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Sensitivity and uncertainty analysis of AAR affected reinforced concrete shear walls

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ABSTRACT

Whereas many publications report on alkali aggregate reaction (AAR) expansion or test analyses, very few address the more pressing issue of its impact on structures. Furthermore, given the uncertainties associated with characterization of the material, probabilistic based approach are not known to have been reported in the literature. This paper addresses these limitations through an analysis of a reinforced shear wall. A two-prone approach is followed: first a sensitivity analysis is performed to narrow the number of random variables (RVs) to the most relevant ones. Then, an uncertainty quantification is performed through Latin Hypercube Sampling with and without AAR expansion. Then the capacity curves (including the summarized ones to 16, 50 and 84% fractiles) are developed. Probability of non-exceedance of a specific capacity (i.e., limit state) is shown though the so-called fragility curves. It is found that in some cases AAR increases the shear capacity, while in others it decreased it. It highly depends on the initial combination of the RVs.

1. Introduction

Increasingly engineers are confronted with the need to perform predictive structural assessment based on limited or incomplete data set. This may include damage up to failure assessment (in the context of so-called performance based engineering), or round robin benchmarks. As such deterministic analyses are of limited predictive values, and a stochastic analysis is warranted.

This paper focuses on the development of a methodology for such assessment, and is believed to be the first such contribution in the context of structural failure following alkali aggregate reaction (AAR) (or alkali silica reaction – ASR) induced expansion. As a vehicle for such an application, analysis of a previously tested concrete reinforced shear wall is performed.

In light of this potential problem which may affect numerous nuclear containment vessel structures (NCVS), various research projects were put in place. The Department of Energy (DOE) is sponsoring large scale mockup tests to assess the effect of confinement on AAR expansion [1]. The Nuclear Regulatory Commission (NRC) has entered into an inter-agency agreement with the National Institute of Science and Technology (NIST) to conduct a multi-million dollars research program on the structural performance of nuclear power plants (NPP) affected by AAR [2]. NRC is also funding a grant and cooperative agreement with the University of Colorado to assess the effect of AAR on the shear strength deterioration, and for the integrity assessment of a NCVS suffering from AAR subjected to seismic loading [3]. Furthermore, Nextera has funded a major research program at the University of Texas to assess the effect of AAR on the shear strength of concrete specimen [4]. Similar effort have been undertaken abroad. Most notably in Canada through funding from the Canadian Nuclear Safety Commission (CNSC) where shear wall affected by AAR have been tested (and whose analyses are reported below) [5]. Finally, a major project on the same theme was recently initiated in France through support from the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) [6].

In terms of related numerical simulations, the authors have investigated the shear response of nuclear containment panels [7], and thus this work constitutes a natural extension of past analyses combined with the separately developed methodology for probabilistic assessment [8,9].

Surprisingly, very few publications address the impact of AAR on the response of an engineering structure (i.e. not a laboratory specimen) through a finite element analysis. Most of the effort at the structural level seems to have been limited on the analyses of dams [10–14]. Fewer publications address the impact of AAR on containment structures. Takatura et al. [15] and Chénier et al. [16] investigated containment structures affected by AAR in Japan and Canada respectively. Again there is a limited number of publications reporting the structural analysis of bridges [17–20] or massive reinforced concrete structures

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[21]. However, many researchers have focused their attention to merely analyze laboratory tests such as [22]. As to the nonlinear finite element analysis of reinforced concrete shear walls, there is a wide set of literature [23–26].

1.1. Objective

Through the auspices of the Organization for the Economic Cooperation and Development (OECD), a project for the Assessment of Structures subject to Concrete Pathologies (ASCET) was setup with one of its objectives being the organization of a blind simulation benchmark to predict the behavior of structural elements with AAR. The selected structure to be modeled was a reinforced concrete shear wall with AAR and subjected to reverse cyclic load. The wall had been tested at the University of Toronto [27]. Participants were given the opportunity to calibrate their models through the first phase (I) of the project where experimental data after eight months was made available, and asked to submit their numerical prediction for the wall responses (with and without AAR) after thirty months of swelling.

This paper will detail the advanced analysis performed, and focus will be placed on its main contribution: casting an AAR analysis (notoriously plagued by large uncertainties) within a probabilistic framework.

