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ALKALI-AGGREGATE REACTION STRUCTURAL EFFECTS: A FINITE ELEMENT MODEL

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In reinforced concrete members or structures, alkali-aggregate reaction causes expansion. This expansion is bound in the structure, first by the reinforcement bars and second by the cohesion between the deteriorated layer and the non affected deeper layers. These bounds increase internal stresses and create cracks in the structure.
In this paper, a new numerical approach to evaluate stresses, strains and displacements generated by alkali-aggregate reaction is presented. This approach is then applied to a case study to determine the distribution of efforts generated by the expansion.

INTRODUCTION

Alkali-aggregate reaction (AAR) produces mechanical damages to concrete infrastructures such as cracking, and strength and Young modulus losses. Up today the relation between AAR gel properties (gel composition and swelling ability) and their mechanical effects on the concrete as material and on the reinforced concrete as structure. Since the expansion due to AAR continues over many years and because the properties of concrete are continuously changing, it is important to develop a mechanical global approach to evaluate stress and strain values induced by AAR phenomenon. In a second step, the determination of residual security level in a structure submitted to operating external loads and to expansion internal destructive stresses has to be made.

The aim of this work is the development of a numerical approach to evaluate stress and strain values generated by expansive phenomena in a reinforced concrete structure by using Finite Element (FE) method. Then a comparison is realized between residual values and ultimate initial strength of concrete. This analysis permits to define a global security level of the structure and, if necessary, the adequate rehabilitation techniques or surveying methods.

AAR STRUCTURAL EFFECTS

Expansive concrete strains

The primary effect of AAR is the development of expansion. This expansion produces internal strains in the structure. The evolution of these strains might create a variation of mechanical stresses value and orientation. Swamy (1) shows that the largest expansive concrete strain in a flexural member occurs at the compressive face remote from the tension steel. This strain will be maximum when the compression face is unrestrained by the presence of steel. This phenomenon is the principal parameter to consider in the FE modeling by introducing the strain value produced by the expansion. This value has to be established from field measurements.

Cracks

One of expansion consequences on the mechanical behavior of concrete is the development of internal stresses, which can create cracking of the concrete. This phenomenon is the first visible indication of AAR presence in the structure. It is important to distinguish structural cracks and cracks induced by AAR. Observations realized on cracks (Ishizuka et al. (2), Swamy (3)) show that cracks produced by AAR can be few millimeters wide and several millimeters deep. In the other hand it is important to remember that AAR is a time dependant phenomenon and can progress during the service life of the infrastructures. Cracking due to AAR in real structures is thus highly complex and very variable. It is very much dependent of the amount of expansion, the nature of the structure and the stress distribution (Hobbs (4)). In our approach, cracks distribution will be the major observation permitting to validate results obtained from FE modeling.

Concrete mechanical properties

The concrete mechanical properties are related to the expansion rate. Tests show that losses in strength and Young modulus are not proportional to the expansion (1, 3). For expansive strains of 0.5 to 1.5 %, loss in compression strength can vary from 40 to 60%, whereas loss in tensile strength can be as high as 70%. Loss in Young modulus can also be high as 60%. But it is important to understand that sometimes high residual compressive strengths are obtained if investigations are realized at an early stage of AAR development. In the FE model developed in this paper, losses in mechanical characteristics are considered by modifying properties of damaged elements in the FE model.

FINITE ELEMENT METHOD

Principle

Engineering structures can be visualized as an assemblage of structural elements interconnected at a discrete number of nodal points. If the force-displacement relationships for the individual elements are known, it is possible, by using various techniques of structural analysis (Zienkiewicz (5)), to derive the properties and to study the mechanical behavior of the assembled structure. The problem of determining displacements, strains and stresses distribution through a structure is approached via the minimization of total potential energy defined as a "functional" of displacements.

