Experimental study of non-linear air flow through a single concrete crack characterised geometrically by X-ray microtomography

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Quantitative predictions of air flow rates through cracked concrete and reinforced concrete structural elements are crucial in many engineering applications. One can cite, among others, air leakage through cement paste layers injected around tubing for gas extractions, or air leakage through concrete walls of nuclear containment structures in the absence of steel liner. This second application is extremely important in France, where many nuclear power plants of such kind (REP 1300 P4, REP 1300 P'4, REP 1450 N4) are still in service. In these applications, air leakage rate estimations are often carried out by considering Loss of Coolant Accident (LOCA) conditions. In that situation, the absolute pressure (p_1) inside the containment building is supposed to reach about 520 kPa and the temperature (T_1) 140 °C, while external pressure (p_2) and temperature (T_2) remains at ambient conditions. The resulting pressure and temperature gradients across the wall induce air flow from inside the containment structure to the external environment. Under these conditions, localized macro-cracks represent preferential pathways for fluid flow and could increase the leakage rate with respect to undamaged or diffusely damaged conditions strongly.

1. State of the art

Several studies aiming to predict structural transfer properties evolution in the presence of one or more macro-cracks were published in the literature (e.g. air flow [6, 8, 7, 1, 2], water flow [4, 5]). In most of these works, the flow was supposed to behave according to the Poiseuille model. For air flows under isothermal quasi-incompressible conditions, this leads to assume that the specific mass flow rate (Q) is a linear function of the square pressure drop ($\Delta p^2 = p_2^2 - p_1^2$) between the inlet and outlet crack sections. The proportionality coefficient between them depends linearly on the so-called crack permeability, conventionally computed according to the parallel plates model as $k_c = \xi a^2/12$. Here, a denotes a representative crack opening value and $\xi \leq 1$ is a phenomenological corrective factor accounting for the reduction in flow rate due to the roughness of crack walls, tortuosity of flow paths and contact areas inside the crack space. Factor ξ is typically assumed as a constant with values ranging in a wide interval ($\xi = 0.5 \div 0.001$). Figure 1 compares mass flow rate values computed using definitions of ξ proposed in cited works and considering LOCA conditions (at least in terms of pressures). Such a comparison put into evidence that there is no consensus on the quantitative estimation of air flow through a single concrete crack. One could expect that this is partly due to some differences in tested materials. Limitations associated with the adopted experimental protocols and results treatment could, however, play an important role. This second aspect is crucial, because recirculation phenomena and fluid compressibility effects can induce the relationship $Q = Q(\Delta p^2)$ to become non-linear even for small Reynolds values (i.e., under laminar conditions). Under these conditions the Poiseuille flow assumption is not still valid, and non-linear Forchheimer-like models could be more pertinent.

2. Experimental protocol coupling flow measurements and X-ray microtomography

Some theoretical studies of nonlinear flow models accounting for compressibility effects in parallel plates channels under different thermodynamic conditions were published. At the same time, some

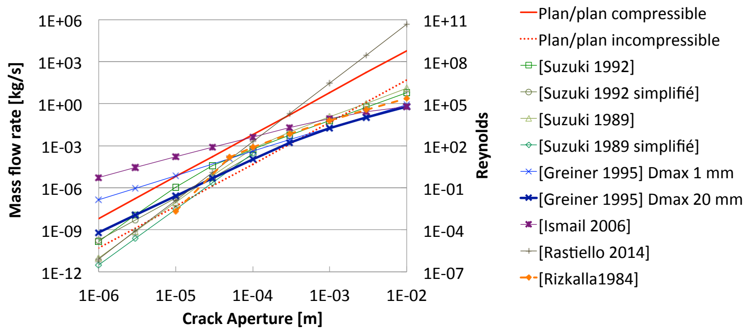

Figure 1: Flow rate estimations for a REP 1450 N4 containment building wall (thickness = 1,20 m) under LOCA pressure conditions. Note that ξ should be a purely geometrical properties. For that reason, also relationships proposed for water flows were retained for sake of comparison

