Modeling the Alkali–Silica Reaction and Its Impact on the Load-Carrying Capacity of Reinforced Concrete Beams

T. N. Nguyen, J. Li, V. Sirivivatnanon, and L. Sanchez

Abstract The alkali–silica reaction (ASR) is one of the most harmful distress mechanisms affecting concrete infrastructure worldwide. The reaction leads to cracking, loss of material integrity, and consequently compromises the serviceability and capacity of the affected structures. In this study, a modeling approach was proposed to simulate ASR-induced expansion considering three-dimensional stress/restraint conditions, and its impact on the structural capacity of reinforced concrete members. Both the losses in concrete mechanical properties and prestressing effects induced by the expansion under restraints are taken into account in the model. Validation of the developed model is conducted using reliable experimental datasets derived from different laboratory testings and field exposed sites. With the capability of modelling both ASR-induced expansion and its impact on structural capacity, the model provides valuable results to specify effective repair and/or mitigation strategies for concrete structures affected by ASR.

Keywords Alkali-silica reaction · Concrete deterioration · Expansion · Finite element

1 Introduction

Many concrete bridges and dam structures in Australia have been reported to be affected by various degrees of deleterious alkali–silica reaction (ASR) [1]. These affected structures require comprehensive diagnosis and prognosis protocols for assessing the current degree of damage, forecasting the potential of further deterioration, and evaluating the impact of ASR on structural capacity. Such information

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is essential to specify efficient method(s) for remedial/rehabilitation and management procedures for the structures.

In terms of the structural implication of ASR, it is interestingly observed from several experimental studies that the load-carrying capacity of ASR-affected structures is not compromised, especially for shear capacity. An exception is evident in Swamy and AlL-Asali [2], where the affected reinforced concrete beams lost up to nearly 25% of their flexural strength at an expansion level of 0.518% measured on the beams. The studies did, however, agree that the impact on load-carrying capacity would become significant if the specimens were subjected to long periods of exposure and underwent high expansion levels. As such, besides the adverse impacts on the material performance of concrete, such as cracking and degradation of mechanical properties, there is a certain favorable effect of ASR on the capacity of structures at low expansion levels, such as a prestressing effect of restrained ASR expansion (e.g., from the reinforcement [3]). The two most important questions herein are: (1) to what extent does the prestressing effect contribute to the capacity of affected structures; and (2) is this favorable outcome maintained or decayed as the expansion increases? Therefore, investigations of the prestressing effect in relation to the expansion advancement and degradation in mechanical properties are deemed necessary.

In this study, an engineering-based finite element (FE) approach was developed to model the ASR in reinforced concrete structures, considering the impact of reinforcement restraints on anisotropic ASR expansion and the loss of concrete mechanical properties. A case study of modeling the expansion and load-carrying capacity of ASR-affected reinforced concrete beams is provided.

2 Methods

2.1 Modelling Approach

The modeling approach to assessing the impact of ASR on structural capacity is presented in Fig. 1. The approach has three main steps: (1) estimating ASR-induced expansion under non-restrained/ non-confined conditions, (2) modeling the effect of restraints/confinements in 3-dimensional expansion, and (3) assessing the impact of ASR on the load-carrying capacity.

In the first step, free ASE-induced expansion was forecasted using the thermodynamically based semi-empirical model proposed by Larive [4], then further developed by Nguyen [5], which is capable of considering the effect of aggregate reactivity, time-dependent temperature and relative humidity, concrete alkali content and alkali leaching for forecasting expansion of field concrete. More details on the semi-empirical model can be found in Nguyen [5].

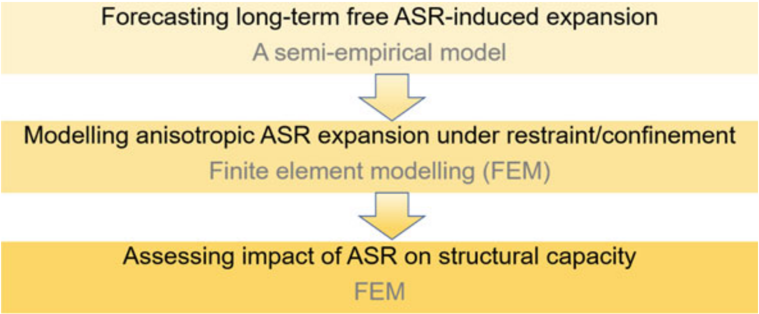

Fig. 1 Modelling of the expansion and load-carrying capacity of ASR-affected concrete members

