EFFECT OF REINFORCING STEEL ON PRESSURIZED AIR LEAKAGE THROUGH CRACKS IN CONCRETE

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ABSTRACT

Concrete containment of a nuclear power plant may develop cracks under pressurized condition during a severe accident resulting in leakage of contained air and radioactive aerosols. Many researchers have suggested air leakage rate formulae through cracks based on experimental studies on reinforced concrete panels. Limited experimental studies have also been reported for pressurized air leakage rate through cracks in plain concrete. A comparison of predicted leakage rate through cracks in reinforced concrete (RC) and plain concrete (PC) show significant difference, the former giving lower leakage rate. The open literature does not appear to have computational studies, which account for modified crack morphology in concrete due to reinforcing steel and its influence on the airflow through such cracks. Approximation of change in crack morphology due to reinforcing steel has been obtained by stress analysis of reinforced concrete panels. Computational studies were performed for air leakage through modified crack morphology. Comparison of computational study results for air leakage through cracks in plain concrete and reinforced concrete is presented to see the effect of reinforcing steel on the leakage rate. The predicted leakage rate from the computational model with modified crack morphology for an RC test specimen was compared with the experimentally measured value and excellent match was observed between the two values. The study also gives insight into the various phenomena responsible for reduced airflow through cracks in reinforced concrete as compared to plain concrete.

INTRODUCTION

A major fraction of the airborne radioactivity within nuclear reactor containment, consequent to a postulated severe accident involving reactor core meltdown, consists of aerosols generated by condensation of volatile fission products. The containment envelope becomes pressurized during a severe accident and there is a possibility of cracks through concrete shell of the containment, which can provide leak paths for pressurized air and aerosol release to the outside atmosphere.

Rizkalla et al. [1] reported experimental data for leakage rate through cracks in reinforced concrete test panels and suggested correlations. Riva et al. [2] performed finite element analysis of reinforced concrete test panels to calculate equivalent average single crack width for evaluating leakage rate with different correlations and reported good match of the test leakage rate with the calculated rate using correlation of Rizkalla et al. [1]. Gelain and Vendel [3] performed experiments on plain concrete panels and computed crack geometry as an equivalent rectangular channel, which would have the same flow rate as the experimental data. Boussa et al. [4] generated cracks in a large number of test specimens of different concrete grades, modeled the crack profile in terms of statistical parameters and reported good agreement of the crack profile obtained from the statistical model with the experimental data. Bishnoi et al. [5] conducted computational studies for airflow and aerosol transport through cracks in plain concrete using statistical crack model of Bousa et al. [4] and reported good match between the computational and experimental results.

The open literature does not appear to have computational studies, which account for modified crack morphology in concrete due to reinforcing steel and its influence on the airflow through such cracks. Approximation of change in crack morphology due to reinforcing steel has been obtained by stress analysis of reinforced concrete panels. Computational studies were performed for air leakage through modified crack morphology as well as through cracks with unmodified morphology to represent cracks in plain concrete. Comparison of computational studies for pressurized air leakage through cracks in plain concrete and reinforced concrete is presented to see the effect of reinforcing steel on the leakage rate.

Commercially available computer codes were used in this study. ANSYS was used for linear stress analysis to derive crack morphology around reinforcing bars and ABAQUS was used for nonlinear stress analysis to derive crack surface distribution across the cross section of a test specimen. FLUENT (version 6.2.16, 2005) was used for airflow study through the cracks. Crack geometric modeling was implemented in MATLAB.

NUMERICAL PROCEDURE

The 2D crack profile is defined in terms of straight segments and deviation of these segments from horizontal line by specifying mean value and standard deviation separately for these two parameters as per the approach suggested by Boussa et al. [4]. Two identical profiles placed at a constant spacing equal to the crack width represent two lips of the crack in 2D. Details of statistical crack models in 2D are reported in Bishnoi et al. [5]. A typical statistical crack model geometry is shown in Fig. 1. Further refinement of the 2D crack model was done to represent roughness due to local tortuousness, introduced by crack tip deflecting material grains, using fractal geometry for each of the straight segments of the crack as shown in Fig.2.

