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Finite Element Analysis of Walls with Alkali Silica Reaction Subject to Simulated Seismic Cyclic Loading

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ABSTRACT

Some form of silica aggregates in concrete react with high alkaline pore solutions to produce a reactive product that can expand with moisture. The reaction is known as Alkali-Silica Reaction (ASR). The ASR is observed in some concrete structures in eastern Canada and the eastern United States. The expanding reaction product can crack concrete structures and reduce their service life. The only structure regulated by the Canadian Nuclear Safety Commission (CNSC) with ASR is the Gentilly-2 Nuclear Power Plant (currently in decommissioning state). ASR-induced concrete expansion and cracking may degrade the mechanical properties of the concrete. The effect of ASR on structural load demand and seismic response of concrete buildings and anchors requires assessment in order to manage concrete ageing and structural integrity. The CNSC is currently developing a regulatory requirements basis for the assessment of existing concrete structures with ASR, as well as a means of avoiding this pathology in new builds. This paper describes the research conducted by the CNSC to predict the behaviour of an ASR wall subjected to constant axial and lateral cyclic loads that simulate seismic loading.

The objective of this paper is to describe the use of the commercial finite-element (FE) code LS-DYNA to model concrete walls with regular concrete and reactive ASR concrete. Adequate modelling of concrete with ASR involves complex chemo-mechanical constitutive models that are outside the sets of available materials in commercial FE packages. The current work analyzes the effect of ASR in a simple phenomenological model by substituting concrete expansion due to ASR with an identical thermal expansion. Concrete strains due to ASR expansion are thus modelled as thermal strains due to a temperature increase of 1°C with a thermal expansion coefficient equal to the longitudinal concrete expansion due to ASR.

Cyclic loading with increasing amplitude was applied to both the ASR walls and the regular non-ASR walls until failure was observed. The FE predictions were compared with available test results for both the regular non-ASR walls and ASR walls subjected to accelerated aging (240 days for regular walls and 260 days for ASR walls). Because there was good agreement between the FE predictions and the test results, an additional FE analysis was conducted to perform a “blind” prediction of the behaviour of both the regular walls and ASR walls after 900 days of accelerated aging. Once the results of this additional test were obtained, the blind FE predictions were compared with the test results, and reasonable agreement was obtained. The FE model was revised to account for real material data, obtained in the additional test. The revised model produced good agreement for all five tests conducted: 240 and 975 days of aging for regular walls, and 260, 610 and 995 days of aging for ASR walls.

Keywords: Reinforced Concrete, Alkali Silica Reaction (ASR), Cyclic Loading, Shear Capacity, FEA

INTRODUCTION

The research program on assessment of structures subjected to concrete pathologies (ASCET) was organized by the OECD/NEA. The objective of this research program is to make general recommendations for aging management of concrete nuclear facilities taking into account the effect of concrete pathologies on structural degradation. The multi-year ASCET program was organized in three phases to provide these tools:

- Phase I: Development of general guidance for ageing management and identifying research needs – completed [1]
- Phase II: Perform a blind numerical benchmark – completed [2]
- Phase III: Calibration and refinement of numerical tools by using additional test data – completed, final report is in preparation stage

The program was based on the wall tests performed at the University of Toronto (UofT) under a CNSC research program. Two sets of walls (one regular non-ASR and another with alkali-silica reaction) with different ages, were tested. It is very difficult adequately represent seismic loading on safety-related Nuclear Power Plant structure at a level leading to complete wall failure. Therefore, a simplified load was applied using a cyclic increasing amplitude shear load in combination with a constant axial load to both regular non-ASR and ASR walls until their failure.

The ASCET Phase II was based on the recommendation of the Phase I Report [1]. The Phase II of the ASCET was defined as a blind simulation benchmark to predict the behaviour of structural elements with Alkali Silica Reaction (ASR) which has concrete swelling, as a consequence.

Reliable numerical tools are needed to predict the temporal structural behaviourof structures with concrete pathologies and degradation mechanisms. Concrete swelling (volume change) is a consequence of several degradation mechanisms of concrete structures (alkali aggregate reaction, delayed ettringite formation, irradiated concrete, etc.) and it is important to assess and quantify the ultimate and service limit states of structures built with such concretes.