In the second step, ASR-induced expansion in concrete under restraints/confinements, which is significantly different and far more complicated in comparison with free expansion of unrestrained concrete, was simulated in a FE model, which required a constitutive model to consider the restraints/confinements effect based on the multiaxial stresses developed in concrete elements. A general form of the incremental ASR strain tensor to be implemented in the FE analysis could be expressed as:

$$\dot{\boldsymbol{\varepsilon}}^{\boldsymbol{ASR}} = \boldsymbol{E}\boldsymbol{W}\boldsymbol{E}^{T} f(\boldsymbol{\sigma})\dot{\varepsilon}_{V}^{ASR,free} \tag{1}$$

where $\dot{\varepsilon}_{V}^{ASR,free}$ is the free volumetric expansion of concrete which was calculated per the semi-empirical model presented previously, $f(\boldsymbol{\sigma})$ is expansion-stress dependent function accounting for the impact of stress state on ASR expansion, $\boldsymbol{E}$ is the eigenvectors derived from the stress tensor, and W is the weight tensor that distributes the volumetric expansion to each of three principal directions, given by:

$$\boldsymbol{W} = \begin{bmatrix} W_1 & 0 & 0 \\ 0 & W_2 & 0 \\ 0 & 0 & W_3 \end{bmatrix} \tag{2}$$

Determining the weight tensor was based on the empirical model from Gautam et al. [6], which was derived from multiaxial testing schemes of ASR-affected concrete. The weights calculated above were equivalent to the weights in three principal directions, as such the incremental ASR strain tensor is as same as in Eq. (1) to capture the ASR anisotropic behavior.

In addition, ASR causes loss of mechanical properties over time (i.e., modulus of elasticity, compressive strength and tensile strength) to various degrees. Expansion-dependent mechanical properties were implemented in the model to consider the impact of the material degradation. With all these considerations, the developed FE model was capable of assessing the impact of ASR on the structural capacity in the third step of the approach.

3 Case Study: Results and Discussion

In this section, a case study is presented for modelling of ASR-induced expansion and consequently the ASR impact on the load-carrying capacity of reinforced concrete beams tested by Fan and Hanson [7]. An overview of the test is presented followed by a modelling briefing and some selected outcomes of the model.

3.1 Test Overview

Fan and Hanson [7] conducted a series of tests on reinforced concrete beams (150 × 250 × 1500 mm) for ASR expansion and capacity. Two reinforced concrete beams were prepared, namely, 5R1 and 5N1 (or reactive beam and non-reactive beam, respectively), which used concrete mixtures containing reactive and non-reactive aggregates, respectively, with the same mixture proportions. They were immersed in an alkali solution at 38 °C with periodic expansion measurements for 1 year. The expansion was measured from Demec studs mounted in the beams' surfaces using a Demec dial gauge at different locations.

After 1-year immersion in an alkali solution, the beams were tested for their load-carrying capacity as shown in Fig. 2a. The load–deflection behaviors of the two beams were almost identical despite a certain reduction in mechanical properties of the concrete of 5R1 due to ASR. The behavior of the non-reactive beam can be referred to as the undamaged concrete beam in comparison with the damaged reactive beam.

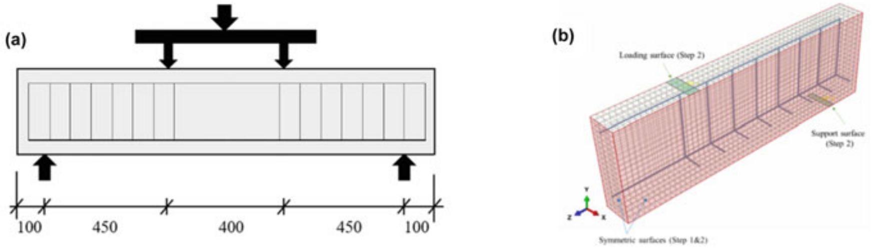

Fig. 2 Geometric and boundary conditions of the reinforced concrete tested by Fan and Hanson [7]

3.2 Modelling for ASR-Induced Expansion and Load-Carrying Capacity

Due to the symmetry of prism geometry and boundary conditions, only one-quarter of the beam was simulated utilizing symmetric boundary conditions as shown in Fig. 2b. The stress–strain behavior of the concrete defined at every 0.025% expansion level (i.e., 0%, 0.025%, 0.05%, 0.075%, 0.1%, etc.) to represent the change in the concrete's mechanical properties as expansion increased.

Distribution of average expansion (FV1) throughout the beam is shown in Fig. 3a. It shows a lower expansion in the area with both transverse and main longitudinal reinforcement at the bottom, and higher expansion on the top and at the beam-end with less reinforcement. Expansion in different locations and directions is plotted in Fig. 3b alongside the measurements. With a higher ratio of reinforcement in the longitudinal direction at the bottom, the expansion obtained at the bar level was significantly lower than at other locations. Similar to experimental observations, at the bar level, the expansion leveled off after 240 days of immersion, but kept increasing in the longitudinal direction on the top.

Load–deflection results for the 5N1 beam are shown in Fig. 4a, indicating a good agreement between the numerical and experimental results of load–deflection behavior. Figure 4b shows the predicted load–deflection curve of the reactive beam using the mean values of residual mechanical properties. First, the numerical results are comparable to the experimental in terms of capacity. The predicted ultimate loading value of the beam is $\approx$175.0 kN, and the value from test results was $\approx$177.3 kN. Similar to the test data, the numerical results showed an insignificant reduction in the capacity of the affected beam despite the reduction in mechanical properties as presented above. Second, the bending stiffness of the beam was slightly higher than the measured result despite the reduction in concrete stiffness. The observation aligned with observations from ISE [3], in which a favorable prestressing effect of restrained ASR expansion helped to increase the stiffness and capacity of several affected structures at low expansion levels.