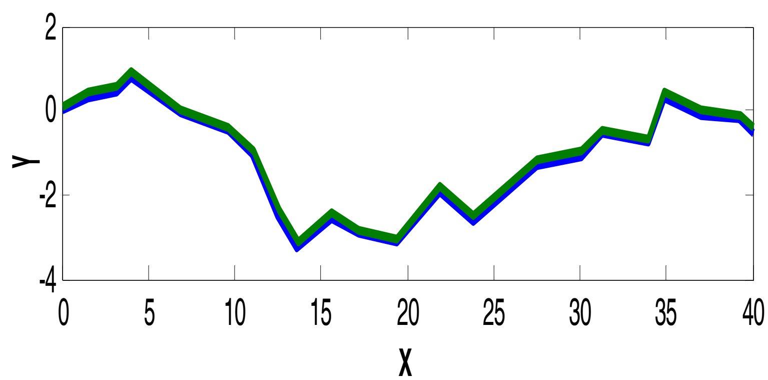


Fig.1: Typical crack model

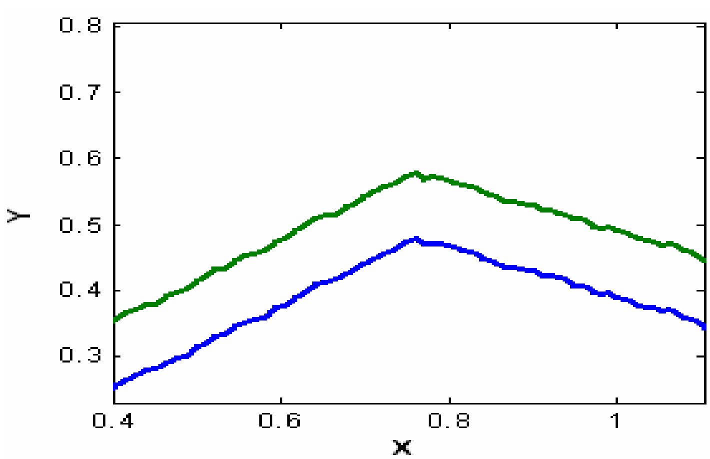
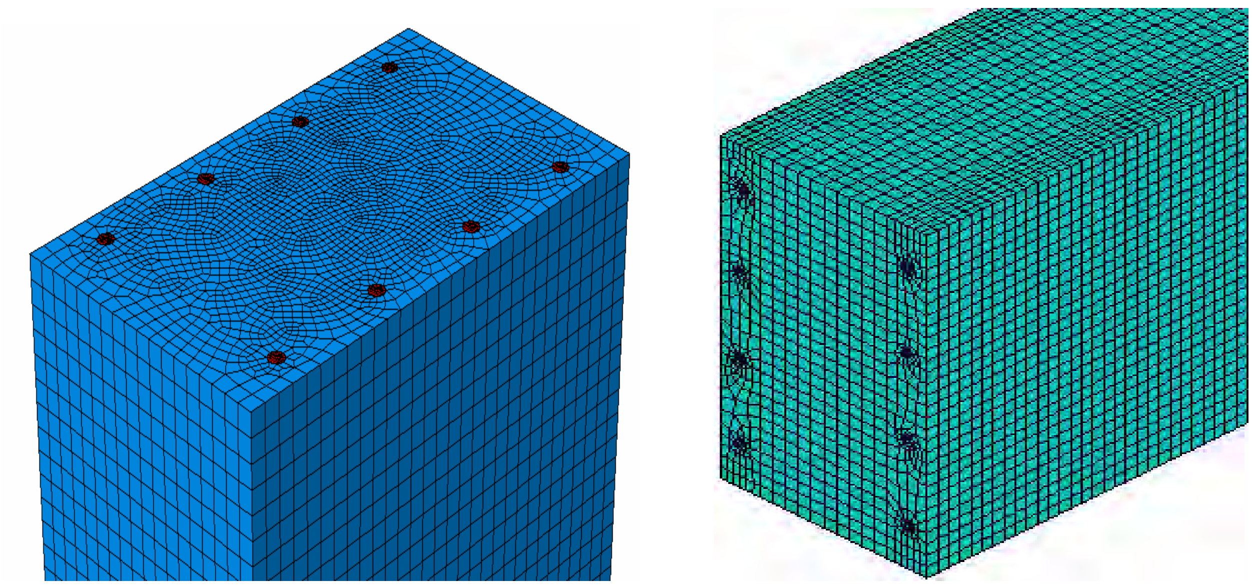