Five walls in total were tested at the University of Toronto under ASCET research program: two sets of two walls (one with regular non-ASR and the other with ASR) and one additional wall with ASR alone. All walls have the same geometry and reinforcement with similar loading, i.e., cyclic horizontal and constant axial forces up to failure. The only deference between the walls in each of the two sets is that one wall was built with reactive aggregate and the other one with regular non-ASR aggregate.

In order to calibrate the models, the participants received the results of the first set of two walls previously tested at the University of Toronto, after 8 months of accelerated ageing.

The second set of walls, on which the ASCET Phase II blind simulation was performed, was tested after ~30 months of accelerated ageing. The simulations provided the information related to the behaviour and the failure modes of structures with Alkali Silica Reaction as well as the difference between the behaviour and failure modes of these structures and the structures built with the regular non-ASR concrete. The analysis results of the ASCET Phase II were mainly focused on capturing the ultimate wall capacity

During the last Phase III material properties and test results after ~30 months of accelerated ageing were provided to all participants. Based on new test results blind predictions were revised. The predictions at this phase were focused on displacements, deformations, the failure modes, the crack pattern, crack width and crack distribution. These results are very important since those output results significantly affect the serviceability of concrete structures. Reduced maximum displacements, loss of ductility and degraded hysteresis loops with the evolution of ASR with age, are other important aspects, especially for seismic loading, and were also studied in details during Phase III.

Eleven teams representing Nuclear Regulators and Universities around the world have participated in the ASCET numerical simulation of shear wall tests. However, the current paper is focused on the work conducted by CNSC. The CNSC work during Phase II was already presented in Reference [3]. Therefore, the current paper is focused on presenting the results obtained during Phase III.

FINITE ELEMENT (FE) MODELING

Following ASCET Phase III objectives, CNSC conducted FEA of all five walls tested at UofT. The walls selected, the testing procedure and the test results are described in [4, 5]. Table 1 shows main parameters of these walls. Figure 1 shows the test setup and the geometry of the tested walls. Walls were subjected to constant axial load and lateral cyclic load with increasing amplitude.

Table 1. Main parameters of the walls tested

	REG A	REG B	ASR A1	ASR B1	ASR B2
Age, days	240	975	260	610	995
Compressive strength, MPa	79.0	80.1	63.7	67.1	63.0
Tensile strength, MPa	4.76	4.39	3.24	3.24*	3.18
Expansion, %	0.0332	0.0331	0.185	0.215	0.233

