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# Study of the size effect in a model to simulate concrete cracking due to rebar corrosion and comparison to accelerated corrosion tests

B. Sanz[1], J.P Planas[1], J.M. Sancho[2]

[1] *Dep. Ciencia de Materiales, E.T.S.I. Caminos, Universidad Politécnica de Madrid, Madrid, Spain, bsanz@mater.upm.es, jaime.planas@upm.es*
[2] *Dep. Estructuras de Edificación, E.T.S. Arquitectura, Universidad Politécnica de Madrid, Madrid, Spain, jose.sancho@upm.es*

An immediate consequence of the corrosion of reinforcement in concrete structures consists in the generation of an oxide layer at the steel surface which, due to the greater specific volume of the oxide with respect to the steel, induces internal pressure on the surrounding concrete and thus cracks the concrete cover [1, 3]. Focussing on the prediction of the mechanical effects of the oxide expansion, a numerical model to simulate the effect of the oxide layer was programmed, assuming that the oxide layer expansion is given at a any specified time [5]. The basic ingredient of such a model is an interface element with zero initial thickness that incorporates both the expansive and mechanical behaviors of the oxide, which is characterized by its ability to debond, with nearly free sliding (very small shear stiffness) and nearly free separation in tension (strongly reduced normal tension stiffness). It was called *expansive joint element* and it has already been presented in previous conferences. Concrete cracking is simulated by finite elements with embedded adaptable cohesive cracks [4] that follow the basic cohesive crack model proposed by Hillerborg et al [2].

In this work, the expansive joint element has been improved by incorporating irreversible behavior and a thorough analysis is carried out to ascertain the (strongly) coupled effect of the size of the mesh, the time step, the numerical tolerance and the fracture properties of the concrete on the cracking pattern.

In parallel, accelerated corrosion tests have been carried out in order to verify the ability of the model to reproduce the oxide behaviour and the mechanical effects over the surrounding concrete. The crack patterns obtained in both cases are compared and discussed. The samples are concrete prisms with a steel tube inside simulating a rebar. The corrosion is simulated by the volumic expansion of the oxide. It is controlled by a single parameter, the corrosion depth, that is implicitly time-dependent. The influence of the element size is studied covering different ranges for the expansive joint element, the steel and the concrete. The cracking of the surrounding concrete is studied at different stages of the process for each case. In accelerated corrosion tests, constant current has been imposed in order to corrode the samples. The crack width at the concrete surface is recorded during the process and the crack pattern is studied after finishing the test. A special surface treatment is applied in order to improve the cracks detection. Finally, the results obtained from the simulations and from the tests are compared and the results are discussed.

An example of the preliminary study of this work is shown in figure 1. The cracking of a concrete prism with an embedded steel bar is studied for a radial oxide expansion of 10 microns. In part (a) of the figure, the results from the simulations are displayed showing the crack width (in mm) and the maximum principal stress (in MPa). A main crack from the steel to the concrete surface and a cloud of finely radial cracks with opening width near to zero are obtained at that stage of the simulation. In parts (b), (c) and (d) of the figure, some pictures of one of the first samples tested are shown. In part (b), a general view of the slice is shown. A main crack is observed from the steel to the concrete surface, similar to the main crack in the simulations, and also some secondary cracks can be noticed. Part (c) is a detail of the

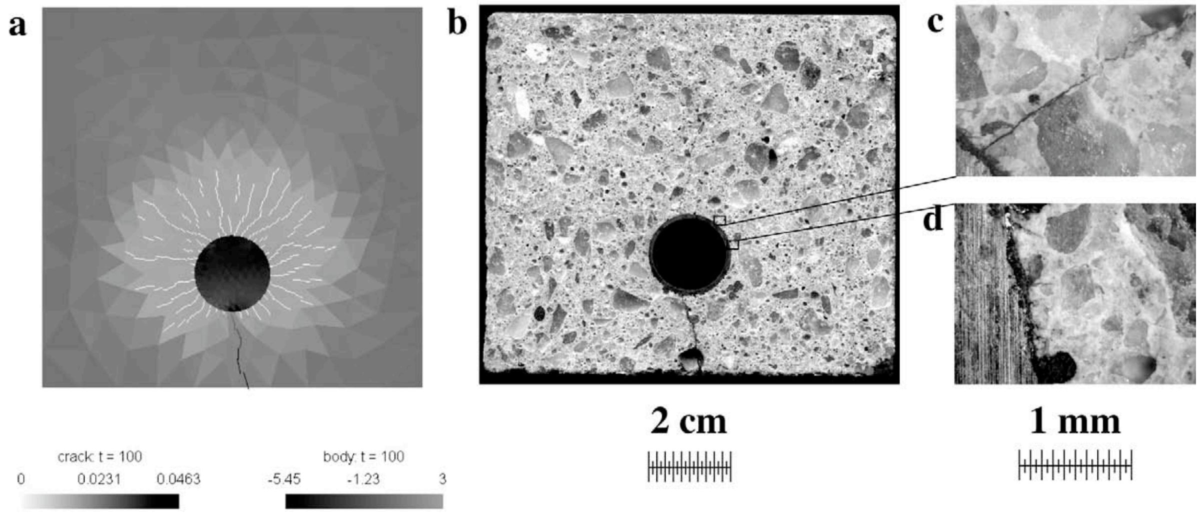


Figure 1: (a) Crack pattern in numerical simulations using the expansion joint element. Crack width (mm) and maximum principal stress (MPa). (b) Crack pattern in accelerated corrosion tests. General view. A main crack is observed. (c) Detail of a secondary crack. (d) Detail of some radial micro-cracks.

root of one of the secondary cracks. However, when looking at the slice under the microscope, many micro-cracks around the bar are also seen, as shown in part (d), in accordance to the predictions of the simulations.

In the paper, the main aspects of the formulation of the element are reviewed and the effects of the numerical settings are analyzed in detail. The experimental procedure for accelerated corrosion tests is briefly described and some pictures of the experimental crack pattern after applying the surface treatment are shown. The results obtained from the simulations for different numerical settings are discussed and compared with the experimental results.

## References


[1] *Cover cracking as a function of bar corrosion: Part I - experimental test*, C. Andrade, M.C. Alonso and F.J. Molina, *Materials and Structures*, Vol. **26**, 453–464, 1993.

[2] *Analysis of crack formation and crack growth in concrete by means of fracture mechanics and fracture elements*, A. Hillerborg, M. Modéer and P.E. Petersson, *Cement and Concrete Research*, Vol. **6**, 773–782, 1976.

[3] *Cover cracking as a function of bar corrosion: Part II - numerical model*, F.J. Molina, M.C. Alonso and C. Andrade, *Mater. Struct.*, Vol. **26**, 532–548, 1993.

[4] *An embedded cohesive crack model for finite element analysis of concrete fracture*, J.M. Sancho, J. Planas, D.A. Cendón, E. Reyes and J.C. Gálvez, *Engineering Fracture Mechanics*, Vol. **74**, 75–86, 2007.