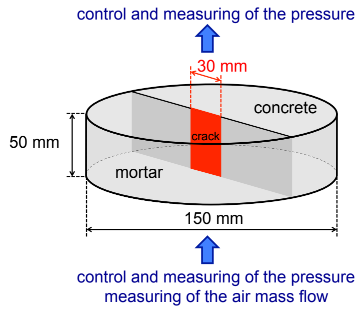

Figure 2: Schematic view of the experimental device and geometry of the cylindrical sample

studies of incompressible flows in non-linear regime due to recirculation phenomena are available. There are, to the best of the author's knowledge, no experimental results aiming to study non-linear air flows through rough and tortuous cracks. The present work proposes an experimental study aiming to fill this gap. For this purpose, a novel experimental procedure for measuring leakage rates through opening controlled cracks in concrete is developed. An enhanced CemBureau protocol [3] is adopted for flow measurements on cracked samples. A cylindrical concrete sample (50 mm height and 150 mm in diameter) comprising a central macro-crack is tested. The crack has a representative aperture a of about 150 μm and is 30 mm in width. It is obtained using a three point bending test after having cut partly the sample along its diameter. This allows obtaining two half specimens, which are further glued together using a special experimental procedure as describe on the figure 2. Air flow measurements are then performed under squared pressure gradients close to LOCA conditions. The crack is then scanned by 3D X-ray tomography to quantify the local apertures distribution with high spatial resolution (4 μm approximately). Air flow measurements are finally put into relation with crack geometrical properties. The experimental procedure is applied to different samples. This finally allows for proposing some enhancements to classic non-linear compressible flow models.

References

[1] Greiner, U. et Ramm, W. (1995). Air leakage characteristics in cracked concrete. *Nuclear Engineering and Design*, 156(1-2):167–172. doi=10.1016/0029-5493(94)00942-R.

[2] Ismail, M., Gagné, R., François, R. et Toumi, A. (2006). Measurement and modeling of gas transfer in cracked mortars. *Materials and Structures*, 39(1):43–52. doi=10.1617/s11527-005-9025-4.

[3] Kollek, J. (1989). The determination of the permeability of concrete to oxygen by the cembureau method - a recommendation. *Materials and Structures*, 22(3):225–230. doi=10.1007/BF02472192.

[4] Li, K., Ma, M. et Wang, X. (2011). Experimental study of water flow behaviour in narrow fractures of cementitious materials. *Experimental study of water flow behaviour in narrow fractures of cementitious materials*, 33(10):1009–1013. doi=10.1016/j.cemconcomp.2011.08.005.

[5] Rastiello, G., Boulay, C., Pont, S. D., Tailhan, J. et Rossi, P. (2014). Real-time water permeability evolution of a localized crack in concrete under loading. *Cement and Concrete Research*, 56:20–28. doi=10.1016/j.cemconres.2013.09.010.

[6] Rizkalla, S. H., Lau, B. L. et Simmonds, S. H. (1984). Air leakage characteristics in reinforced concrete. *Journal of Structural Engineering*, 110(5):1149–1162. doi=10.1061/(ASCE)0733-9445(1984)110:5(1149).

[7] Suzuki, T., Takiguchi, K. et Hotta, H. (1992). Leakage of gas through concrete cracks. *Nuclear Engineering and Design*, 133(1):121–130. doi=10.1016/0029-5493(92)90096-E.

[8] Suzuki, T., Takiguchi, K., Hotta, H., Kojima, N., Fukuhara, M. et Kimura, K. (1989). Experimental study on the leakage of gas through cracked concrete walls. *In SMiRT 10 Conference*, pages 145–150, Anaheim, CA, USA. International Association for Structural Mechanics in Reactor Technology. Division Q - Q05/659.