Non-linear problems

Classic differential equations governing the FE method are linear and lead to a quadratic form of the functional. In elastic mechanics this implies:

- Linear form of strain-displacement relationships
- Linear form of stress-strain relationships

These linearities are not preserved in concrete modeling problems because of its non-linear behavior induced by cracks and plastic deformations. This class of problems can be simply dealt with without reformulation of the complete problem (i.e., without recourse to rewriting of the basic variational postulates). If a solution to the linear problem can be arrived at by some iterative process in which, at the final stage, the material constants are so adjusted that the appropriate new constitutive law is satisfied, then a solution is achieved. However, if the strain-displacement relationship is non-linear, then a more fundamental reorganization for the formulation is necessary. But the basic iteration process remain unchanged and indeed combination of both types of non-linearities may be achieved. In non-linear problems, it is important to choose small-step incremental approaches to obtain significant solutions. The iterative approach used can be interpreted as "numerical analysis" process such as Newton-Raphson method.

STRUCTURAL ANALYSIS OF EXPANSION DUE TO AAR

Mechanical analysis of structures behavior has to consider static and elastic stabilities. Usually static stability is analyzed in function of applied loads to ensure security against buckling, reversing etc... In the other hand, elastic stability is governed by stress and strain states. These states might change in function of the structure damages induced by the concrete expansion (macroscopic cracks modifies stiffness and therefore efforts distribution while microscopic cracks attenuate the concrete mechanical strength) which provoke a reduction of the structure carrying capacity. Strains generated by expansions develop an overloading which modify the elastic equilibrium state of the structure. In an advanced step it might provoke its ruin.

AAR mechanical modeling parameters

In infrastructures, the effect of expansion is showed usually on the structure's walls by the presence of cracks and fractures maps having a random distribution. However, it is important to define parameters which characterize the FE modeling.

1- Depth of the expanded layer: this depth can be evaluated by ultra-sonic measurements or concrete sampling.

2- Expansion rate: It might be evaluated by one of these two methods:

- direct measurement: strain gages can be installed in the concrete in transversal and longitudinal directions (Carse and Dux (6)). This method permits the evaluation, in function of time, of the expansion evolution and gives a direct estimation of induced strains. The inconveniences of this method are its cost and the necessity to glued strain gages immediately after the construction of the structure. If the measurement bases are installed many years after the construction, no indication can be obtained about ulterior concrete expansion.
- indirect evaluation: this approach is based on the relation between cracks and strains and between strains and expansion.

The advantage of this method is its application facility, but it cannot be reliable for structures submitted to AAR phenomenon in its first step. In summary, we can say that the first method is preventive and presents a high reliability degree for structures in the first steps of AAR. The second method is appropriate for structures having a multitude of cracks (very damaged).

FE Modeling

The FE analysis program used to model structural behavior of structures attacked by AAR is ANSYS in its version 4.4A (DeSalvo and Gorman (7)). The static analysis of this program is used to evaluate displacements, stresses, strains, and forces in structures under the loading actions. Capabilities include elastic, plastic, creep, swelling, large deflections, stress stiffening, and non-linear elements. The following procedures are introduced in the FE analysis:

Reinforced concrete law behavior. A multi-linear law with a multi-direction failure criterion is introduced to simulate elasto-plastic behavior of concrete. Steel reinforcement behavior is considered linear with yelding limit. No slippage will take place between the concrete and the reinforcement. To resolve the non-linearity problem, the incremental Newton-Raphson solution procedure is used. To consider the plasticity an iterative solution is required. Plasticity is also non conservative and requires that the load history will be followed.

FE mesh and reinforced concrete element. FE mesh presents the structure geometry, allowing nodes and elements localization and in the same time permits to define connectivity of the different elements and the boundary conditions of the structure. A specific isoparametric, solid, volumic reinforced concrete element was selected (7). The geometry, nodal point locations, face numbers and loading system for this element are shown in Fig. 1. This element is capable of cracking in tension and crushing in compression in three orthogonal directions. The re-bars are also capable of plastic deformations.

Applied loads. Two kinds of loads might generate a variation of stress and strain states in the analyzed structure:
- External loads: the evaluation of applied loads is a function of the structure sort. We can quote: weight of the structure, earth loads and water loads if available, and the concentrated surface loading applied by highway trucks, vehicles and railways.
- Internal loads: the principal applied load is the strain generated by the concrete internal expansion's created by AAR. The final expansion rate is introduced directly in the FE model as parameter, but its application is realized by defining incremental loading steps.