[5] *Modelling concrete cracking due to rebar corrosion using finite elements*, B. Sanz, J. Planas, A.M. Fathy and J.M. Sancho, *Anales de Mecánica de la Fractura*, Vol. **25**, 623–628, 2008. Publication in Spanish.

# STUDY OF THE SIZE EFFECT IN A MODEL TO SIMULATE CONCRETE CRACKING DUE TO REBAR CORROSION AND COMPARISON TO ACCELERATED CORROSION TESTS

B. Sanz, J. Planas, J.M. Sancho

Dep. Ciencia de Materiales

Universidad Politécnica de Madrid, Spain

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# Outline

1. Introduction

2. Model of the oxide layer

3. Numerical simulations and size effect study

4. Crack pattern in accelerated corrosion tests

# Motivation

Main aspects of corrosion:

- Decrease in the net cross-sectional area
- Volumetric expansion of the oxide
- Cracking of the concrete cover and spalling

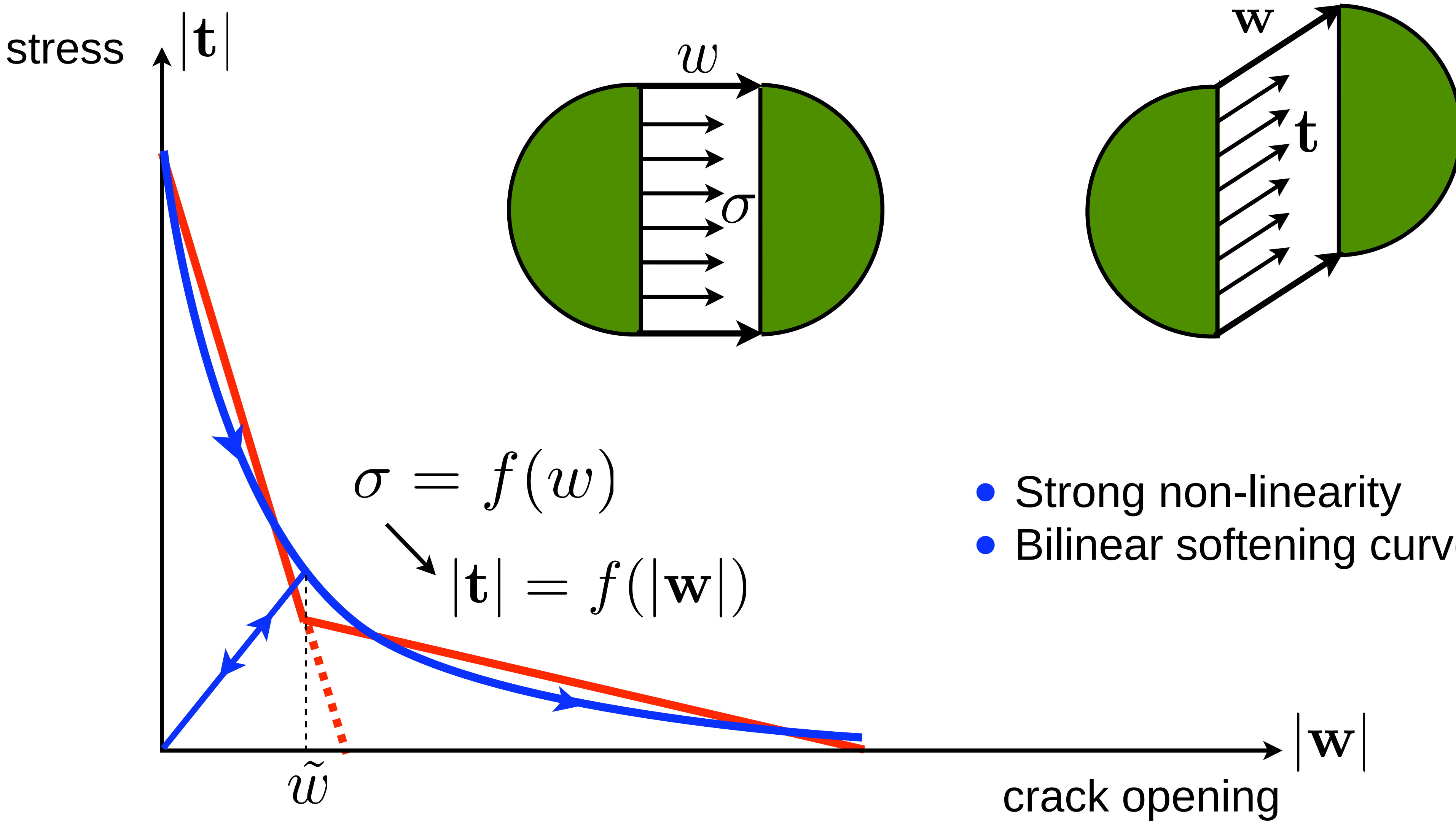
Objective:

- To predict the mechanical effects of the oxide over the concrete

Numerical model for the oxide

Expansive joint element

# Concrete craking: Standard cohesive model

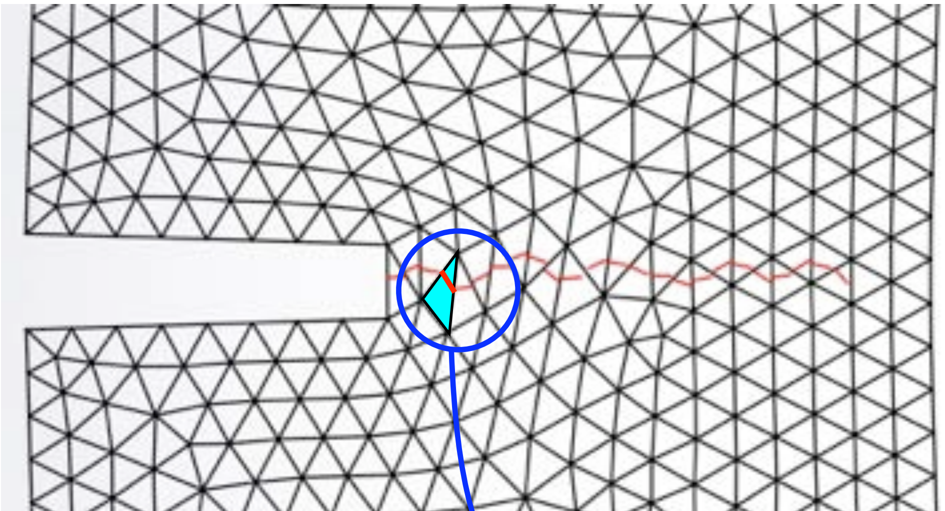



- Strong non-linearity
- Bilinear softening curve

$$\mathbf{t} = \frac{f(\tilde{w})}{\tilde{w}}\mathbf{w} \quad \text{with } \tilde{w} = \max(|\mathbf{w}|)$$

