60
	H1	Horizontal	223	220
	H2	Vertical	90	86
	H2	Horizontal	227	not available

CONCLUSION

This study indicated that the numerical model developed in VecTor4 can accurately predict the strain changes in the perimeter wall due to increasing internal pressure. Experimental tests were performed at the University of Toronto to characterize the flow of air through cracks in containment structures. Data from the experimental tests, normalized by crack length, was used to predict the leakage rates during pressurization tests and moderately agree with the measured results.

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