REAL CASE ANALYSIS

In this paragraph the behavior of the supporting vertical wall of an infrastructure attacked by AAR is analyzed. This analysis is based on visual observations and on the numerical modeling results.

Visual analysis

The expansion generated by AAR creates specific cracks on the wall's facings. Field measurements indicate that only few centimeters of the external facing react to the expansion which, consequently, is not free. Indeed, on one hand reinforcement bars of expanded areas are submitted to tension stresses made from the imposed concrete expansion, and on the other hand, some adjacent layers constrict the concrete expansion.

These two constrictive aspects create new efforts which are analyzed using the developed FE model and by introducing the expansion rate, geometrical and mechanical properties of the wall. It is important to note that in our knowledge this approach is bright new and has never been used before to analyze mechanical consequences of AAR. Nevertheless it is limited because of the multitude of parameters affecting the mechanical behavior and the importance of time factor and its influence on volumic variations.

Numerical analysis data

Geometry. Because of the non-linearity high level (cracking propagation, materials' behavior) an iterative simulation is realized. Only the central area of the wall is analyzed. The dimensions of this area are:
- Width = 2.64 m
- Height = 4.08 m
- Thickness = 0.43 m

Re-bars are located in two layers (first and third layers), each one is composed of horizontal and vertical bars. Boundary conditions are the followings:
- Displacements rubbles following the directions X, Y, Z in the horizontal basis of the wall.
- Following the two sides (X= 0 and X=2.64 m): vertical continuity because of the big width of the wall.

Materials' properties.
Vertical reinforcing bars: Ø 20, distance between centers of two successive bars = 40 cm
Steel elasticity modulus (E) =210 000 MPa; steel Poisson ratio (v) = 0.25
Horizontal reinforcing bars: Ø 14, distance between centers of two successive bars = 20 cm
Steel elasticity modulus (E) =210 000 MPa; steel Poisson ratio (v) = 0.25
Concrete compressive strength (F_c) = 30 MPa
Concrete tensile strength (F_t) = 2 MPa
Concrete initial elasticity modulus (E_c) = 15 000 MPa; concrete Poisson ratio (v) = 0.2

Finite Element Mesh. The FE mesh is realized by using volumic elements (brick; Fig. 1). Following the width direction, the wall is divided in three layers having a width of 0.10 m, 0.15 m and 0.18 m (Fig. 2). The element sizes in horizontal and vertical directions are respectively 0.33 and 0.34 m. Thus the elements dimensions are:

0.10 x 0.33 x 0.34 for area 1 (external layer)
0.15 x 0.33 x 0.34 for area 2 (middle layer)
0.18 x 0.33 x 0.34 for area 3 (internal layer)

The expansion is applied only in the external layer. The width of 0.10 m has been adopted according to field measurements.

Loading. The FE modeling has been realized for a volumic expansion equivalent to 2.6 ‰. This expansion rate corresponds to a strain ratio of 8.7 x 10^{-4}. This value has been obtained from measurements in field and laboratory. The FE model reaches this expansion's value after 17 loading increments. The transition from the step (i) to the step (i+1) happened after numerical convergence (stability of cracks and stresses) in the step (i).

Numerical analysis results

Deformations. The deformation of the wall is showed on Fig. 3. The plot following axes of symmetry demonstrates the presence of concave and convex series of curves which presents a high agreement with field observations. The lower calculated bend radius is equal to 200 meters which presents a high agreement with measured values (Fig. 4). The maximum value of differential displacements is equal to 2.0 centimeters while field measurements indicate a displacement of about 2.1 centimeters. The deformation of the wall in association with the bridge paving is showed on Fig. 5.