Fig.2: Local tortuousness in a crack segment

The standard Navier-Stokes and continuity equations are solved for the flow domain defined by the crack morphology using the finite volume method with SIMPLEC algorithm for pressure-velocity coupling and second order upwind scheme with under relaxation factor of 0.5 for discretization of momentum equations. Atmospheric pressure was assumed at outlet and inlet pressure was calculated according to the specified pressure gradient. No-slip condition was imposed at crack wall boundaries. All case studies were conducted for a constant temperature of 300 K. Since the pressure drop across the crack is not large the flow is assumed incompressible and confirmed by checking the flow Mach numbers, which remained much below unity for all the cases. Details of optimized computational grid and validation of the crack model for 2D airflow computations are reported in Bishnoi et al. [5]. Numerical procedure established for airflow through 2D crack path was extended to 3D crack surfaces.

Stress analyses were performed on finite element (FE) model of a reinforced concrete experimental test specimen (L4) from Rizkalla et al. [1] of size 760X304X178 mm (30"X12"X7"), reinforced with steel bars of 10 mm diameter spaced at 76 mm (3") c/c oriented along the direction of application of tensile load (i.e. along the height, 760 mm) of the specimen near each face and clear cover of 12 mm (1/2"), to derive morphology and extent of crack surfaces to be used for airflow calculations. Reinforcing steel in the transverse direction (i.e. along the length, 304 mm) was not included in the model, assuming not so significant role of this reinforcement in the crack propagation as no load was applied along these bars. Specimen L4 was selected because complete details of geometry, reinforcement, cracking and airflow results are reported for this specimen only. Uniaxial tensile load was applied to reinforcing steel bars in the stress analysis models as was done in the experimental study.

Concrete damage plasticity model available in ABAQUS was used for nonlinear stress analysis. Two nonlinear analyses were conducted; one with reinforcing steel and another with plain concrete without reinforcement. This was done to see the effect of reinforcing steel on crack surface pattern growth compared to the plain concrete. The uniaxial tensile load was applied as a surface pressure in case of the model for plain concrete specimen. An isometric view of a part of the FE model with reinforcing steel, used for nonlinear stress analysis, is shown in Fig.3 (a). Linear stress analysis was conducted with a priori crack in the form of a slit of finite width to obtain the likely morphology of the crack around reinforcing steel bars under uniaxial tensile load. Fig.3 (b) shows a part isometric view of the FE model used for linear stress analysis.



(a) For nonlinear stress analysis **(b) For linear stress analysis**

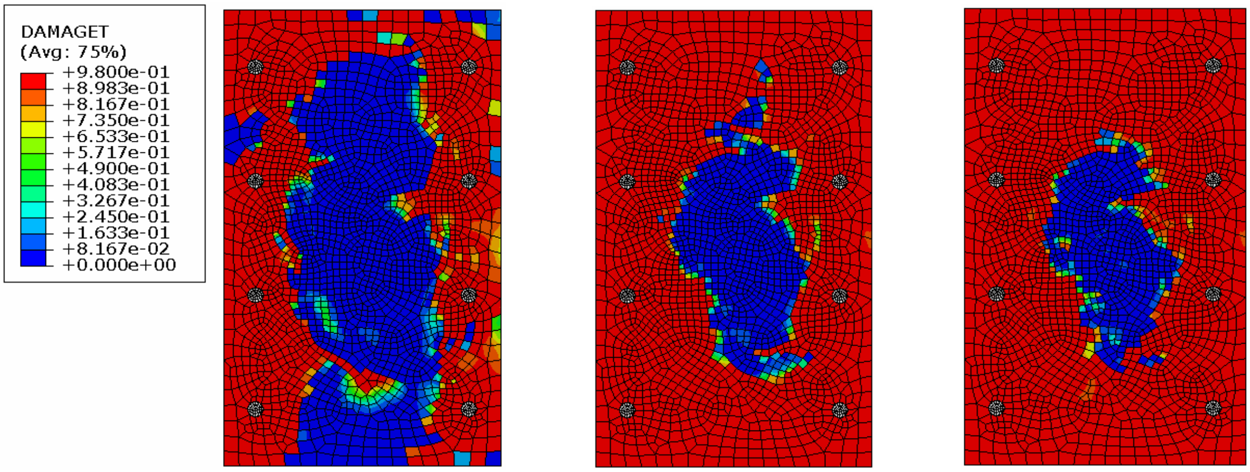
Fig.3: Finite Element Models for Stress Analysis