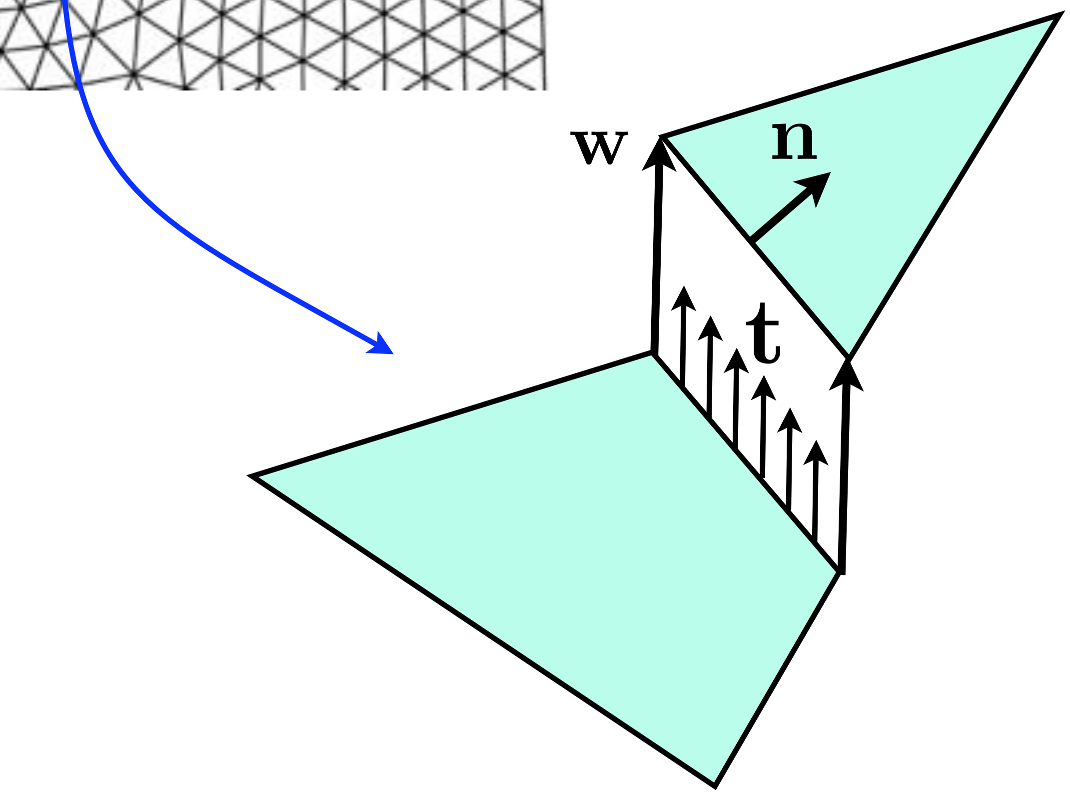
# Finite element program: COFE (Sancho et al, 2003)

*Continuum-Oriented Finite Elements*



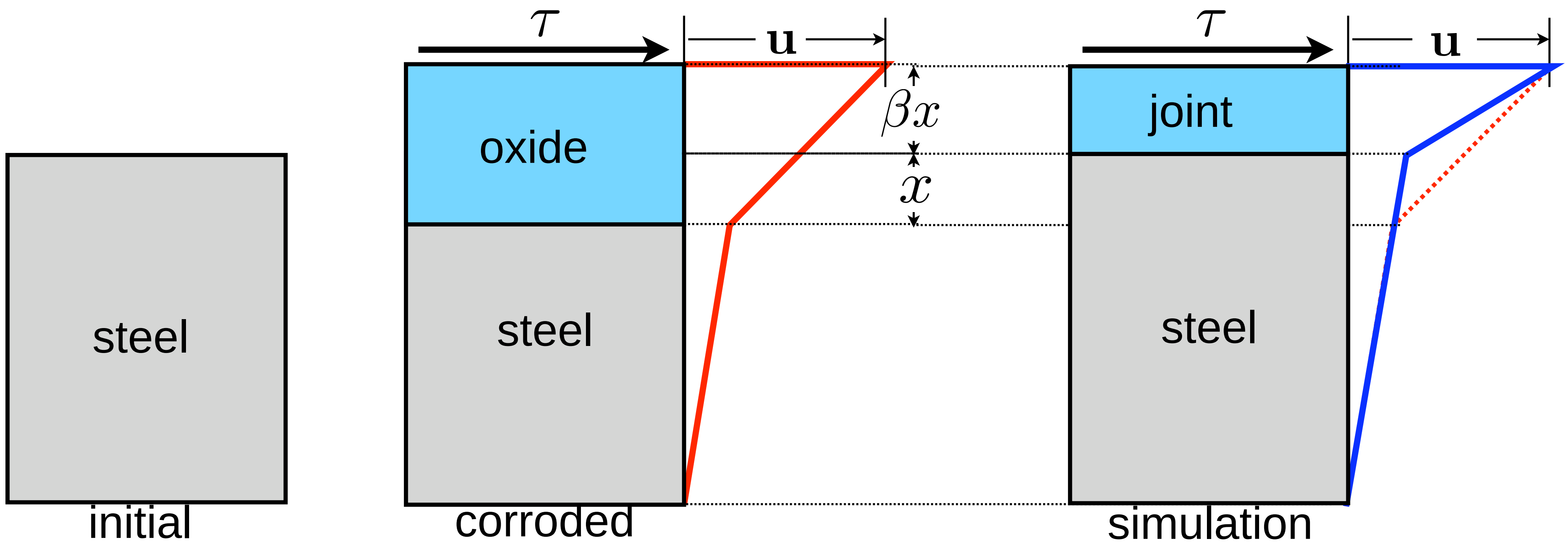
Adaptable embedded crack

- Strong discontinuity kinematics
- Constant strain elements
- Simple cohesive model
- Limited local crack adaptation



# Oxide layer: Expansive joint element

- The oxide is already forming
- The corrosion depth is given at any specified time



