Nuclear Safety
NEA/CSNI/R(2018)4
January 2019
www.oecd-nea.org

Phase II of the Assessment of Structures Subjected to Concrete Pathologies (ASCET): Final Report

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NEA/CSNI/R(2018)4

Unclassified **English text only**

21 January 2019

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

Phase II of the Assessment of Structures Subjected to Concrete Pathologies (ASCET): Final Report

JT03441991

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ACKNOWLEDGEMENTS

Gratitude is expressed to Neb Orbovic from the Canadian Nuclear Safety Commission (CNSC) for his great effort in implementing and managing the ASCET programme and for managing the workshop with the help of Jacob Philip from United States Nuclear Regulatory Commission (US NRC); to the CNSC and Chris Cole for organising and hosting the ASCET workshop; to Dave Newland (CNSC) for the support to the Organising Committee of ASCET.

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EXECUTIVE SUMMARY

The objective of the CSNI ASCET activity is to make general recommendations for ageing management of concrete nuclear facilities taking into account the effect of concrete pathologies on structural degradation. The ASCET Phase II is based on the recommendation of the workshop held at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland, United States, from June 29th to July 1st 2015, and the Phase I Report. Phase II of ASCET is defined as a blind simulation benchmark to predict the behaviour of structural elements with alkali aggregate reaction (AAR). This report describes the results of the ASCET Phase II benchmark and the Phase II workshop recommendations for further work, which are addressed in ASCET Phase III.

The benchmark was based on tests of walls conducted at the University of Toronto under a CNSC research programme. The results for two sets of two walls (one sound and one with AAR in each set) and one extra wall with AAR were provided for this benchmark. The results of one set of walls were provided to calibrate numerical tools and the results of the other set of walls were used to perform blind simulations. The analysis and comparison of analysis results of the ASCET Phase II were mainly focused on the ultimate wall shear capacity. It shall be noted that overall difference in ultimate shear capacity for five test walls was within 13%, which stays within uncertainties of test measurements.

The benchmark results were discussed during the ASCET Phase II workshop, with the following observations:

- almost all participants predicted the higher shear capacity of the AAR walls than the regular walls, which is in accordance with the test results,
- Alkali Aggregate Reaction (AAR) extension of volume was less than 0.3% in the five test walls used in this benchmark, and
- wall ageing was performed in laboratory conditions without exposure to any other degradation mechanism. In actual environmental conditions, the consequences of AAR can be more severe.

However, despite the well predicted ultimate shear strength, the failure mechanism of both regular and AAR walls observed in the tests needs to be better understood. There is a need for additional analysis with better documented results from these tests to understand the failure mechanism of regular walls and the difference in the failure mechanism compared to AAR walls.

According to benchmark participants, the wall measurements were not sufficiently characterised. A single measurement of the displacement of the upper beam is not enough to calibrate numerical models, which could explain the problems in prediction of maximum displacements of participants. It shall be also noted that the simulated displacements are lower than measured displacements in all simulations. Based on the calculation results of participants the wall boundary conditions have a more important impact on wall displacements than the concrete constitutive laws. Therefore, it is

recommended for future tests that detailed information regarding the boundary conditions and measured wall displacements should be provided to the participants. The losses of ductility and degraded hysteresis loops, with the evolution of AAR with age, are very important aspects, especially for seismic loading, and should be studied in detail. The understanding of the wall behaviour under cyclic loading is important in the design and assessment of structures under cyclic seismic loading. The presented simulations did not capture all important phenomena with effects to the walls with AAR, which is quite important from the viewpoint of the usability of simulation tools in design and assessment of concrete structures.

During the ASCET workshop a series of questions was raised related to the size effect and the effect of accelerated ageing of the specimens and their relevance to the development of the reaction and its consequences:

- Since the benchmark of the ASCET Phase II was performed using the test results with thin wall concrete specimens, the input conditions such as internal humidity were probably almost the same in the wall thickness direction. However, the humidity conditions are differently distributed in the wall thickness direction in the thick walls. In actual concrete structures of nuclear power plants (NPPs) the speed and magnitude of the reaction with humidity would change and therefore the crack pattern and damage distribution would change in three dimensions.
- The accelerated AAR degradation does not necessarily reflect actual degradation shown in the real structure. For example, the AAR gel might seep out when the temperature is elevated and AAR-reaction is fast. Therefore, there is a question about the validity of using accelerated AAR samples to evaluate the structural performance. From this viewpoint, degradation specimens taken from real structures should also be studied for the validation of the models.

The discussions of the simulation results show the need to arrange for additional test data, especially related to boundary conditions, displacement measurements and measurements on the condition of walls prior to testing and during testing with available photos and videos to the participants. In this kind of benchmark it is recommended to correlate not only the results of destructive tests and the analysis results, but also the results of the non-destructive tests.

The ASCET benchmark also shows the need for analysing samples of real AAR with ageing effects experienced by NPP structures. To address this question, samples should be harvested from NPP structures affected by AAR and aged in environmental conditions. Therefore, an international activity for harvesting samples of real NPP structures affected by AAR and aged in environmental conditions is recommended to start in the near future.