*not measured, selected as for ASR A1 wall

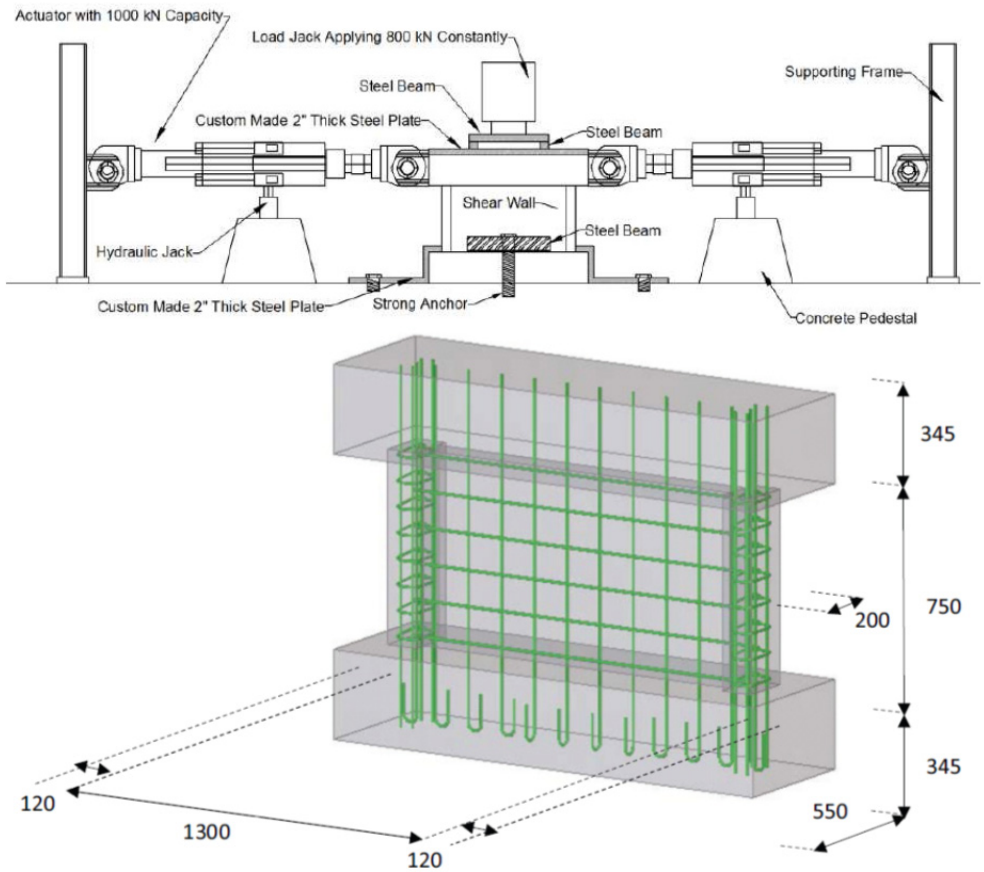


Figure 1. Test setup [4] and wall geometry. All dimensions are in cm [6]

Constitutive models for ASR and non-ASR concrete

The objective of this work was to use commercial the FE codes ANSYS and LS-DYNA for modeling of concrete walls with and without ASR. Adequate modeling of concrete with ASR involves complex chemo-mechanical constitutive models [5, 7] that are outside the sets of available materials in commercial FE packages. The current work tries to analyze the effect of ASR in a simple phenomenological model by substituting concrete expansion due to ASR with identical thermal expansion. Consequently, concrete strains due to ASR expansion were modeled as thermal strains due to a temperature increase of 1^{O}C and a thermal expansion coefficient α_T equal to the longitudinal concrete expansion ε_0 due to ASR.

The implicit code ANSYS has only one concrete material model with cracking possibility that can be used in conjunction with special 3-D (solid) FE SOLID65. However, the simulations conducted show that implicit modeling using ANSYS cannot reach the state of wall failure in shear due to non-convergence. Therefore, the explicit FE code LS-DYNA was selected for all simulations described in the report.

The LS-DYNA version 8.0 used has several material models suitable for modeling cracked and crushed concrete. To adequately capture crack initiation and propagation until complete failure, the density of the FE mesh should be much higher than in the analysis of non-cracked concrete. This was shown in the sub-section 2.3 below. Therefore, only 2-D analysis of shear walls using shell FE was conducted.

Among all concrete models in LS-DYNA, only one material model (*MAT_172/*MAT_CONCRETE _EC2) could be used for 2-D analysis of shear walls using shell FE. Material data and equations governing the behavior of this model are taken from Eurocode 2 Part 1.2 (General rules – Structural fire design). The material model can represent plain concrete only, reinforcing steel only, or a smeared combination of concrete and reinforcement. The model includes concrete cracking in tension and crushing in compression, reinforcement yield, hardening and failure. Temperature-dependent properties were available in the model, however they were not used.

Although the material model offers many options and, generally, requires input of more than 40 parameters, a reasonable response may be obtained by entering only concrete density and strength in tension and compression for plain concrete. If reinforcement is present, Young's modulus, ultimate stress and reinforcement ratios in FE plane must be defined. The model cannot account for transverse reinforcement (perpendicular to shear wall plane).

As was stated earlier, the ASR expansion was modeled in this model as thermal expansion of concrete for a temperature increase of 1^{O}C using values provided in Table 1. No thermal expansion was assumed for the reinforcement to account for its "confining" action. For non-ASR (regular) walls a small thermal expansion was also selected for the concrete according to Table 1 values.

Finite Element Mesh, Loading and Boundary Conditions

2-D Belytschko-Tsay 4-noded shell FE was used for wall modeling. The mesh density was selected based on several runs described in Reference [3]. As evidenced from these runs, high mesh density is required to adequately capture crack initiation and propagation and subsequent wall failure.