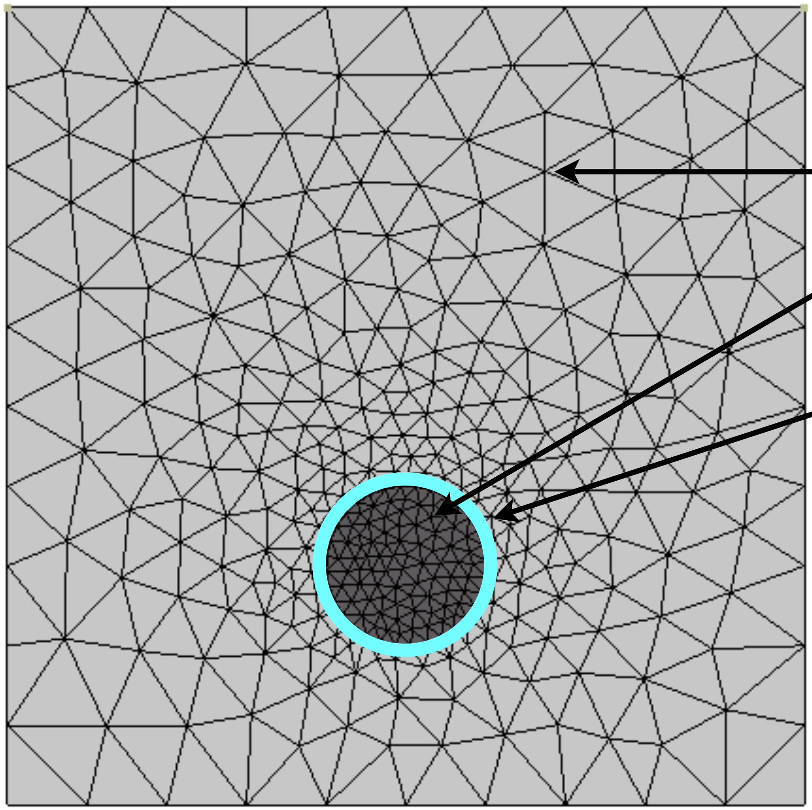

Mechanical equivalence oxide - element

- $k_t$ related to oxide & steel properties by a series-coupling
- $k_t$ is inversely proportional to x

Debonding ability

- *Nearly free sliding*: very small shear stiffness
- *Nearly free separation*: very small tensile stiffness

# Parameters of the simulations



Concrete: cohesive embedded crack

Steel: linear elastic

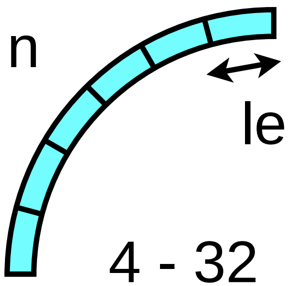
Oxide: expansive joint element

- GMSH (Geuzaine)
- Constant Strain Triangles

### Corrosion

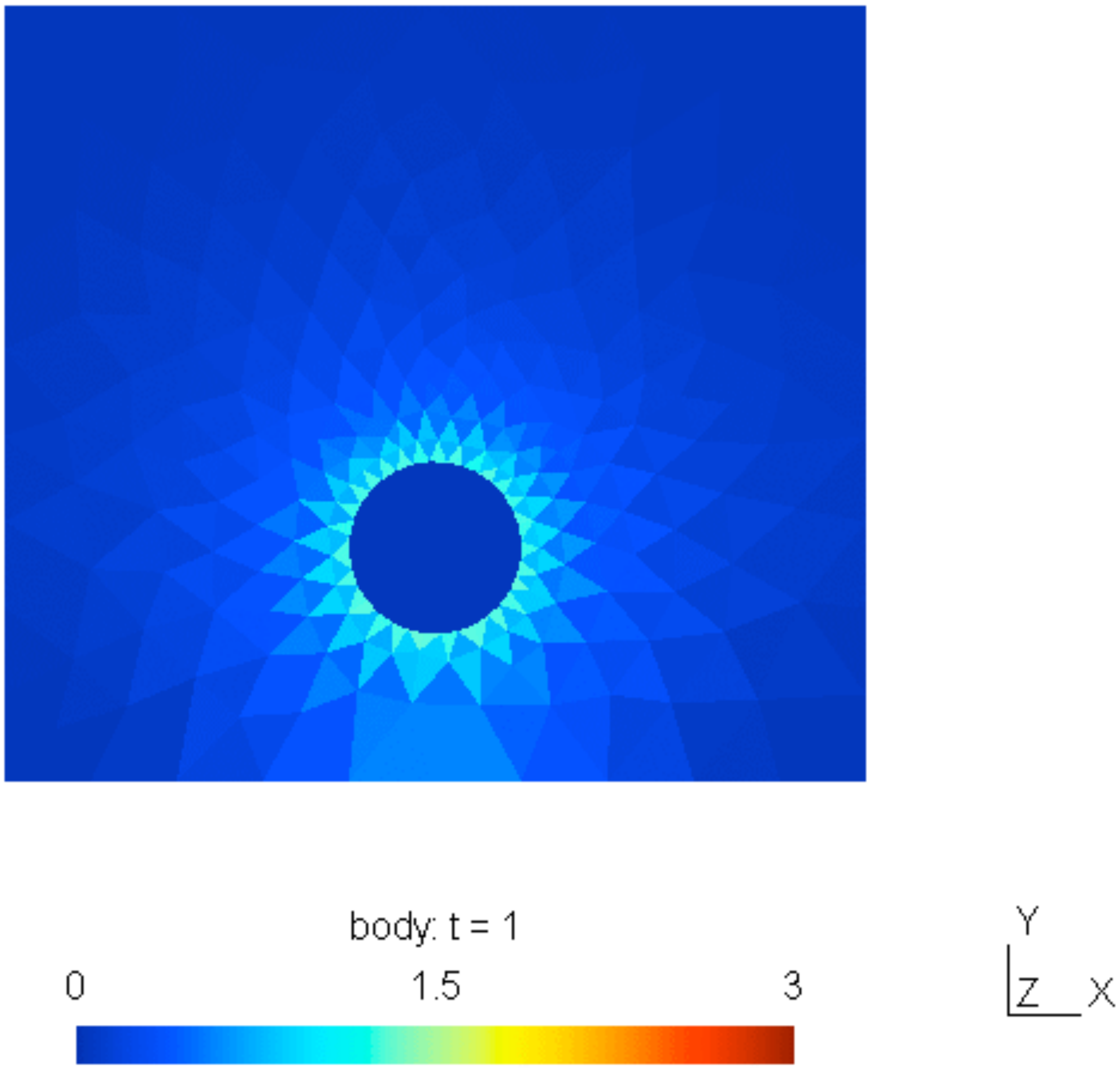
- Total radial expansion: 25 μm
- 50 steps