ABBREVIATIONS & ACRONYMS

AAR	Alkali aggregate reaction
ACC	Accelerated carbonation test
ASCET	Assessment of Structures subjected to Concrete pathologies
ASR	Alkali silica reaction
CAPS	CSNI Activity Proposal Sheet
CDP	Concrete damaged plasticity (model)
CEBTP	Centre Expérimental de Recherches et d'Études du Bâtiment et des Travaux Publics (Center for Experimental Research and Studies of Building and Construction)
CNSC	Canadian Nuclear Safety Commission
CSNI	Committee on the Safety of Nuclear Installations
DEF	Delayed ettringite formation
DiD	Defence in depth
DRI	Damage rating index
EDF	Électricité de France
EPRI	Electricity Power Research Institute (USA)
FE	Finite element
FEA	Finite element analysis
GPR	Ground penetrating radar
HECR	High energy computed radiography
IAEA	International Atomic Energy Agency
IFSTTAR	French Transports and Public Works Research Institute
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France)
ITZ	Interfacial transition zone
LVDT	Linear variable differential transformer
MASW	Multi channel analysis of surface waves
MCFT	Modified compression field theory
NEA	Nuclear Energy Agency
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
RIVE	Radiation-induced volumetric expansion
SLS	Serviceability limit state
SPH	Smoothed particle hydrodynamics
TSO	Technical Support Organisation
ULS	Ultimate limit state
UPV	Ultrasonic pulse velocity
WGIAGE	Working Group on Integrity and Ageing of Components and Structures

1. INTRODUCTION

Public acceptance of existing nuclear facilities depends on demonstrating adequate structural performance of these facilities during their entire lifetime. The goal of the CSNI Activity Proposal Sheet (CAPS) on **A**ssessment of **S**tructures subjected to **C**oncr**e**te pa**t**hologies (ASCET) is to organise and implement a research activity that can be publicly vetted as a means of establishing and validating evaluation techniques for structures with degraded concrete.

The ASCET Phase II is based on a recommendation of ASCET Phase I. In ASCET Phase II the goal was to organise a blind numerical simulation benchmark of a representative AAR-affected structure, the evolution of which has been well controlled and documented, and the final capacity checked.

2. OBJECTIVE

The objective of CSNI ASCET CAPS is to make general recommendations for ageing management of concrete nuclear facilities taking into account the effect of concrete pathologies on structural degradation. The ASCET Phase II is based on the recommendation of the workshop held at the National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, United States, from June 29th to July 1st 2015, and the Phase I Report - NEA/CSNI/R(2016)13. The Phase II of the ASCET is defined as a blind simulation benchmark to predict the behaviour of structural elements with Alkali Aggregate Reaction (AAR).

There is a need for reliable numerical tools to predict the structural behaviour, as a function of time, of structures with concrete pathologies/degradation mechanisms. Concrete swelling (volume change) and associated concrete cracking are consequences of several concrete degradation mechanisms of concrete structures (alkali aggregate reaction, delayed ettringite formation, irradiated concrete...) and it is important to assess and to quantify the ultimate and serviceability limit states of concrete structures that may experience such pathologies.

Five walls in total were tested at the University of Toronto under a Canadian Nuclear Safety Commission (CNSC) research programme: two sets of two walls (one sound and one with AAR in each set) and one wall with AAR alone. All walls had the same geometry, the same reinforcement and they were loaded with the same cyclic horizontal force, inducing primarily shear loading, up to the failure. The only difference between the walls in each of two sets is that one wall was built with reactive aggregate while the other with normal, sound, aggregate.

In order to calibrate their models the participants got the results of the first set of two walls tested at the University of Toronto, after eight months of accelerated ageing.

The second set of walls, which was used for the ASCET Phase II blind simulation, 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 aggregate reaction as well as the difference between the behaviour and failure modes of these structures and the tested structures built with the sound concrete.

3. BENCHMARK SUMMARY

3.1. Test Setup

Habibi et al., (2015) reports the test results for both regular, sound concrete and AAR-effected concrete shear walls, along with those for the associated control specimens. The ageing of the specimens were performed in laboratory conditions. At the age of 28 days, all five walls were stored in an environmental chamber for 7 months to accelerate the AAR. The chambers maintained an environment temperature of 50°C and a relative humidity greater than 95%. The following Section provides a brief review of these tests and their results, which this study used for benchmarking the modelling approach used for the pre-testing and sensitivity analysis. The test setup and the reversed cyclic displacement applied are shown in Figure 1 below (Habibi et al., 2015).

Figure 1. Testing setup for shear walls (top) and applied reversed cyclic displacement at the top of the wall (bottom) [Habibi et al., 2015]