The loading was applied in two stages as follows:

1. Thermal expansion due to temperature increase 1^{O}C was applied at the 1st stage
2. Constant vertical (axial) loading and lateral cyclic loadings were applied at the 2nd stage. The vertical loading was applied using an appropriate distributed load on the upper edge of the wall.
   The lateral cyclic loading was obtained through contact interaction between two rigid plates representing actuators and the tested structure, see Fig. 2. No rotation restrains were applied at these places.
   The lateral cyclic loading was selected as described in [4]:
   - For the first two cycles applied lateral displacement of 0.2 mm was applied in the plane of the wall in each direction
   - Subsequent cycles were at maximum displacements of 0.4, 0.6, 0.8, 1, 1.4, 1.8, 2, 2.5, 3, 4, 4.5, 5.5, 6, and 7 mm. For each displacement two complete cycles were applied
   - Additional cycles with displacements 8, 9, 10, 11 and 12 mm were applied to ensure wall failure and analyze the post-failure behavior. For each displacement two complete cycles were applied

The outline of FE model and applied loading are shown in Figure 2.

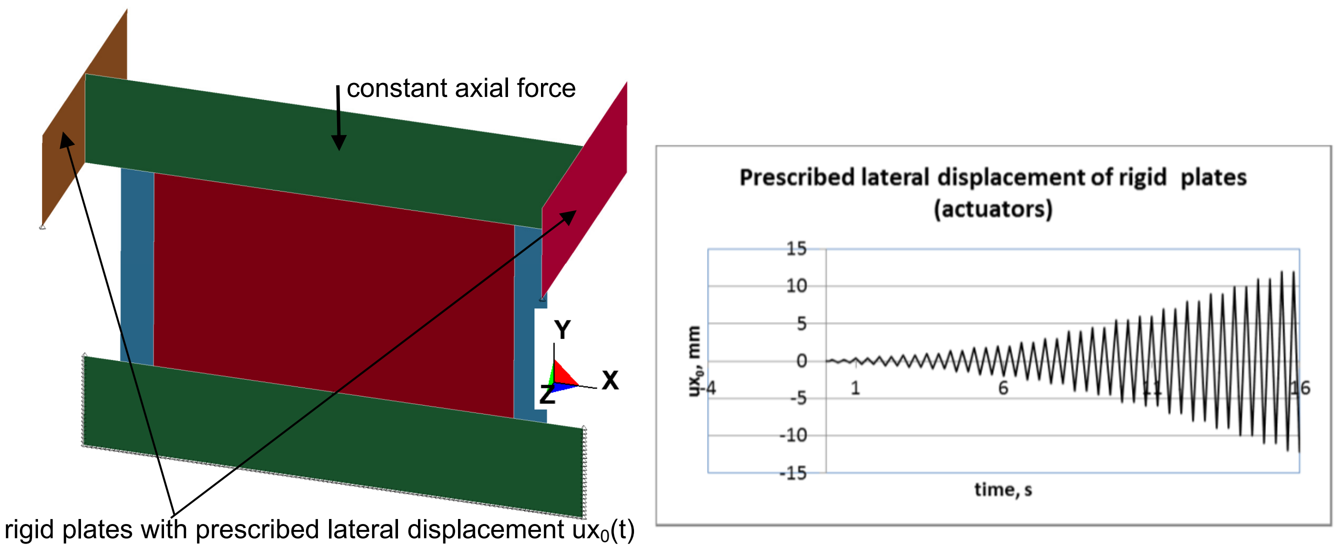


Figure 2.Outline of FE model and applied loading

LS-DYNA code used is an explicit code that treats quasi-static behavior as slow dynamic. The maximum allowable value of time step in an explicit code is very small due to convergence restrictions. However, the total simulation time often is smaller than in implicit analysis since each time step requires significantly less computer time. To reduce simulation time, the cycle period was selected as 0.4 s for all loading amplitudes. This resulted in a total simulation time of 16 s. A further decrease of the cycle period could result in artificial oscillations caused by inertia forces. Since the behavior of the walls during the tests was essentially quasi-static, the cycle frequency was not an important factor.

The imposed Boundary Conditions (BC) were as follows:

- Out of plane (z-) displacements were fixed for all nodes.

Additional BC for the bottom beam:

- Bottom was fixed in all directions, except the x-direction, during both stages
- Both sides of the bottom beam were free during the 1st stage to allow for an unconstrained thermal expansion and fixed in x-direction at the beginning of the 2nd stage to reflect the test set-up
- y-displacement of node connected to anchor bolt (see Fig. 1) was unconstrained during the 1st stage and fixed during the 2nd stage; x-and z-displacements of this node were fixed during both states

Additionally, a small Rayleigh damping was applied to suppress unwanted residual oscillations: a stiffness proportional damping of 5% and a mass proportional damping of 4%. These values were selected based on numerous test runs.