RESULTS AND DISCUSSION

The measured airflow rate through crack surface area of 0.23 m^2 over six cracks of average crack width 0.06 mm in the L4 test specimen of thickness 178 mm was 5.18×10^{-4} m^3/s with inlet pressure of 207 kPa and outlet pressure of 101 kPa [1]. This indicates that the crack surface area is less than the cross sectional area (0.304X0.178X6 = 0.325 m^2) of the test specimen; it is about 70%. This difference could be seen in the nonlinear stress analysis of the test specimen also as explained below. Though the average crack width is 0.06 mm, there was significant difference in the individual values of the crack widths, which were measured along the centerline of the specimen [1].

Non Linear Stress Analysis

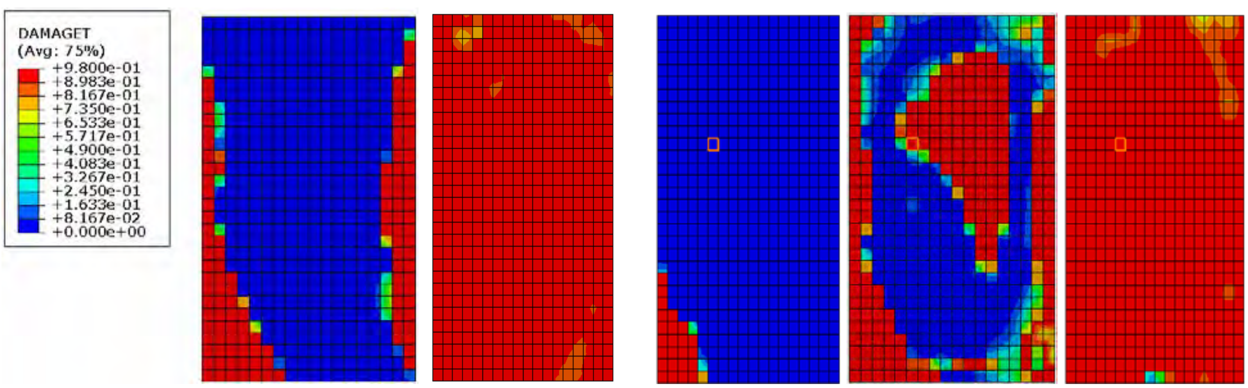
The spread of concrete damage over the specimen cross section at different load increments is shown in Fig.4 in the reinforced concrete (RC) model and in Fig.5 for the plain concrete (PC) model. It is seen from Fig.4 that reinforcement does not allow spread of the damage and hence the crack surface over the entire cross section, though the extent of spread keep increasing with load increments. The cracks seem to appear first near the exterior faces around the reinforcing bars. The exterior face damage then spreads along the edges parallel to the airflow direction and become through-thickness.



(a) 12% of ultimate load **(b) 24% of ultimate load** **(c) Ultimate load**

Fig.4: Damage propagation in RC specimen model at a typical location at different load increments

Subsequently it spreads into the interiors of the specimen. The extent of damage at different cross sectional locations was found to be different in case of RC specimen model. The damage spread in plain concrete is sudden from exterior faces to the entire cross section and the rate of spread varied a bit from location to location as seen from Fig.5.



(a) Typical location-1 **(b) Typical location-2**

Fig.5: Damage propagation in PC specimen model at two typical locations during consecutive load increments until damage spread over entire cross section

Linear Stress Analysis

The purpose of this analysis was to derive crack surface morphology as affected by the reinforcement due to the bond between the concrete and the reinforcement. Fig.6 shows typical displacement contours of the crack surface around the reinforcing bars (rebars). It is seen that the rebar holds the crack faces together in its vicinity such that the crack opening is maximum at the mid-point of two rebars. The concrete around the bar is pulled along with the bar due to the bond and thus creating a dumbbell type of obstruction in the flow path. Since the crack width (opening) measurements were done along the centerline of the test specimen that coincided with the mid-point of two rebars, the reported crack widths at the face of the specimen correspond to the maximum value in the mid-region of the two rebar.