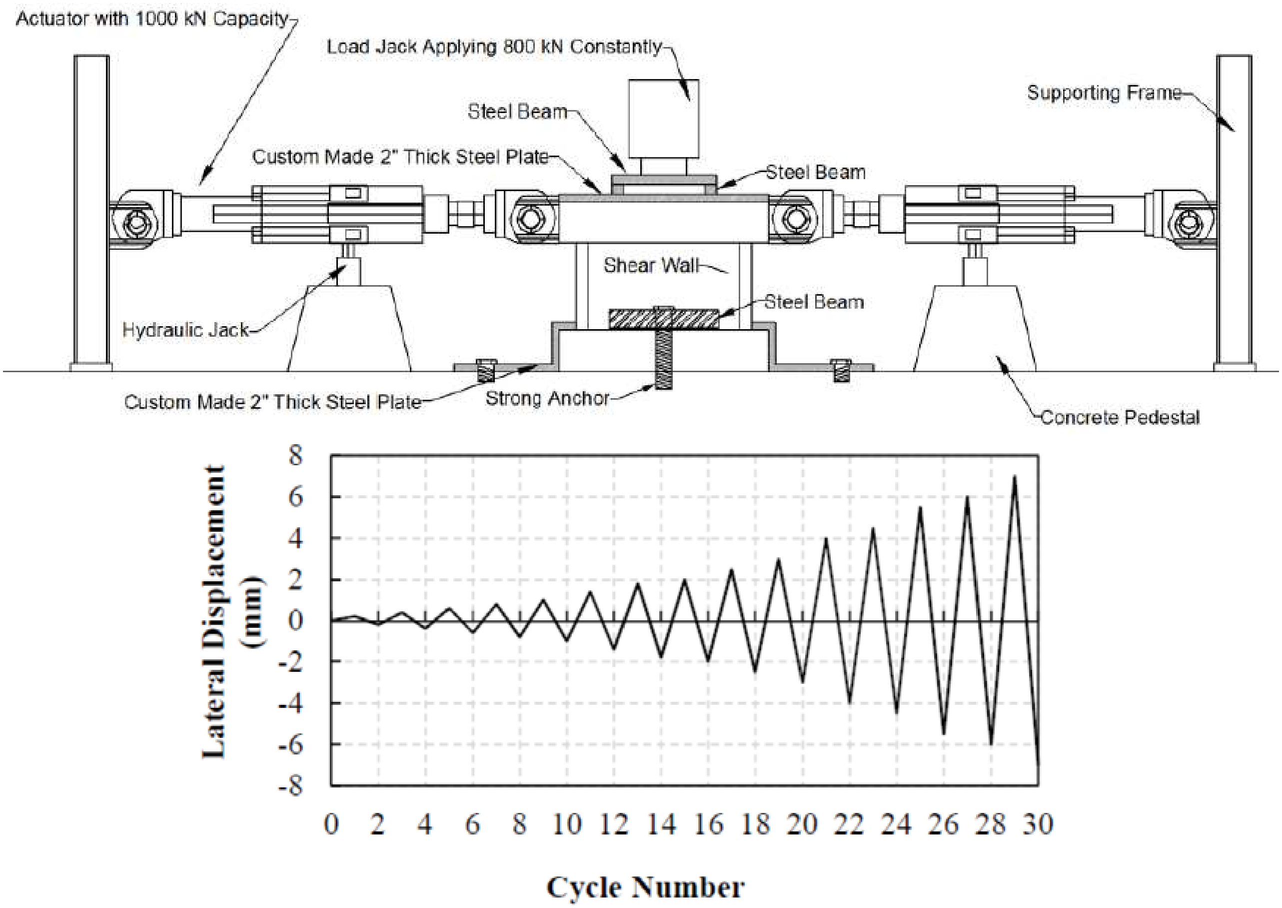
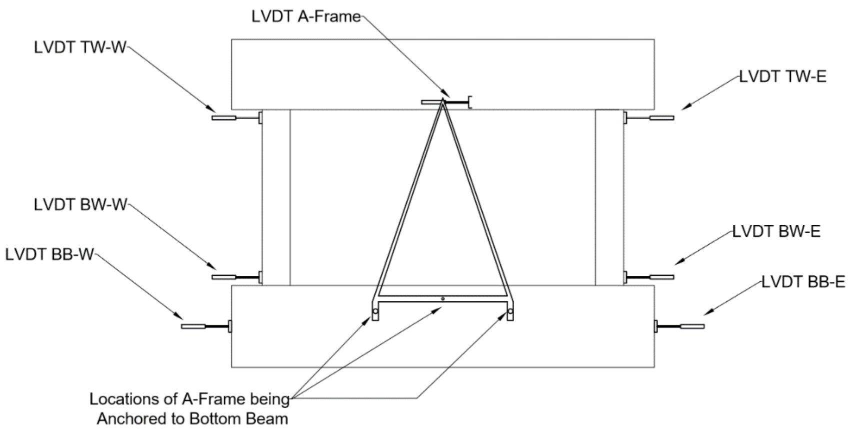


Figure 2. Experimental lateral displacement measurements



3.2. Boundary conditions

The test setup and the cyclic displacement shown in Figure 1 are the basis of the boundary conditions and loading conditions used in the current finite element analysis. The lower beam is fixed on the strong floor with a steel beam and the strong anchor in its centre and laterally, with 2 inches steel plates. The upper beam is free to rotate during the lateral cyclic loading. Figure 2 shows the position of linear variable differential transformer (LVDT) gauges for lateral displacement measurements.

3.3. Test Results

The set of two first wall tests results REG A and AAR A1 were provided to the participants to calibrate their models. The testing was performed at the ages of 240 days and 260 days, respectively. Figure 3 shows the average longitudinal and transversal expansion of concrete prisms due to AAR.

As shown in Figure 4, failure in shear for both regular and AAR specimens was observed after a diagonal crack developed along the diagonal of the shear wall panel. However, the failure mechanism is not identical for both walls. In the AAR wall, inclined shear cracks from the applied reversed cyclic displacements seem to cross the initial cracks from the AAR expansion. The regular wall failed with what seems to be a main horizontal crack roughly 10-20 cm above the fixed end. Inclined cracks were formed for this wall as well as shown on Figure 4.

The compressive strength (Table 1) of the concrete for the first two walls was 79 MPa for sound /regular wall and 63.7 MPa for AAR wall. The modulus of elasticity was 47 150 MPa for regular wall and 35 750 for AAR wall. The recorded maximum or peak capacities were 1 180 kN and 1 355 kN for the regular shear wall and AAR shear wall, respectively. At 240 and 260 days, the maximum lateral displacement was 8.2 mm for regular wall and 7.1 mm for AAR wall. The peak shear capacity for the AAR wall was about 14% greater than that for the regular shear wall although the compressive strength of the regular concrete was about 24% higher than that of the AAR concrete. The displacements of the AAR wall were lower despite the lower modulus of elasticity.

Although the reasons for higher shear capacity and lower displacements for the AAR-affected wall are unclear, a possible explanation is that the AAR expansion would stress the reinforcing steel in tension, which would then confine the concrete. This confinement, for this level of AAR expansion, would then enhance the performance of the wall. Boundary conditions (beams and barbells) also provide additional concrete confinement under the AAR expansion.