Verification of the proposed FE model was conducted as follows [3]:

- 2-D shell and 3-D solid models were compared to assess the suitability of using 2-D model
- Models with different mesh densities were examined to select the adequate mesh density.

The results of this verification showed clearly that for the applied shear loading shell model with the mesh size of 16mm is adequate for the analysis [3].

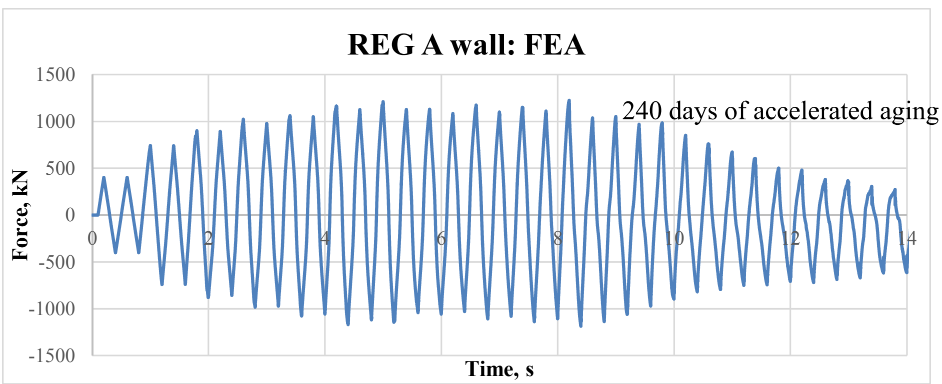
Additionally, the effect of BC at the wall bottom was examined. Simplified BC described earlier in this section were compared with more accurate modeling of the bottom wall-floor contact including bottom post-tensioned bolts.

Finally, a filtering of FE results was applied to mitigate parasitic numerical oscillations caused by employing explicit FE algorithms. Based on different runs a ten points moving average was selected as the best smoothing method for all cases examined.

DETAILED FE ANALYSIS OF ASR AND NON-ASR (REGULAR) WALLS

FE predictions were obtained for all five walls and compared with test results.

Figure 3 shows predicted time histories of the total lateral (shear) force for regular (REG A) and ASR A1 walls, respectively. This force is defined as the reaction force acting on rigid plates with prescribed lateral displacement in FEA and actuator force in tests. Since only Force-Displacement curves were recorded during testing, no test results are shown on Figure 3. Similar Figures were obtained for the remaining 3 walls.



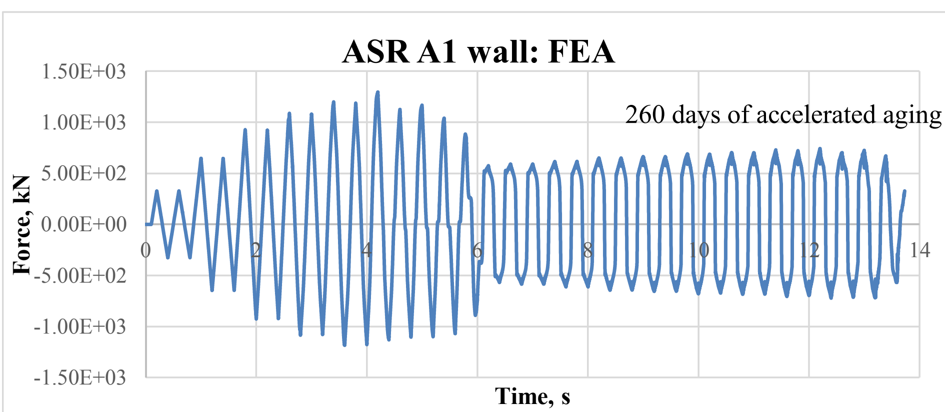
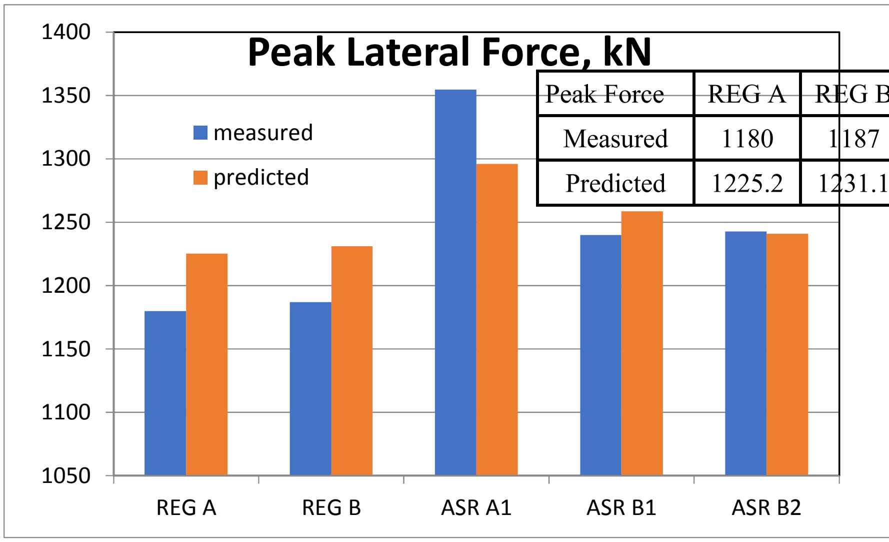