4 Conclusions

This paper presents a modeling approach for the ASR expansion and capacity of reinforced concrete members. The approach consists of both the semi-empirical model and numerical model (i.e., FEM). The FE model could transfer the expansion modeling results such as strains, stress state, residual mechanical properties of concrete to modeling for load-carrying capacity of the affected concrete structural members. Outcomes from utilizing the proposed approach for simulation of reinforced concrete beams tested in Fan and Hanson [7] show good agreement between modeling and testing results, which indicates the capability of the model for forecasting long-term ASR-induced expansion and its impacts on structural capacity

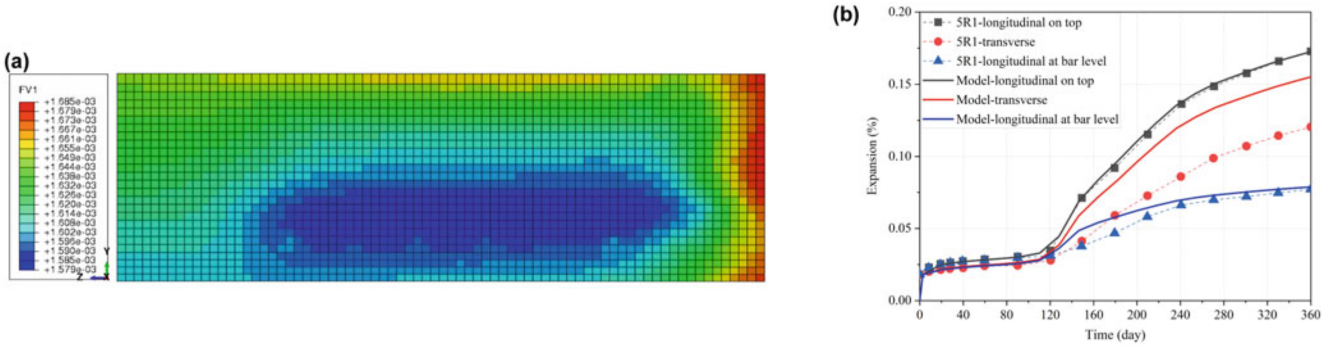

Fig. 3 Numerical and experimental ASR expansion at different locations for the reactive beam

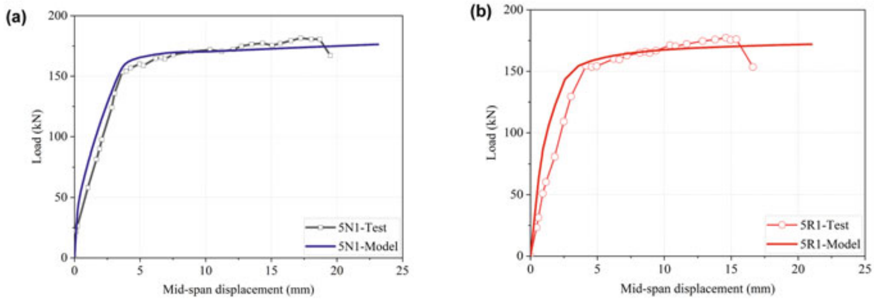

Fig. 4 Load–deflection behavior of **a** the non-reactive beam 5N1 and **b** reactive beam 5R1

of reinforced concrete structures in the field. In addition, the case study shows an insignificant impact of ASR on the load-carrying capacity at the expansion level of lower than 0.2%.

References

1. HB79 S (2015) Alkali aggregate reaction: guidelines on minimising the risk of damage to concrete structures in Australia, Cement and Concrete Association of Australia, and Standards Australia, North Sydney, NSW
2. Swamy RN, AlL-Asali M (1989) Effect of alkali-silica reaction on the structural behavior of reinforced concrete beams. Struct J 86(4):451–459
3. ISE (1992) Structural effects of alkali-aggregate reaction: technical guidance on the appraisal of existing structures. UK
4. Larive C (1997) Apports combinés de l'expérimentation et de la modélisation à la compréhension de l'alcali-réaction et de ses effets mécaniques. École Nationale des Ponts et Chaussèes, Paris
5. Nguyen TN (2021) Modelling alkali-silica reaction effects for condition assessment and capacity evaluation of reinforced concrete structures (Doctoral dissertation)
6. Gautam BP, Panesar DK, Sheikh SA, Vecchio FJ (2017) Multiaxial expansion-stress relationship for alkali silica reaction-affected concrete. ACI Mater J 114(1)
7. Fan S, Hanson JM (1998) Effect of alkali silica reaction expansion and cracking on structural behavior of reinforced concrete beams. ACI Struct J 95:498–505