Figure 3. Average Longitudinal and Transverse Expansions of the Concrete Prisms [Data from Orbovic et al., 2015 and ASCET II, 2016]

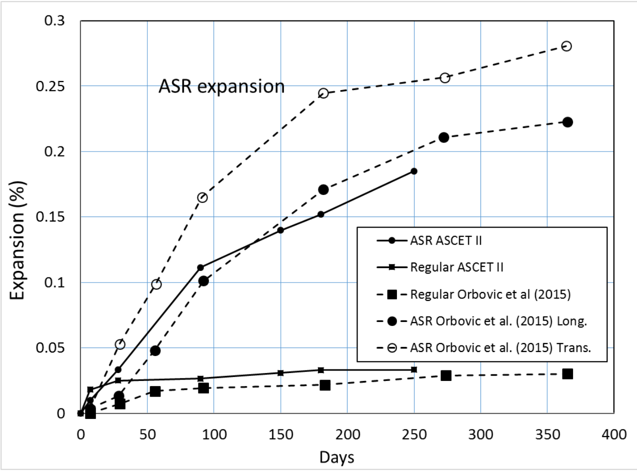
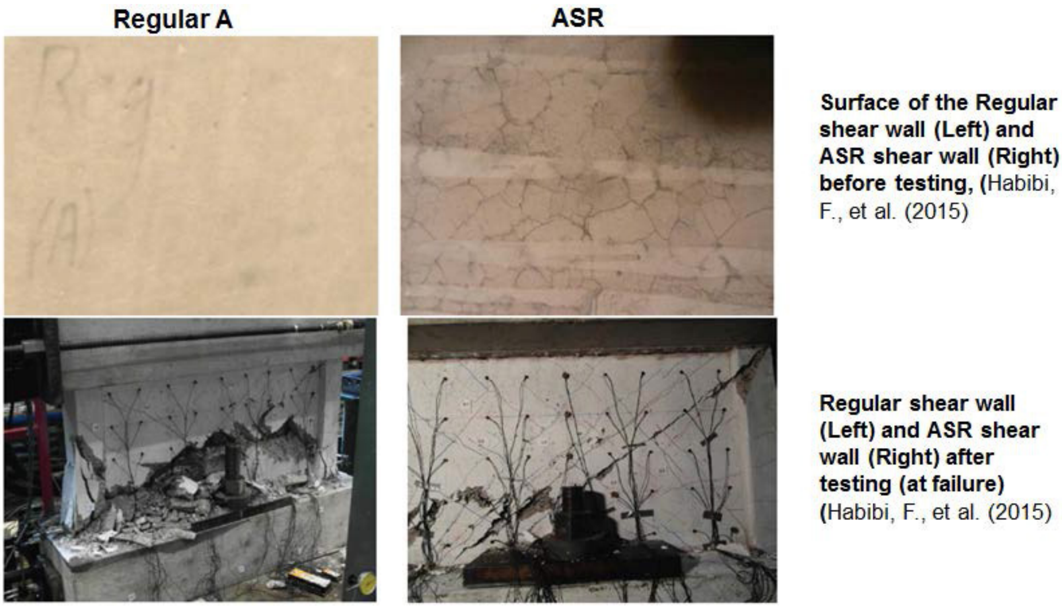


Figure 4. The first set of shear walls REG A and AAR A1 before and after testing [Habibi et al., 2015]



The tests results of REG B and AAR B2 walls were not provided to the participants. The participants were asked to provide the predication of the wall behaviour after 900 days. The results of an intermediate test AAR B1, tested after 600 days, were not provided either. Based on the concrete properties and the wall test results provided in Tables 1 and 2 and in Figure 5, it can be seen that the walls with advanced AAR (AAR B1 and AAR B2) have lower modulus of elasticity but also lower displacements. Lower maximum displacements at failure indicate large reduction in ductility as the AAR progressed from 260 to 995 days. Failure modes of the regular and AAR walls are different and that could be related, at least in part, to the difference in displacements. Another important point is decreasing strain energy before the peak force (area under the hysteretic loops) with ageing of AAR specimens. This is one of the most sensitive parameters in this test campaign.

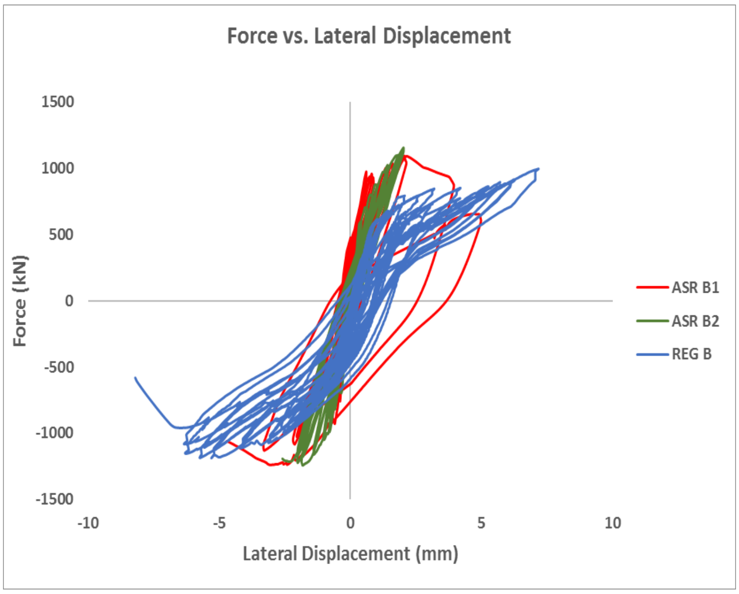
Table 1. Concrete properties of five tested walls

Wall	Age (days)	Compressive Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (MPa)	Modulus of Rupture (MPa)	Expansion %
REG A	240	79.0	4.76	47150	7.26	---
REG B	975	80.1	4.39	46652	6.89	---
AAR A1	260	63.7	3.24	35750	4.64	0.190
AAR B1	610	67.1	N/A	32600	N/A	0.215
AAR B2	995	63.0	3.18	28100	4.68	0.223

Table 2. Results of five wall tests

Wall	Expansion %	Peak Force (kN)	Maximum Displacement (mm)	Strain Energy (J)	Mode of Failure
REG A	---	1180	8.2	31081	Diagonal and Sliding
REG B	---	1187	7.3	28759	Diagonal and Sliding
AAR A1	0.19	1354.5	7.1	37766	Diagonal
AAR B1	0.215	1240.0	4.9	17278	Diagonal
AAR B2	0.223	1242.7	2.6	7183	Diagonal

Figure 5. Load versus lateral displacements for three tested walls



The load versus lateral displacement hysteretic curves presented on Figure 5 was drawn using LVDT A-frame from Figure 2 and should represent the differential displacements between the lower and the upper beam. It should be noted the increasingly pinched shape of the hysteretic curves before the peak force which can be seen as well in Table 2 in terms of decreasing strain energy (the area under force-displacement curves) from REG B wall to AAR B2 wall. The curves indicate somewhat higher strength and higher initial stiffness for the walls with AAR but lower ductility compared to the regular wall. This decrease in ductility is other very sensitive parameters in this test campaign.