Figure 3. Predicted time histories for the total lateral force for regular (REG A) and ASR A1 walls

Figure 4 shows predicted and measured Maximum Shear Capacity for all walls.



Peak Force	REG A	REG B	ASR A1	ASR B1	ASR B2
Measured	1180	1187	1354.5	1240	1242.7
Predicted	1225.2	1231.1	1295.9	1258.5	1240.9

Figure 4. Predicted and measured Maximum Shear Capacity for all Walls

The results show clearly that the main features of all five tests were adequately captured by the FE model as follows: (i)the maximum values of lateral load (maximum shear capacity), and (ii) the established test result that maximum shear capacity of ASR walls is higher than regular concrete walls despite lower concrete strength

Next Figures 5 - 9 show Lateral Force vs. Displacement Curves until wall failure for all walls. The failure in FEA was defined as a significant drop in enveloping values of shear force.

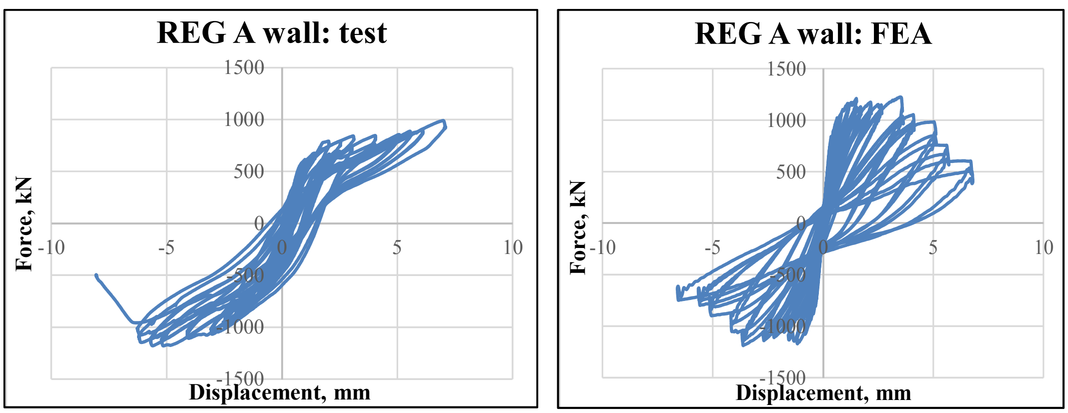


Figure 5. Lateral Force vs. Displacement Curve for REG A wall (after 240 days of accelerated aging)