Cracks. All the elements of the expansive (first) layer are cracked in either two or three directions (Fig. 6). Some elements of the second layer are also cracked following one direction (Fig. 7) whereas no cracks has been observed in the third layer (Fig. 8). Most of the cracks are normal to the wall surface, they follow essentially horizontal and vertical directions. Some cracks opened in an intermediate step of the expansion process, are submitted to compression stresses which might close these cracks. Indications concerning the cracking mode are given in Fig. 6 for the first layer, in Fig. 7 for the second layer, and in Fig. 8 for the third layer.

Concrete stresses. The compression stress average in the first layer is between 5 and 7 MPa with maximum of 13 MPa. In the second layer, the tensile stress average is around 4 MPa with a maximum of 6 MPa. Stresses in the third layer are very low. The average is around 0.3 MPa with a maximum of 0.7 MPa.

Stresses in steel reinforcement bars. In the first layer, the average of stress values in reinforcement bars is around 50 MPa with a maximum of 120 MPa in the reinforcement bars located near the border. In the third layer, the average of stress values in this area is around 10 MPa with a maximum value of around 30 MPa

Discussion

The evaluation of forces in the different layers permits to verify observed damages in function of efforts in each layer. Tensile strains in the second layer are around 4 x 10^{-4} with a stress average of 4 MPa which corresponds to an effort value of 600 KN/lm of width. Compression strains in the third layer are around 3 x 10^{-5} with a stress average of 0.3 MPa in the concrete and 6 MPa in the reinforcement. The corresponding effort is 54 KN/lm for the concrete and 5 KN/lm in the reinforcement. In the expansive layer, the stress level in the reinforcement is between 50 and 120 MPa which correspond to an effort between 78 and 188 KN/ml for expansive strains between 6 x 10^{-4} and 8 x 10^{-4}. To verify the equilibrium of the structure, the effort in the concrete of the first layer has to be between 619 and 729 KN/lm which corresponds to a stress value around 7 MPa. This value of stress is in high agreement with the FE modeling results.

Moreover, the results of numerical modeling show high agreement with field measurements especially for displacements, deformations and bend radiuses. Therefore, the stresses obtained in the central area of the wall are likely to realistic. However, stress values are too high in the border of the mesh which can be explained easily by the excessive fixity of the border nodes. To resolve this problem, a research program is carried out to define realistic continuity functions.

In the end the following notes can be given: (1) layer 3 is submitted to a combination of compression and tensile stresses; (2) no cracks appear in the third layer (law tensile stresses); (3) the neutral axe is located between the layer 1 and 2 (9 centimeters).

CONCLUSION

Using numerical modeling to evaluate mechanical behavior of structures affected by AAR permits the evaluation of stress, strain and displacement values. Its permits also the analyze, in function of these values, the security level of the structure.

Results obtained from our modeling show good agreement between field observations and numerical values. This agreement permits on one hand to validate the used methodology and in the other hand to continue investigations concerning boundary conditions and mechanical law behaviors of concrete damaged by AAR.

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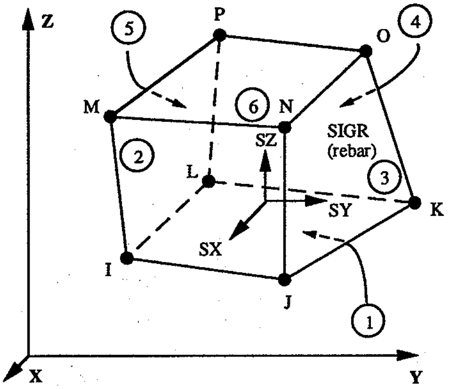