3.4. Experimental Uncertainties

In this present context, an important question is how are the reported measurements recorded? Whereas the load can only be recorded by the calibrated load-cell, what about the displacements? The load-displacement curves were recorded using LVDT A-frame only. The question is whether it was directly recorded as a differential between the lower and upper beams? Other questions are whether the laterally imposed displacement driven by the actuator stroke and whether the lower beam experienced any uplift?

3.5. Numerical Benchmark

Ten teams have participated in ASCET Phase II numerical simulation of shear wall tests: the CNSC and the University of Toronto (Canada), IRSN and EDF (France), NRA, Kansai and Nagoya Universities (Japan), Scanscot (Sweden), University of Colorado at Boulder and US NRC (USA).

Different software and concrete models were used by the participants from the simple phenomenological model substituting concrete expansion due to AAR with identical thermal expansion, used by the CNSC to complex modelling of a large number of elementary physical phenomena (concrete reactivity, thermal activation, moisture dependence, concrete creep and shrinkage and damage interaction), used by EDF.

The following paragraphs summarise the different software and concrete models were used by the participants:

The CNSC used Ls-Dyna explicit software in the simulation with the concrete model, *MAT_172/*MAT_CONCRETE_EC2 applicable to 2D analysis of shear walls. Material data and the governing equations are taken from Eurocode 2. The model includes concrete cracking in tension and crushing in compression as well as reinforcement yield, hardening and failure.

The current work attempts to analyse the effect of AAR with a simple phenomenological model by substituting concrete expansion due to AAR with identical thermal expansion. Consequently, concrete strains due to AAR expansion were modelled as thermal strains due to temperature increase of $1^{O}C$ and thermal expansion coefficient α_T equal to longitudinal concrete expansion ε_0 due to AAR. Outside of AAR no other processes were modelled (creep, shrinkage, etc.)

EDF (France) used Code Aster with a concrete model FLUA_PORO_BETON and ENDO_PORO_BETON. This model is able to consider different pathologies (AAR, RSI…). It takes into account large number of elementary physical phenomena to be taken into account (concrete reactivity, thermal activation, moisture dependence, concrete creep and shrinkage, and damage interaction). The model is based on elementary physical principles that lead to the formulation of a visco-elasto-plastic orthotropic damage model including chemical pressure induced by AAR due to a poro-mechanics framework. The anisotropic plasticity and damage allow the realistic modelling of the strong cracking and swelling anisotropy observed on affected structures. It also considers the anisotropic stiffness recovery due to oriented crack reclosing during cyclic loading. The AAR model was calibrated on the prism volume expansion tests. Reinforcements were modelled explicitly by 1D elements without possibility of sliding between rebars and concrete. The boundary conditions included a contact element at the bottom part of the mesh to consider a possible partial uplift of the lower beam.

The University of Toronto and US NRC used VecTor 2 software. The program was developed at the University of Toronto. It employs a smeared rotating crack model for concrete suitable for a macro-modelling approach. The Modified Compression Field Theory (MCFT) (Vecchio and Collins, 1986) and the Disturbed Stress Field Model (DSFM) (Vecchio, 2000) form the theoretical basis for both programs. Six different models for the evaluation of AAR-induced expansion were implemented: uniform in all directions, Charlwood model, Curtis model (personal communication, August 19, 2014), Saouma and Perotti model (2006), Sellier model (2009), and Gautam model (2016). Apart from the model which distributes AAR strains uniformly in all directions, the others calculate anisotropic expansion along the principal directions as a function of the stress state. The level of expansion developed under stress-free conditions is a required parameter for the AAR analysis. It may be directly input by the user, or it may be evaluated using the Saouma and Perotti or Sellier models, which include a kinetics component. Thus, provided that experimental data describing the reaction, specific to each model, is available from laboratory tests, the free expansion may be determined. The concrete model used by US NRC contains 15 parameters with Charlwood AAR extension model.

NRA (Japan) used improved version of FINAS/STAR which was modified to be able to cope with the AAR degradation. In the FINAS / STAR, the non-orthogonal 4-directional cracking model of Maekawa and Fukuura et al. is used to introduce a non-linear material model of reinforced concrete. In this analysis, an AAR model based on V. Gocevski's paper which simply expressed the AAR degradation phenomenon was incorporated with the non-orthogonal 4-directional cracking model of the FINAS / STAR. In addition, the results of uni-axial experiment by Clayton et al. were applied to introduce the expansion strain due to AAR for concrete dependent on constraint stress.

Kansai University (Japan) proposed an integrated analytical method in order to evaluate the structural performance of AAR damaged RC structures. In the analytical method, two different analysis, AAR expansion analysis and loading analysis were combined. The AAR expansion analysis is for prediction of expansive behaviour such as deformation, strain and stress due to AAR expansion. The loading analysis is so-called structural analysis and it is for evaluating the structural response subjected to the external load. Different constitutive models of concrete are assumed in each analysis and two analyses are combined by considering the consistency of stress and strain fields. An in-house macro model for AAR expansion, based on damage theory, was developed by Kansai University, including the time-dependent deformation such as creep and shrinkage. By applying this model to orthotropic material AAR expansive behaviour is evaluated not only for the magnitude but also the directionality.