### Size effect study



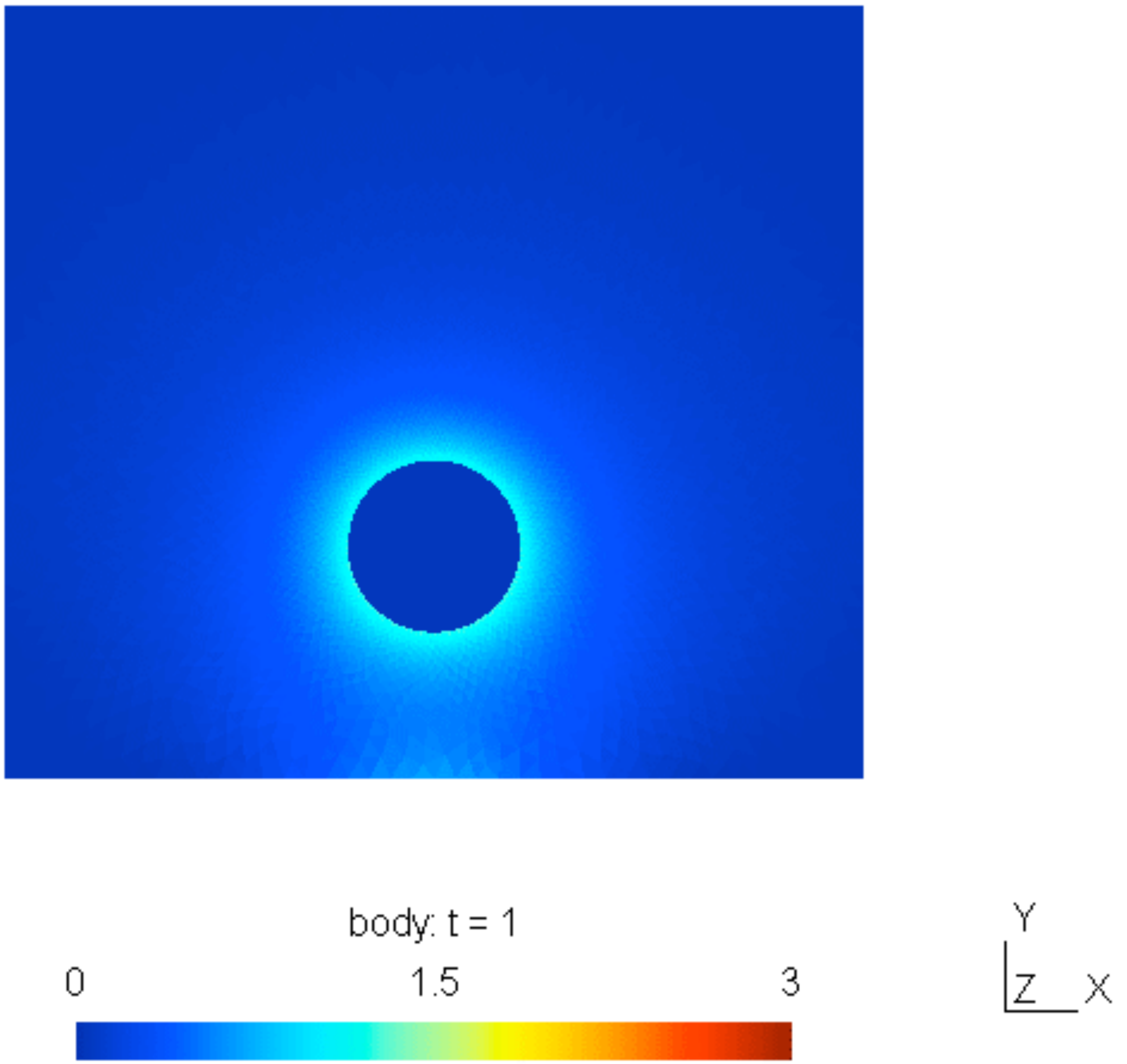
# Simulation 1. Coarse mesh

n = 8
(elem/quarter)