Figure 1 Volumic solid reinforced concrete Finite Element

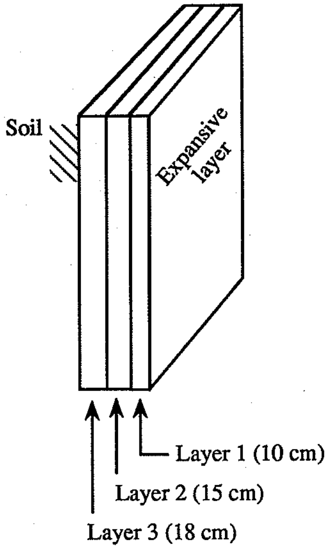

Figure 2 Position of three layers composing the wall

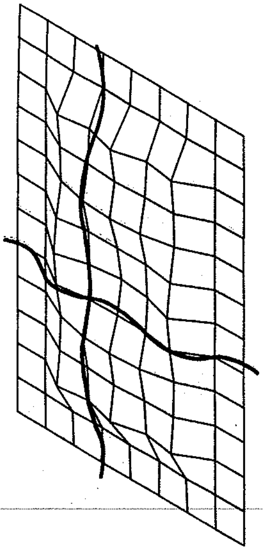

Figure 3 Calculated deformation of the wall (concave and convex curves)

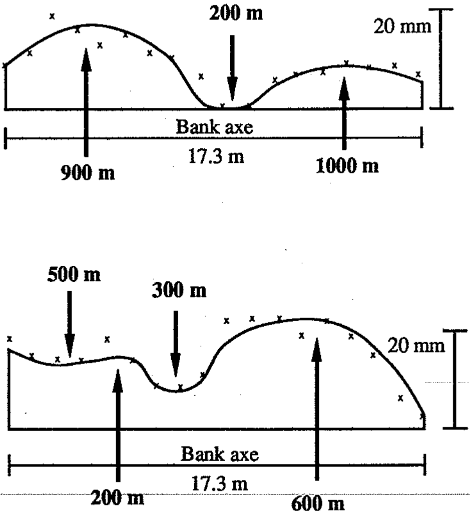

Figure 4 Measured wall deformation

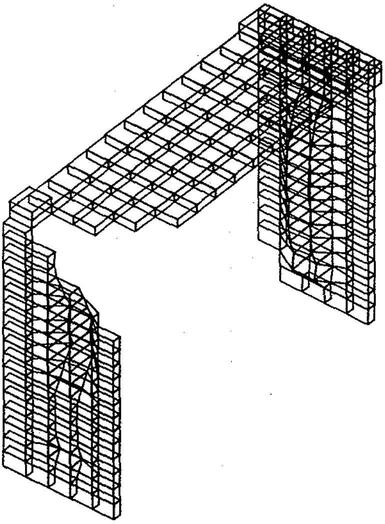

Figure 5 Deformation of the wall associated with the paving of the structure

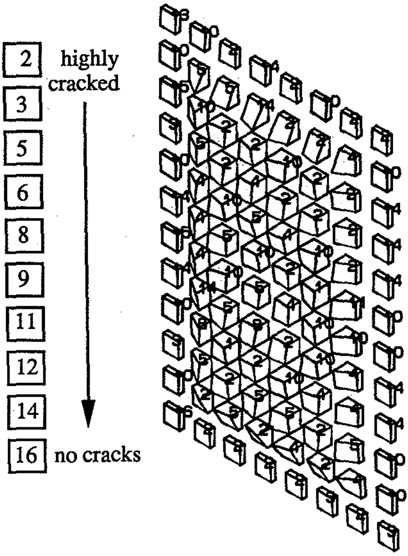

Figure 6 Expansion and cracking distribution in the first layer

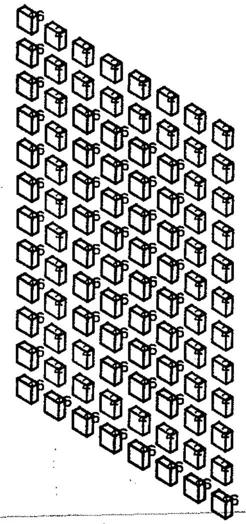

Figure 7 Cracking distribution in the second layer (same legend as Fig. 6)

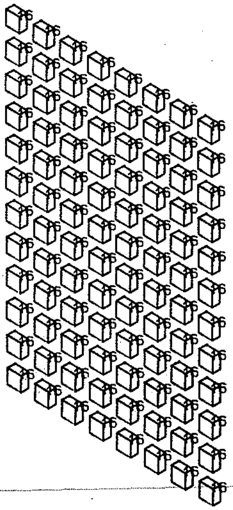

Figure 8 Cracking distribution in the third layer (same legend as Fig. 6)