CAS3M by IRSN (France) performed 2D and 3D modelling. The concrete is a simple Mazars' damage model with an energy-based regularization. The material parameters (9 parameters in total) are identified with respect to the experimental information in terms of fracture energy and strength. In the model only the wall and lateral columns exhibit non-linear behaviour. The lower and upper bam are considered elastic. The AAR parameters were calibrated using the expansion data up to 250 days. The study takes into account random swelling distribution due to the AAR and aims to link this distribution to aggregate size effect, which is estimated as a relevant parameter.

Scanscot used the ABAQUS explicit finite element software. Numerical simulations within this work are performed using the Finite Element (FE) solver ABAQUS/Explicit, which is a well-known and, for many types of problems, thoroughly tested general purpose finite element program. The concrete material model used in the numerical simulations is called Concrete Damaged Plasticity (CDP). Material expansion in the concrete is modelled using an equivalent isotropic thermal expansion. The expansion is modelled uniform in the entire test specimen, The macro-scale modelling technique used in this study prioritize simplicity before accuracy, and results are used as conceptual indicators on the structural phenomenon of concrete material swelling. The material expansion, as well as material property degradations, is considered in this simplified approach.

The University of Colorado at Boulder (USA) developed and used code Marlin by for the ASCET Phase II benchmark. The analysis hinges on two constitutive models: one for concrete non-linearity and the other one for AAR. The concrete smeared crack model with total of 12 parameters was used. The parameters are taken into account with the mean value as well as the upper and lower bounds for uncertainty quantification and minimum-maximum for sensitivity analysis. The possible bond-slip was taken into account in reducing the reinforcement area crossing the beam-web intersection.

Nagoya University (Japan) developed and used a Rigid-Body-Spring Model. Analysis domain with this modelling is divided by 3D rigid particles connected with springs, similar to SPH (smoothed particle hydrodynamics) computational methods. One integral point has two kinds of springs: normal and shear. Cracks are expressed by the failure of springs and cracking behaviour can be show directly. The set of material parameters were calibrated by fitting the average (macro) stress-strain curves (1.4E, 0.8Ft, 1.5 fc). The reinforcement is modelled as a series of beam elements attached to the concrete particles through link elements. Each link element consists of zero-length link-springs and the spring parallel to reinforcement is used to represents the bonding characteristics. The model was validated using uni-axial compression as well as beam's flexural and shear tests. The AAR expansion model (expansion strain) is established based on the amount of AAR gel [mol/l], the capacity of AAR gel due to Interfacial Transition Zone (ITZ) and the capacity of AAR gel due to crack.

Northwestern University (Prf. Cusatis), USA, made a presentation during the ASCET Phase workshop on Time-Dependent Behaviour Simulation or Reinforced Concrete Structural Elements Affected by Alkali Silica Reaction in Variable Environmental Conditions" but this presentation was not related to the simulations of the shear walls tested at the University of Toronto.

4. MAIN RESULTS

The main results are presented in terms of wall maximum capacity, wall stiffness and displacements, the ductility and the shape of hysteretic curves, failure modes and crack pattern.

Strength Capacity: The maximum capacity of the tested walls was well predicted by the participants. The exiting differences are within 10% range. Most of the participants found higher capacity of AAR walls than regular walls, which is consistent with the experimental results. However the ultimate capacity of five tested walls is in between of 1180 kN (REG A) 1354.5 kN (AAR A1) which represents the difference of only 13% which stays within uncertainties of test measurements. This parameter should be regarded in light of concrete properties of the tested walls. All major concrete properties (compressive strength, tensile strength, modulus of elasticity and modulus of rupture) of AAR walls were lower than the regular walls despite slightly higher ultimate capacity. It shows that the code correlations between the wall capacity on one hand, and the concrete compressive strength, tensile strength as well as the modulus of elasticity on the other hand, are not applicable in the case of concrete structures with AAR.

Stiffness: The prediction of maximum displacements was not that successful. The calculated displacements are well below the measured displacements and this brings to two issues brought by the participants: the boundary conditions of the walls and the way how displacement measurements were performed. To achieve the measured displacements provided by the University of Toronto the participants used different artifacts such as multiplying the calculated displacement by a coefficient (e.g. 2.3 used by the University of Colorado) or modifying boundary conditions to allow structural lift-up (EDF simulations - Figure 6). Moreover, the question remains why the pre-peak displacements decrease with decreasing modulus of elasticity?

Ductility: All blind simulations underestimated the maximum displacement that the wall with AAR will be able to sustain at 995 days. They did not capture the wall ductility. The reason of pronounced decrease in ductility is not clear at this time and further analysis with additional information about the tests would provide additional understanding. A possibility might be in the change in post-peak response in compression for AAR-affected concrete which has not been addressed yet, and which may have significant influence on the behaviour of shear wall specimens.

The prediction of the shape of hysteretic loops was not very successful either. The pinched form of hysteric curves and associated strain energy, especially of the walls with advanced AAR, were not well predicted by the participants (Figure 7). The hysteric loops remain too large for both regular and the AAR-affected walls.