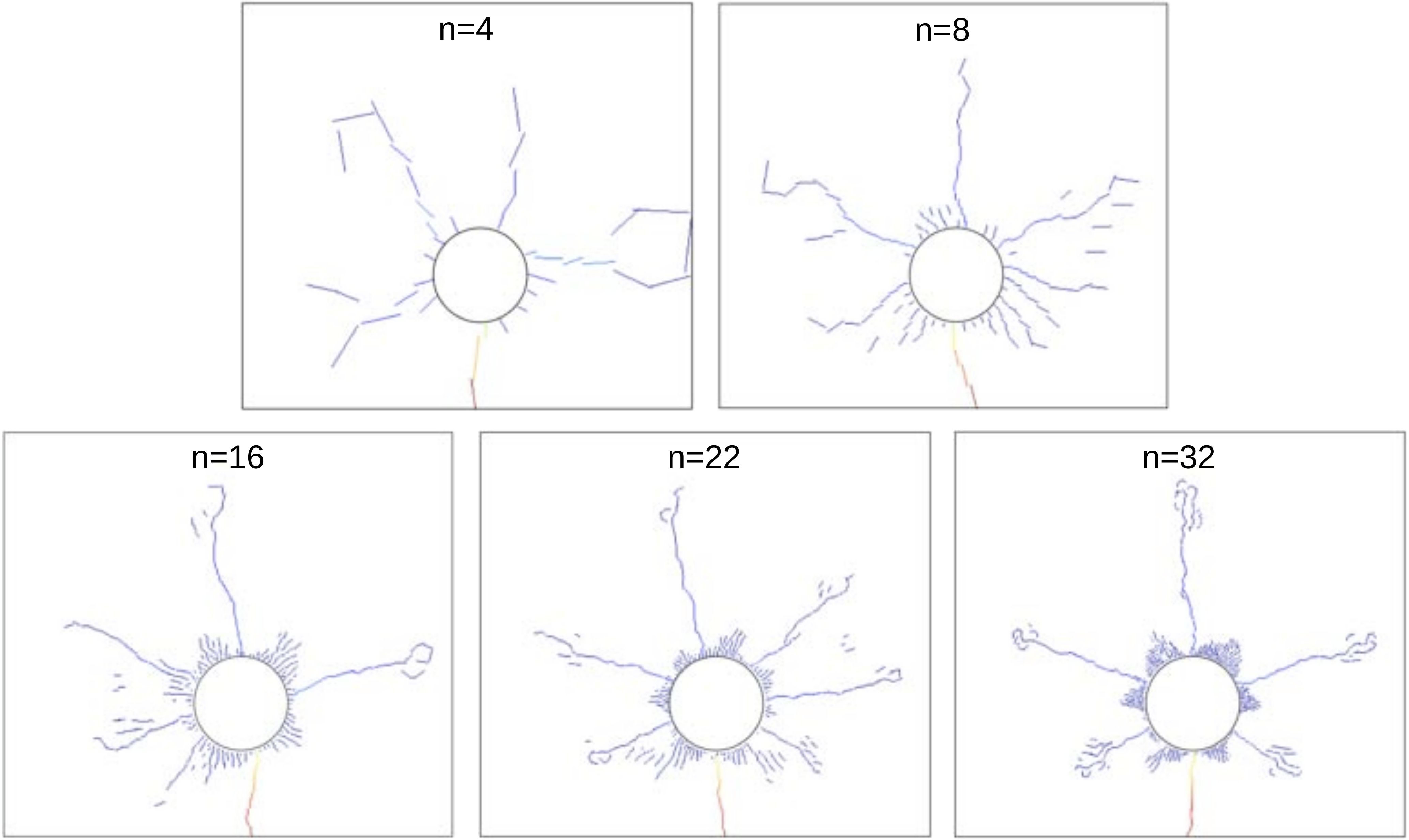


# Simulation 2. Fine mesh

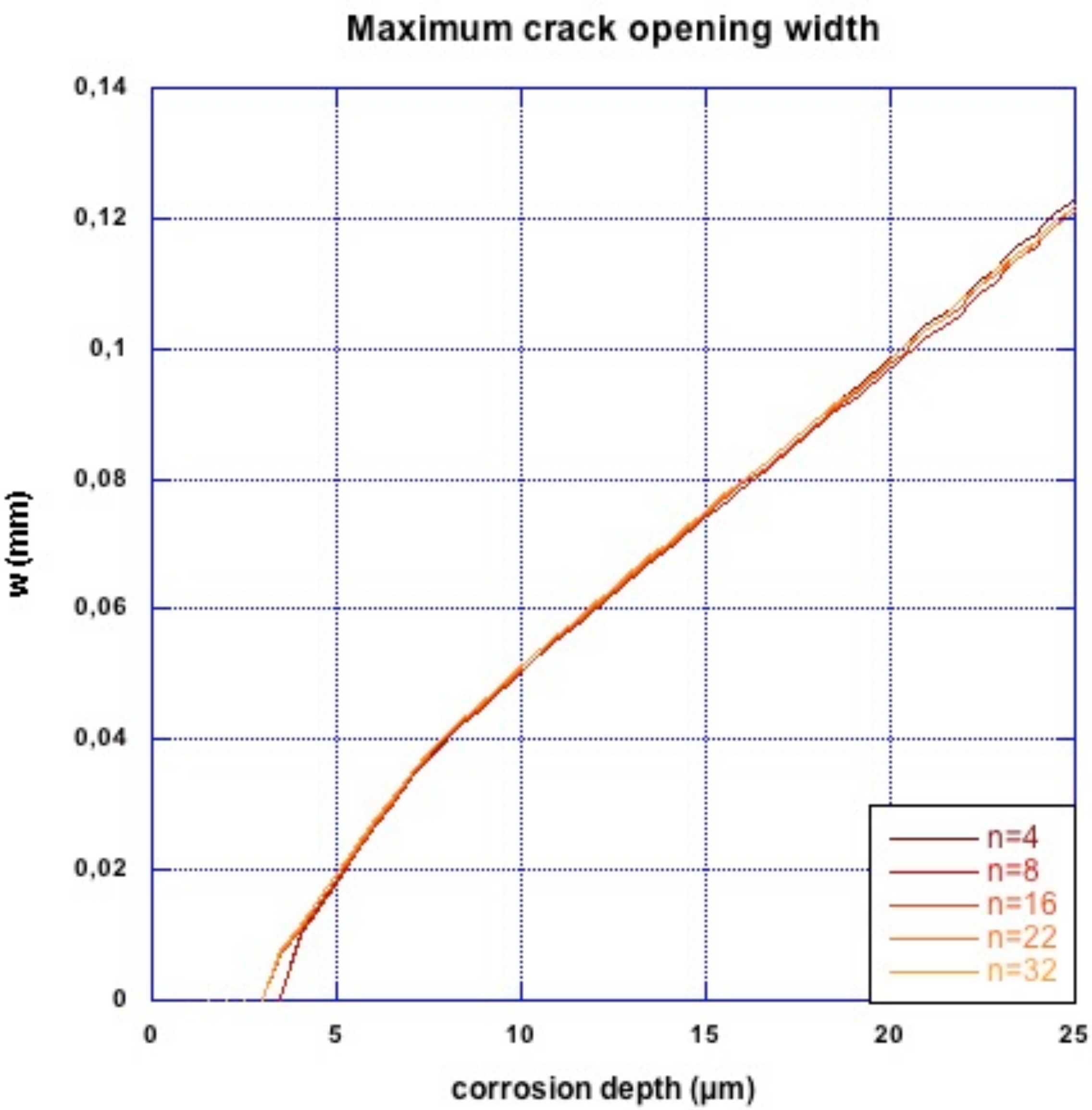
n = 32
(elem/quarter)