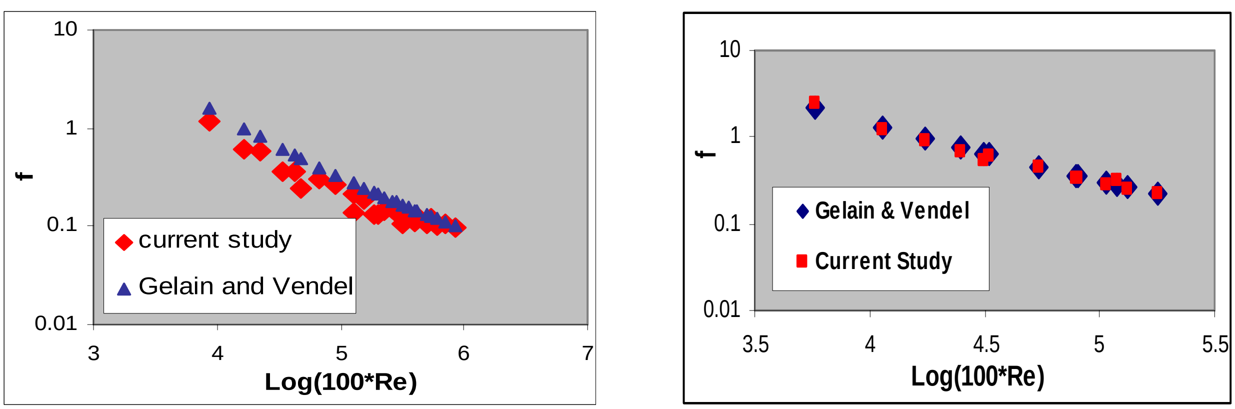
(a) (b) (c)

Fig.6: Crack surface contours around rebar (a) cross section along crack path through rebar (b) typical crack profile across the flow path between two rebar at the edge (c) typical crack surface contour in plan around a rebar.

Approximate crack morphology around rebars was generated in 3D using the information obtained from the linear stress analysis. The maximum gap between two crack surfaces away from the rebars was kept to the specified crack width.

Airflow Calculations

The numerical procedure for airflow calculations through 2D cracks was validated by comparing the results with experimental values reported by Gelain and Vendel [3] for cracks in plain concrete as shown in Fig. 7(a) [5]. The comparison in Fig.7 (a) shows plots of Darcy Friction Factor (*f*) versus Reynolds Number (R_e). Comparison of computational results from the refined 2D crack model with the experimental values is shown in Fig.7 (b) as plots of *f* versus R_e. It is seen that the refined model predictions show further improvement over the original model predictions. The difference in mass flow rate between the two crack models for the crack width of 0.06 mm is about 25%, the refined model giving lower flow rate.



(a) Study without local tortuousness [5] (b) Study with refined model

Fig.7: Plots of *f* versus *Re*

Airflow calculations were performed for specified pressure difference of 106 kPa across the specimen thickness of 178 mm (i.e. pressure gradient of 5.96bar/m) and specified average crack width of 0.06 mm. The computational model generated for 3D crack morphology of the test specimen is shown in Fig. 8. Because of large computational resource requirements, only quarter model was used with appropriate boundary conditions. The same 3D crack model was modified by restricting the crack flow surface area in the central region of the model as shown by grey shade in Fig. 9, as observed in the nonlinear stress analysis. The crack flow surface area in this case is about 85% of the cross section of the test specimen, an arbitrarily chosen value based on the ease of modeling and to get an idea of the effect of such constrictions on the flow rate. This value is likely to vary at different crack locations and at different stress levels in the specimen.