Figure 6. Modelling of boundary condition with the wall lift-up in EDF simulation

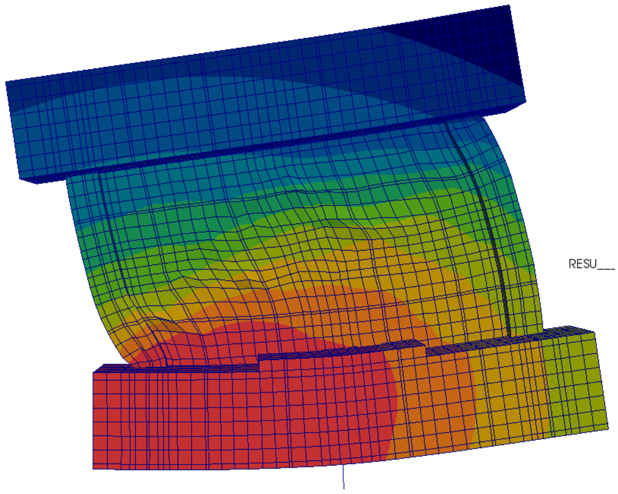
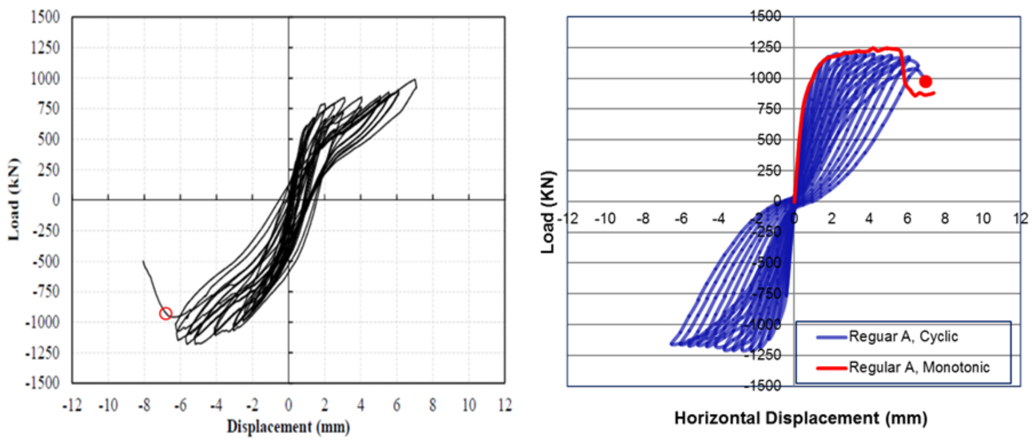


Figure 7. Comparison of hysteretic curves obtained in tests (left) and numerical simulations (right) from Huan Li et al. (US NRC)



Failure modes: The failure modes and the crack pattern corresponding to the failure modes were another difficult task for the participants as was the difference in the failure modes of the regular walls and walls with AAR. The combined failure mode with inclined shear crack and one horizontal crack was achieved only in one simulation (US NRC) and for the AAR wall although this failure mode appeared in the test of the regular wall. Further analysis coupled with additional information setup of the tests and relevant material properties will permit further interpretation of the tests data and understanding of the test results.

5. SENSITIVITY STUDIES

Different sensitivity studies were performed by the participants. The following paragraphs summarise some of those sensitivity analyses.

In the study by the University of Colorado, uncertainty analysis, after the selection of the most sensitive parameters, was performed using a Monte-Carlo simulation to provide a probabilistic estimate of the prediction.

The parameters were taken into account with the mean value as well as the upper and lower bounds for uncertainty quantification and minimum-maximum for sensitivity analysis.

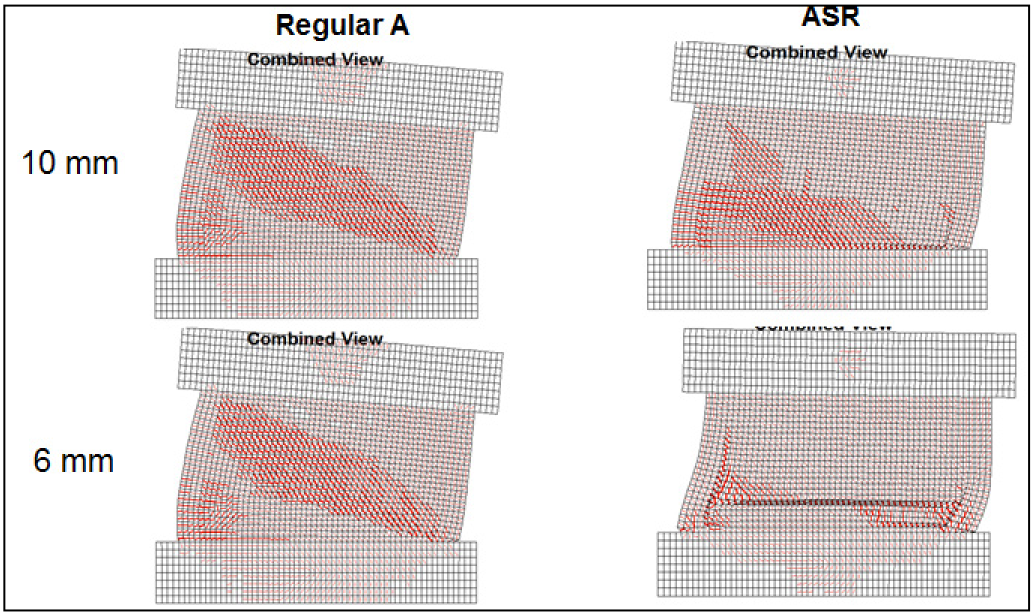
It was determined that for the ultimate shear strength the steel reinforcement whose crossing the beam-wall interface plays a prominent role in the response through the yield stress and cross-sectional area). As to the concrete, the predominant variables affecting the shear wall carrying capacity is: the compressive strength, plastic strain at compressive failure, modulus of elasticity are amongst the major factors influencing the response. The least important variables are the yield stress of the stirrups and onset of concrete nonlinearity in compression and concrete compressive critical displacement. Concrete tensile strength and fracture energy are among the intermediary sensitive variables.

The CNSC assessed the shear wall capacity as a function of longitudinal expansion (between 0% and 0.5%) and the compressive strength. Regarding the longitudinal expansion, the most sensitive range was between 0.15% and 0.25%. However, even for the entire studied range (0%-0.5%) the difference in the shear capacity is less than 13%. Regarding the sensitivity to the concrete compressive strength in the entire studied range 50 MPa-90 MPa the most sensitive part was 50 MPa – 65 MPa. Even in this part the variation of the maximum shear capacity is less than 5 %.