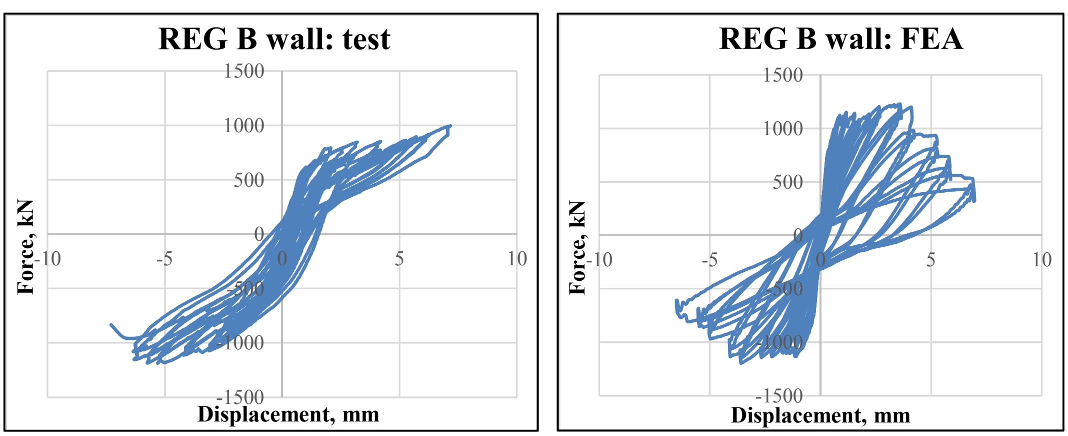


Figure 6. Lateral Force vs. Displacement Curve for REG B wall (after 975 days of accelerated aging)

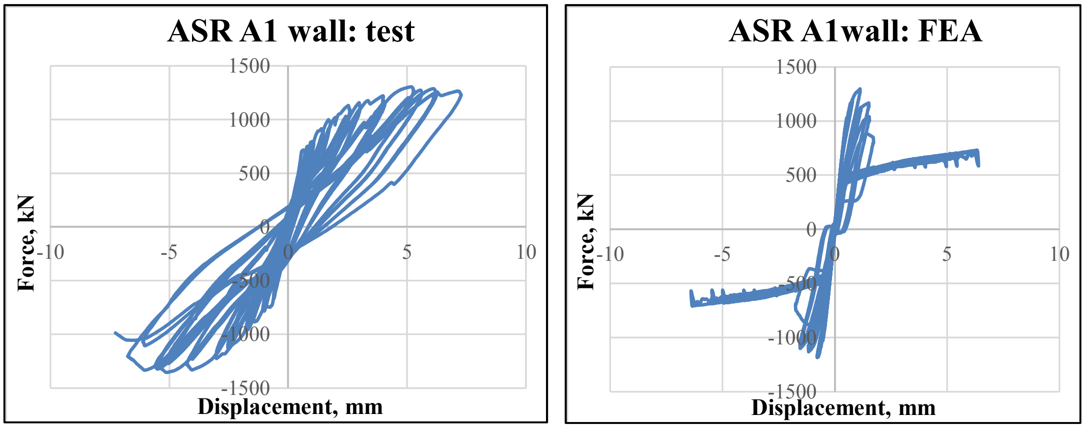


Figure 7. Lateral Force vs. Displacement Curve for ASR A1 wall (after260 days of accelerated aging)

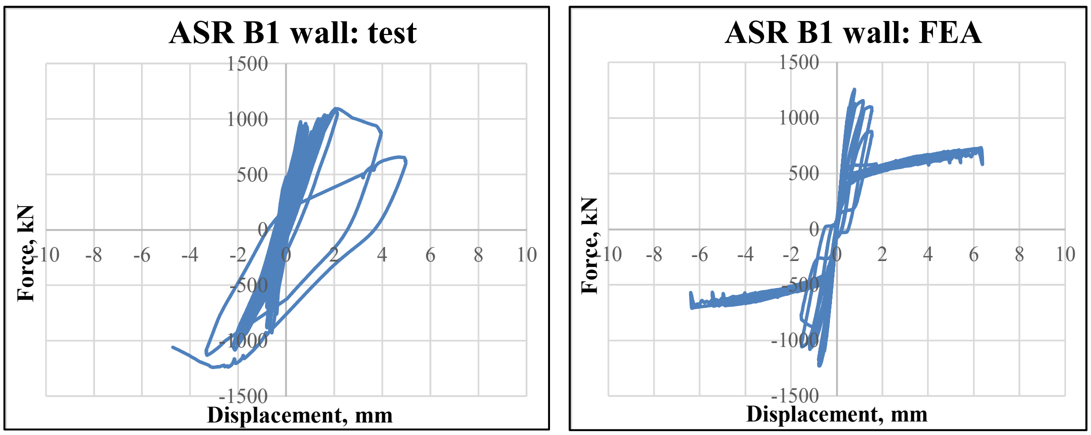


Figure 8. Lateral Force vs. Displacement Curve for ASR B1 wall (after 610 days of accelerated aging)