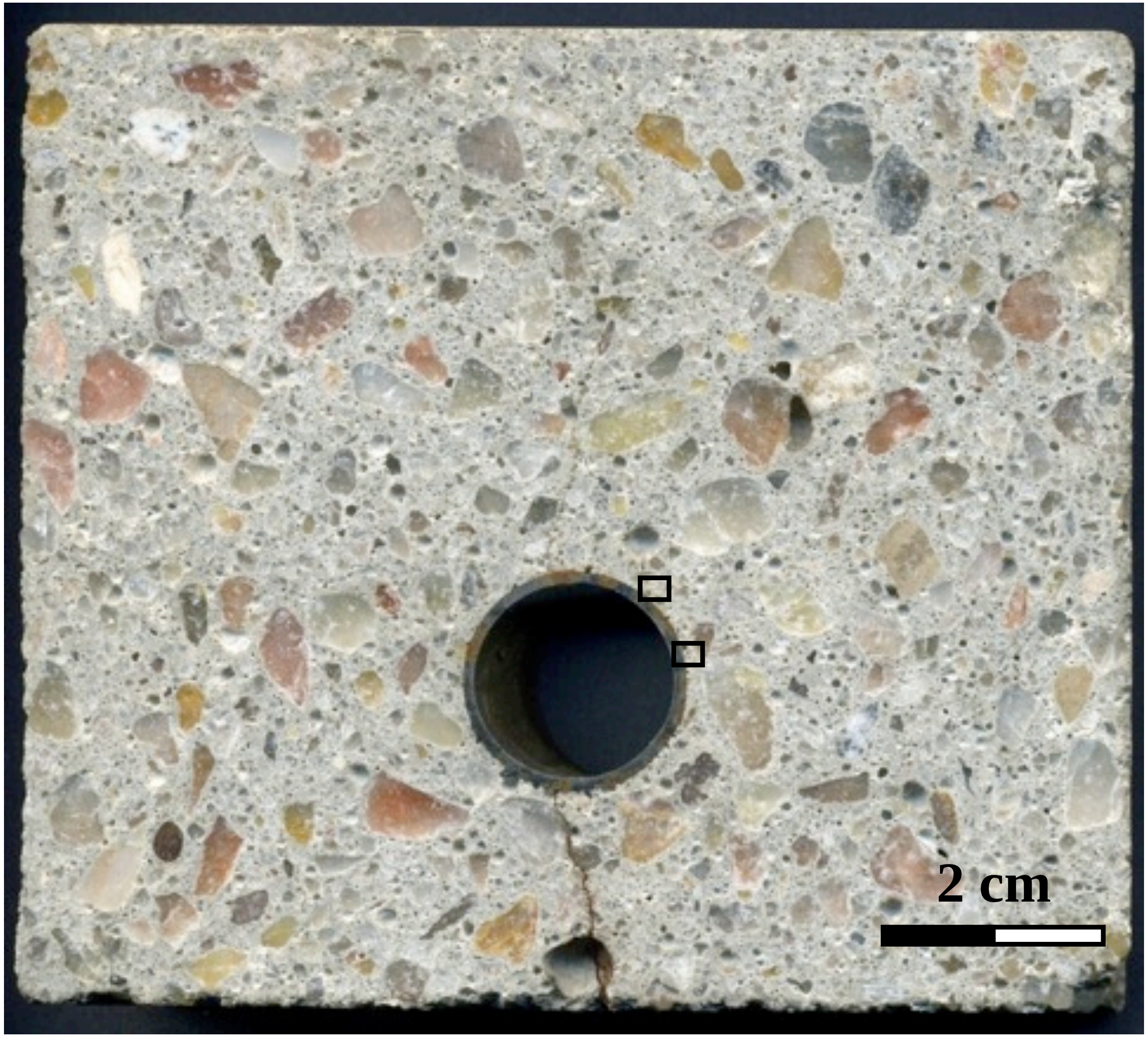
# Crack pattern in the simulations

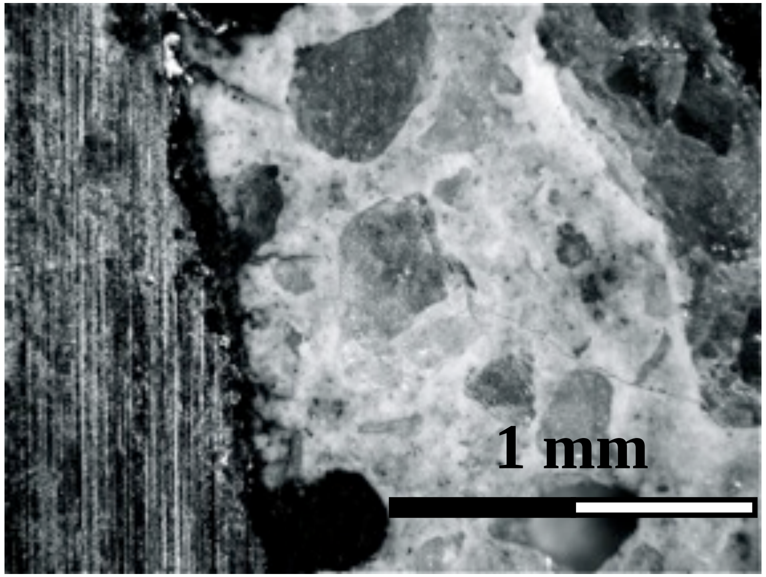


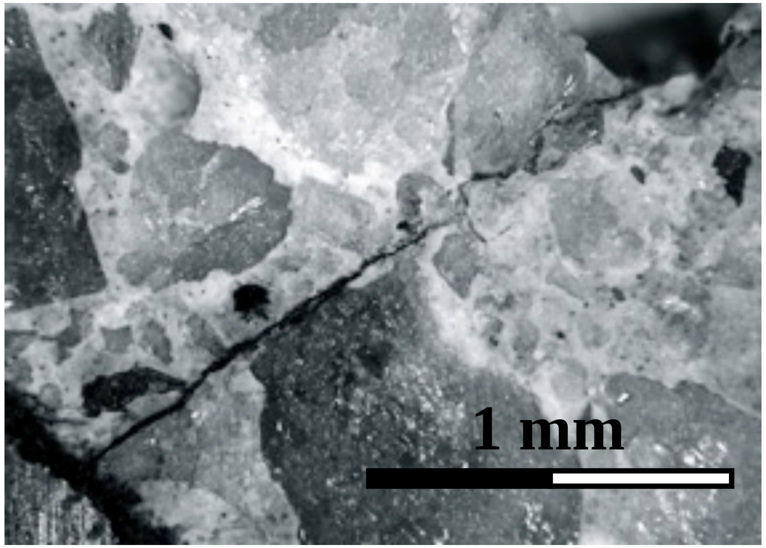
# Crack opening width vs corrosion depth



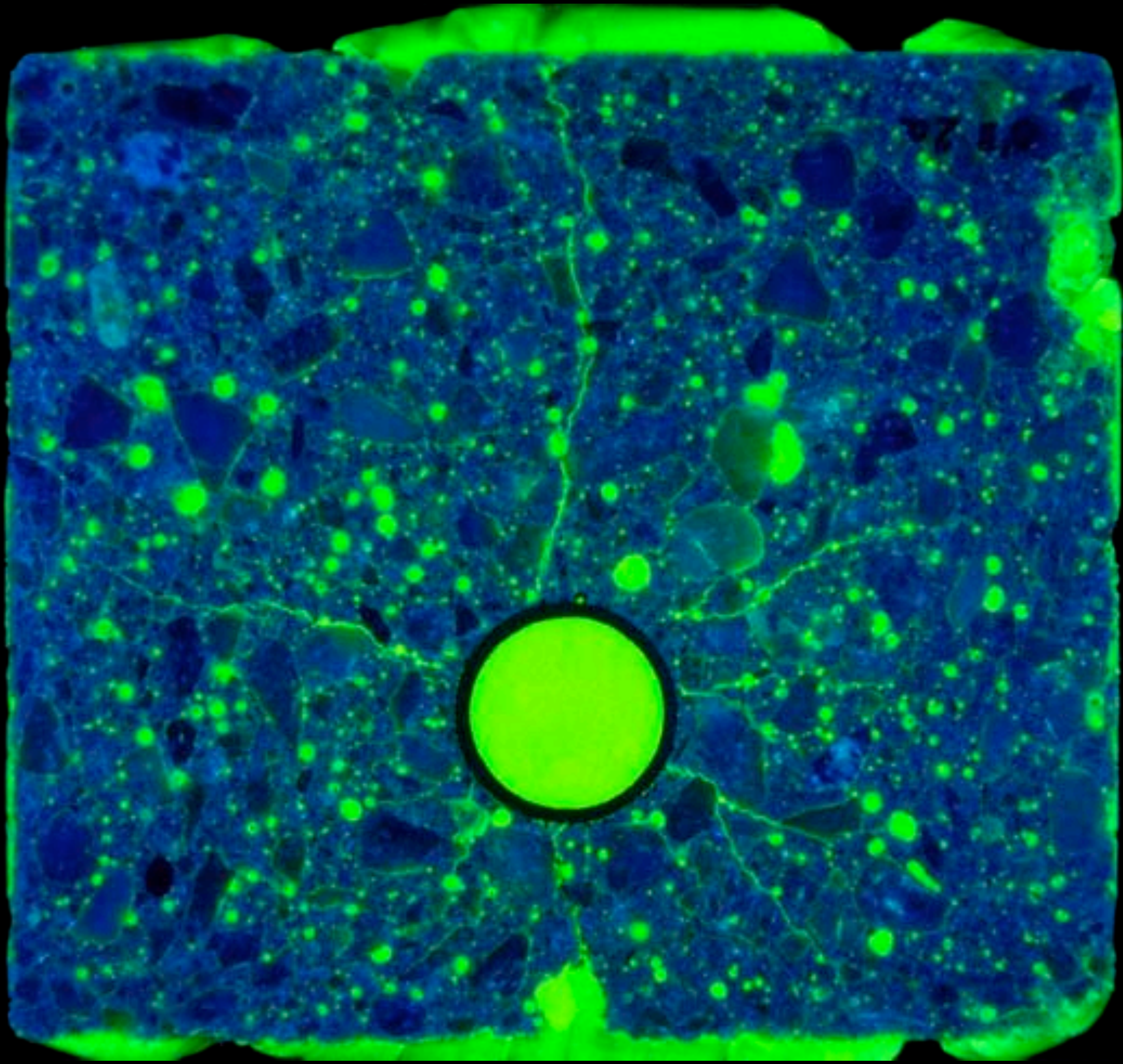
# Crack pattern in accelerated corrosion tests