These sensitivity studies are related to the ultimate shear strength. However, as stated above, the shear strength is the most predictable result. The displacements, hysteretic curves and failure modes were much more difficult to predict and should be more studied in the next phase of the programme.

In the US NRC study, the effect of maximum aggregate size was analysed, taking the aggregate sizes of 10 mm and 6 mm. The AAR wall with smaller aggregate size showed a different crack pattern and associated failure mode with the significant horizontal crack 10-20 cm form the connection of the wall with the lower beam, similar to the test results obtained in the case of the regular wall. On the other side, despite the important difference in the failure mode between to different aggregate size, the ultimate shear capacity of the AAR wall is the same and slightly superior of the capacity of regular walls. The report doesn’t provide the value of displacements for these cases and once again, they should be more studied in the next phase of the benchmark.

Figure 8. Results of the sensitivity related to the maximum aggregate size performed by Huan Li et al. (US NRC)



6. CONCLUSIONS

Fruitful exchange and discussions took place during two days of the ASCET Phase II workshop. The following points were raised and discussed.

1. The participants concentrated their effort mainly of the prediction of the ultimate capacity of walls under monotonic and cyclic loading which were predicted well. Despite some differences, almost all participants predicted higher capacity of the AAR walls than the regular walls, which is in accordance with the test results. However, several points should be noted:
   - the overall difference in ultimate capacity for five tests walls was within 13%,
   - the AAR extension was limited to 0.223% in this benchmark,
   - the wall ageing was performed in laboratory condition without exposure to any other degradation mechanism which can occur in environments conditions and make the consequences of AAR more severe.

2. However, despite the well predicated ultimate strength the failure mechanism of both regular and AAR walls observed in the tests needs to be better understood. The basis for the wall design was in the IRSN tests performed at CEBTP (Center for Experimental Research and Studies of Building and Construction) (France) in 2001 with similarly designed regular walls. Despite the similar design and loading conditions, the failure mechanism of regular walls was different. These tests should be analyzed in order to understand the failure mechanism of regular walls and the difference of failure mechanism of regular and AAR walls,

3. According to benchmark participants, the wall measurements were not sufficiently documented. A single measurement of the displacement of the upper beam is not enough to calibrate numerical models. Simulated displacements are lower than measured displacements in all simulations and based on numerical simulations, the wall boundary conditions have more important impact on wall displacements than the constitutive laws. Detailed information regarding the boundary conditions and measured wall displacements should be provided to the participants.

4. The information regarding crack pattern: the crack width and spacing should be provided to participants.

5. The calculated force-displacement curves for both regular and AAR-affected walls overestimates the strain energy dissipated in the walls. The hysteresis loops, especially before the peak force, become narrower and the energy consumption was divided by a factor of four comparing to regular, sound wall. The

understanding of the wall behaviour under cyclic loading and the modification of the hysteretic loops are very important points.

6. The loss of ductility with time of AAR walls, as the degradation progressed from 260 to 995 days was discussed as a very important point, especially for seismic loading. The presented simulations do not capture this very important phenomenon. The reactive shear walls AAR B1 and AAR B2 exhibited a notably less ductile response compared to the FEA response and to the AAR A1 specimen. This may be attributed to the post-peak response in compression for AAR-affected concrete, which has not been addressed yet, and which may have significant influence on the behaviour of shear wall specimens.

The additional test data described in 3) and 4) will be provided to participants by December 2017.

7. RECOMMENDATIONS

The analysis results of the ASCET Phase II were mainly focused on the ultimate wall capacity. The planned next phase of the ASCET benchmark should be focused on prediction and evaluation methods related to the output results such as:

- Displacements;
- Deformations;
- the failure modes;
- the crack pattern, crack width and crack distribution,

These are quite important from the viewpoint of the usability of simulation tools, since those output results significantly affect the serviceability of concrete structures.

The losses of ductility and degraded hysteric loops, with the evolution of AAR with age, are other important aspects, especially for seismic loading, and should be studied in detail.

In order to perform successful benchmarks in the planned next phase of ASCET there is a need for additional test data from the University of Toronto, especially related to boundary conditions, displacement measurements and the condition of walls prior to testing and during testing with available photos, videos and measurements.

In addition the tests of similar regular/sound walls performed at CEBTP (France) in 2001 could be used in the next ASCET Phase.

It is recommended to correlate not only the results of destructive tests and the analysis results but also the results of the non-destructive tests. Therefore the results of non-destructive tests performed on the walls by the University of Sherbrooke could be used in the next ASCET Phase.

During the workshop a series of questions was raised related to the size effect and the effect of accelerated ageing of the specimens and their relevance to the development of the reaction and its consequences.

- Since the benchmark of the ASCET Phase II was targeted at thin wall concrete specimens, the input conditions such as moisture inside were probably almost the same in the wall thickness direction. However, the moisture conditions are differently distributed in the wall thickness direction in the thick walls. In actual concrete structures of nuclear power plants the speed and magnitude of the reaction with moisture would change and that the crack pattern and damage distribution would change in three dimensions.
- The accelerated AAR degradation does not necessarily reflect actual degradation shown in the real structure. For example, the AAR gel might seep out when the temperature is elevated and AAR-reaction is fast. Therefore, there is a question about the validity using accelerated AAR samples to evaluate the structural

performance. From this viewpoint, degradation specimens taken from the real structure are also needed to be studied for the validation of the models.

The ASCET benchmark shows a need for analysing samples of real AAR and ageing effects on NPP structures. To address this question there is a need for harvesting samples from NPP structures affected by AAR and aged in environmental conditions. Therefore, an international activity for harvesting samples of real NPP structures affected by AAR and aged in environmental conditions is recommended to start in near future.

8. REFERENCES

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APPENDIX

Full papers of ASCET 2 workshop are available in .pdf format only on the NEA website.