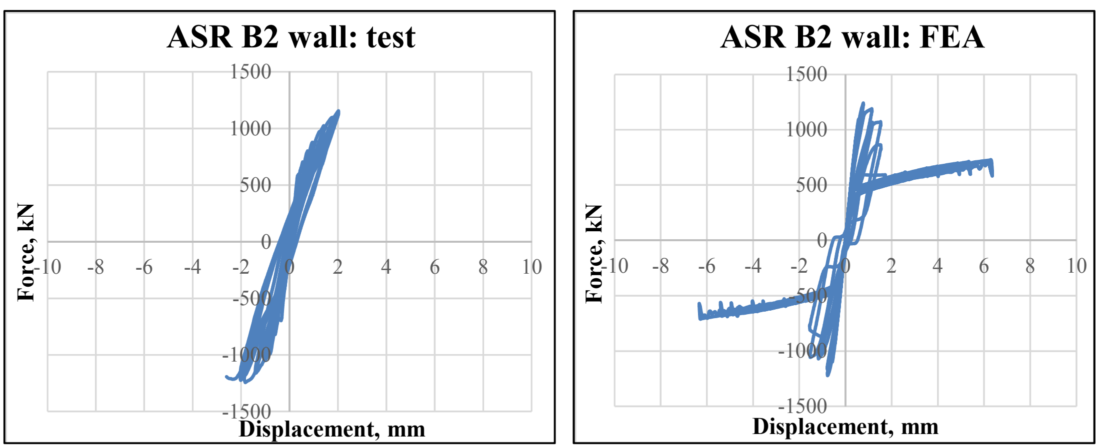


Figure 9. Lateral Force vs. Displacement Curve for ASR B2 wall (after 995 days of accelerated aging)

The results of this section allow to conclude that FEA predicts similar to test shear (lateral) forces and smaller correspondent lateral displacements for loading cycles before maximum shear capacity is reached. After this, FEA predicts similar or larger displacements. The results also show a significant difference between tests and FEA predictions during progressive wall failure. There are three factors for this discrepancy: (i) comparing with FEA the tests were stopped significantly earlier during failure progression for safety reason, (ii) the axial load removal time and sequence in tests were not recorded, and (iii) the exact time of switching from cyclic to constant shear loading for the last few test cycles was also not recorded. The sensitivity analysis shows that these factors greatly influence the results during failure state.

CONCLUSIONS

Explicit commercial code LS-DYNA was successfully used to model shear behavior of regular and ASR walls subjected to quasi-static cyclic loading. Based on simulation runs, the adequate 2-D FE model was created with concrete constitutive model *MAT_172/*MAT_CONCRETE_EC2 which accounts for the concrete cracking in tension and crushing in compression, and reinforcement yield, hardening and failure. Since this model does not include ASR induced expansion, an equivalent initial thermal expansion was introduced in the FE model to account for ASR. The FEA conducted shows that the FE predictions are in reasonable agreement with the test results except for some notable deviations that need further evaluation. The main features of the tests conducted were adequately captured by the FE model as follows:

- The shape of the Load versus Displacement curves for both regular and ASR concrete
- The maximum values of lateral loading representing the maximum shear capacity of the wall
- The established test result that maximum shear capacity of ASR wall is higher than regular concrete wall despite lower concrete strength
- A sudden failure for ASR wall versus softening response for the regular wall after reaching maximum shear capacity
- FEA predicts similar to test shear (lateral) forces and smaller corresponding lateral displacements for loading cycles before maximum shear capacity is reached. After this, FEA predicts similar or larger displacements
- The results also show a significant difference between tests and FEA predictions during progressive wall failure. There are three factors for this discrepancy: (i) comparing with FEA the tests were stopped significantly earlier during failure progression for safety reason, (ii) the axial load removal time and sequence in tests were not recorded, and (iii) the exact time of switching from cyclic to constant shear loading for the last few test cycles was also not recorded. The sensitivity analysis shows that these factors greatly influence the results during failure state.

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