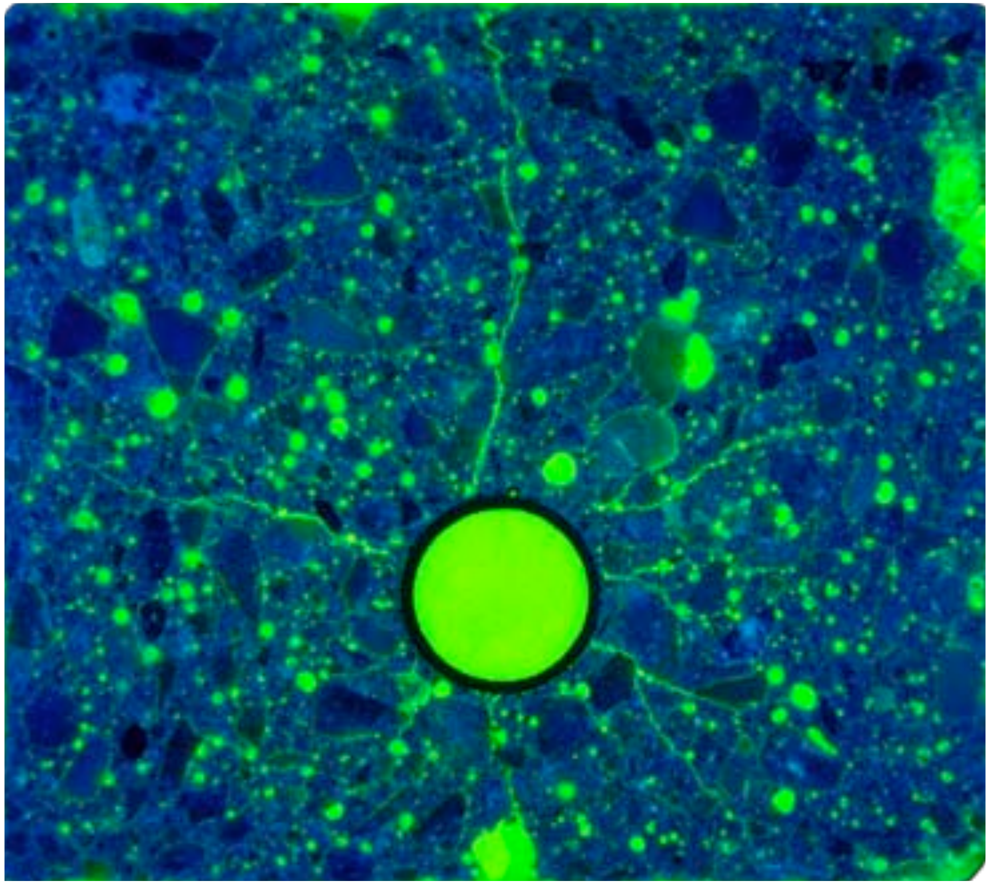



# Crack pattern in accelerated corrosion tests

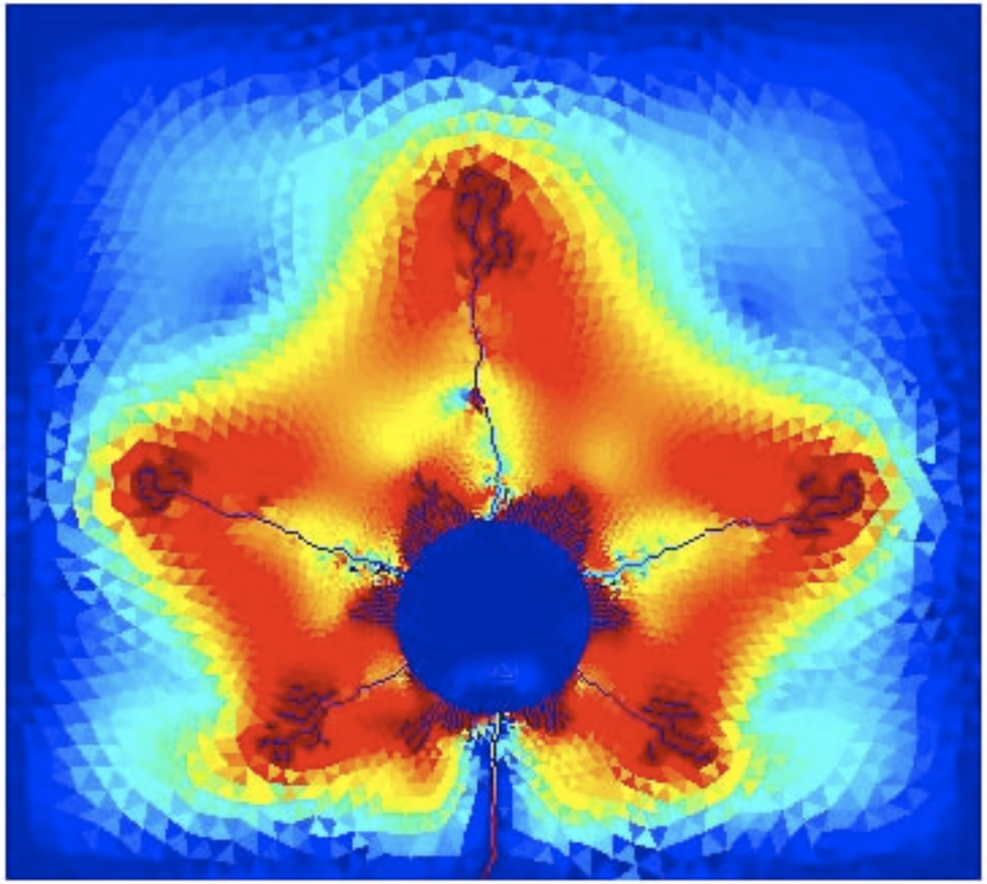


# Comparison of the crack pattern

Experimental pattern



Simulations pattern



# Summary

- A model called expansive joint element was programmed to simulate the oxide layer behaviour
- This model incorporates sliding and debonding effects to reach cracks localisation and to release the stresses in the steel
- The element size has not effect on the predictions of the crack width and the main crack pattern
- The overall crack pattern obtained numerically closely resembles the experimental cracks

Thank you for your attention