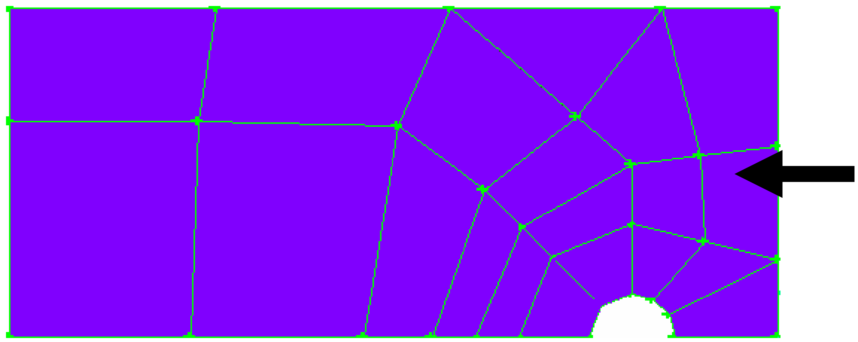


Fig.8: Quarter model of the test specimen for airflow computation

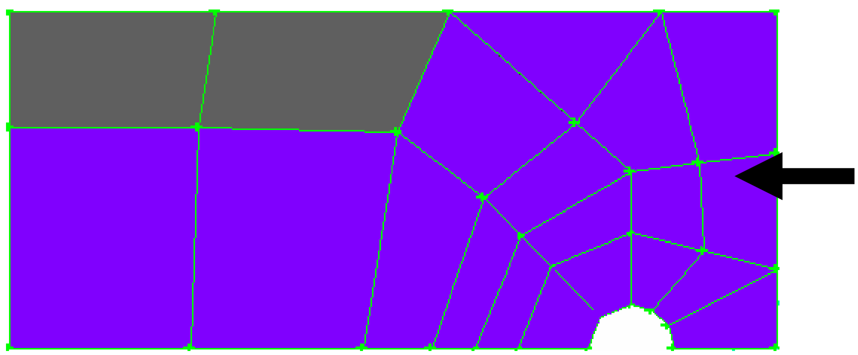


Fig.9: Quarter model of the test specimen for airflow computation with restricted flow in the central region of the specimen

The mass flow rates through the cracks with morphologies depicted in Figs. 8 & 9 were compared with the flow rate through a 3D plane crack in which two plane surfaces were separated by the average crack width value instead of the actual crack morphology. All the 3D crack morphology computations were reduced by 25% to account for the correction due to local tortuousness, which could not be accounted in these models. Air density was assumed to be a constant value of 1.225 kg/m^3. The comparison of flow rates (m^3/s) from different models is provided in Tables-1 & 2 below.

Table-1

Measured flow through reinforced concrete test specimen L4 [1]	Flow calculated from refined 2Dcrack model for plain concrete	3Dcrack model for plain concrete		3D crack model with modified morphology due to rebar			
		Calculated flow	diff. w.r.t. (2) (%)	Calculated flow	diff. w.r.t. (1) (%)	diff. w.r.t. (2) (%)	diff. w.r.t. (3) (%)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
5.18e-4	7.084e-4	8.288e-4	+ 17	6.805e-4	+31.4	-3.9	-17.9

From the above comparison, it is seen that the 3D crack model incorporating the crack morphology derived by considering the local effect of rebar including flow obstruction because of the rebar and its bonding with the concrete as well as the restricted flow surface area in the central region of the test specimen, a phenomenon revealed in RC members through nonlinear stress analysis, provide excellent comparison with the flow obtained experimentally. However, the assumed reduction of the flow cross section in the central region of the RC members, as observed in the stress analysis in the form of undamaged zone, is accounted rather qualitatively through arbitrarily defined uncracked zone. Hence sensitivity of the flow with respect to this parameter needs to be studied further and methodology of defining the extent of flow constriction in RC members needs to be looked into based on further analyses and experiments.

Table-2

3D crack model with modified morphology due to rebar and flow area constricted in the central region of the test specimen				
Calculated flow	diff. w.r.t. (1) (%)	diff. w.r.t. (2) (%)	diff. w.r.t. (3) (%)	diff. w.r.t. (5) (%)
(9)	(10)	(11)	(12)	(13)
5.305e-4	+2.4	-25.11	-36	-22.04

The difference between the flow rate calculated from 2D crack model for plain concrete and 3D model for plain crack is attributed to the global crack tortuousness, which has been incorporated in the 2D model only and not in 3D model for plain concrete. The close agreement between the flow rates calculated from 2D refined crack model and the 3D crack model with modified morphology due to rebar, without flow area constriction in the central region, confirms the reasonableness of the 3D crack morphology derived from linear stress analysis.

CONCLUSIONS

The stress analyses to derive 3D crack morphology in RC members and then airflow computations through the crack channels represented by the 3D crack morphology has given insight into the phenomena responsible for reduced airflow through cracks in reinforced concrete compared to plain concrete, as noted from the results of experimental studies. The important phenomena noted from the results of the computational studies are; (i) rebars control spread of crack surface in the interiors of the reinforced concrete elements and thus constrict the flow cross section, and (ii) the bond between rebars and concrete modify the crack morphology around the rebars, generally reducing the crack width in its vicinity and providing increased obstruction to the flow through the crack.

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