2. Test description

The tested shear wall is shown in Fig. 1, as well as the location of LVDTs (which measure the displacement between the bottom of the upper beam and the top of the lower beam). Detailed dimensions of the shear wall itself as well as two columns and two beams are illustrated in Fig. 2. Reinforcement distribution is also shown in this figure. The 10 M and 20 M reinforcements have cross-sectional areas of 100 and 200 mm^2, yield stresses of 430 and 465 MPa, and elastic moduli of 182,000 and 190,000 MPa, respectively. In the experiment, a constant vertical force of 800 kN is applied through a 2″ thick steel plate, and the wall is subjected to a reverse cyclic pushover displacement (not to be confused with a seismic load). The bottom beam is anchored to the strong floor.

A total of three walls were cast, one without AAR (SW) and two others with AAR (SW-260 and SW-1000). The first two (one with and the other without AAR) were tested about 260 days (one of them was tested couple of days earlier) after casting, and the results made available for calibration. The third wall was tested about 1000 days after casting and participants in the benchmark round robin were asked to make predictions. The reported mechanical properties for the concrete at 260 days are: 79.0/63.7 MPa for f_c', 4.76/3.24 MPa for f_t', 179.3/120.2 N/m for G_F, and 47,150/35,750 MPa for E.

Results of the tests are summarized in Fig. 3. It should be noted that the peak loads with (SW-260) and without AAR (SW) expansion are 1354 and 1180, or 14% difference. This is a relatively small change, and given the uncertainties in measurement that difference may not be entirely attributed to the effect of expansion.

As no creep data was made available, and in light of the relative young age of the tested specimens, creep was ignored. On the other hand, based on simple “engineering judgment”, it was apparent that potential bond loss at the juncture between column and base had to be addressed. This could be done by either wrapping joint elements (with hard to define characteristics) around the rebars at this location, or approximately by reducing the cross-sectional area of the steel at that location. This reduced cross-section will trigger large plastic deformation (akin of the ones induced by debonding) before the other segments yield.

3. Modeling approach

In performing the numerical simulation of an experimental test, one must recognize that four possibilities are present:

1. An inconsequential analysis where results are simply to meet basic engineering common sense expectations.
2. *Post-mortem* simulation where one has the luxury to fine-tune/calibrate a model until near exact results are obtained (which is nearly always possible, irrespective of the model accuracy).
3. Predictive analysis for the future response of a structure.
4. Blind simulation benchmark of an experimental test. However, it should be noted that there are two major sources of uncertainties:

- Experimental: How accurately was the test performed?, how credible are the results?, are the reported results sufficiently clear and unambiguous?, and is it the model or the test that is being checked?
- Numerical: Can one perform a single deterministic and predictive analysis, or wouldn’t a probabilistic-based analysis be more appropriate given the epistemic nature of the uncertainties?

The current benchmark study does allow calibration (level 2 above) and requires prediction of known results (level 4). As to the two level of uncertainties (experimental and numerical), those are separately addressed below prior to the analyses results.

3.1. Uncertainties

Experimental: Though experimental uncertainties (accuracy and precision) are inherent in any test program, this benchmark exercise suffered from the additional pitfall of limited and incomplete data.[1] This made the exercise quite intractable problem, if it was to be handled in detail, and as a (partial) remedy a stochastic analysis is reported.

Epistemic: Simply put, epistemic uncertainties are those caused by an incomplete knowledge of the exact material properties [29].

3.2. Study objectives

Given that a nonlinear constitutive model for concrete contains numerous variables, most of which not provided or even measurable, a two prone approach should be followed:

Sensitivity Analysis: To determine which of the many random variables in the shear wall model are most sensitive.

Uncertainty Analysis: After selection of the most sensitive random variables, perform a Monte Carlo Simulation to provide a probabilistic estimate of the prediction.

This approach was recently followed by the authors for the analysis of a major bridge suffering from AAR [20].

4. Data preparation

The analysis hinges on two constitutive models: one for the concrete nonlinearity (a fracture-plasticity smeared crack model) [30], and the other for the AAR [21]. Both have been implemented in the authors finite element code Merlin [31], and most importantly validated in accordance with the RILEM TC 259 report [32].

4.1. Concrete smeared crack model

The concrete constitutive model was a fracture plasticity model [30] implemented as a so-called smeared crack model. As most constitutive models, this one has a number of parameters and not all can be directly measured experimentally. Hence, some are assigned values based on other calibrations or experience. This will invariably lead to

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[1] During the ensuing meeting, it was evident that boundary conditions assigned lead to many differing assumptions, and only one set of load displacement was given to participants.