SMEARED VERSUS DISCRETE FAILURE ANALYSIS WITH APPLICATION TO PULL-OUT PROBLEMS-CONCLUDING REMARKS

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1 Motivation and Objectives

The description of cracking and failure within finite element analysis of quasi-brittle structures and materials such as concrete has led to two fundamentally different approaches: the discrete and the smeared crack methodology. Traditionally, they represent two distinct viewpoints: The discrete approach is based on the principles of fracture mechanics or fictitious crack concepts which require adaptive remeshing techniques when progressive failure is to be captured. The smeared approach is based on equivalent continuum concepts of elastic degradation and/or softening plasticity within the fixed mesh approach. In recent years, new developments such as mesh adaptation in smeared calculations, generalizations of the fictitious crack method with zero and finite thickness interfaces, as well as continuum elements with embedded cracks blur that well-defined separation. In addition, recent developments in localization analysis of weak and strong discontinuities and their interrelation with traditional crack models multiply the variety of failure analysis methodologies in quasibrittle structures and materials.

One of the important engineering applications is anchorage technology, in which the pull-out problem has been extensively studied with the aid of all these techniques. The workshop was intended to foster discussion and interchange on this hot topic from the theoretical, numerical, and the engineering point-of-view.

2 Workshop Agenda

The workshop developed in two parts: in the first part, three introductory papers were presented on the problem of anchor pull-out (R. Eligehausen, N. Bićanić and J. Nienstedt), which were followed by discussion; in the second part, four short presentations examined the differences between the discrete and the smeared crack approaches (J. Rots, J. Mazars, J. Červenka and I. Carol), which were followed again by discussion. The workshop was attend by 25 participants, as listed below.
The content of this summary is structured as follows: After the introductory remarks and the list of participants, the original transcript of the Recorder's notes is included, as well as a summary of one of the main topics which arose during the discussion: the round-robin test on anchor pull-out. Finally, the written contributions of the introductory presentations are enclosed for publication in Volume III of the FramCos 2 Proceedings.

3 List of Participants

Bakhrebah, Saleh
Bićanić, Nenad
Carol, Ignacio
Červenka, Jan
Červenka, Vladimir
Eligehausen, Rolf
Ghrib, Faouzi
Gylltoft, Kent
Hasegawa, Toshiaki
Irobe, Makoto
Jirásek, Milan
Larsson, Ragnar
Mazars, Jacky
Millard, Alain
Navi, Parvez
Nienstedt, Juergen

Ohlsson, Ulf
Phillips, David
Polanco-Loria, Mario
Pukl, Radomir
Rots, Jan G.
Uchida, Yuichi
Weihe, Stefan
Willam, Kaspar
Zeitler, Ralf

4 Transcript of the Recorder

Introductory Presentation:

Kaspar Willam (CU–Boulder): *"Failure Analysis in Concrete"*

- Smeared models
- Discrete models
- Embedded crack models

Part I - Physical Problems of Anchor Pull-Out

1. Rolf Eligehausen (IWB Univ. Stuttgart): *"Behavior of anchor bolts in concrete"*
   - Physical behavior
   - numerical examples
   - tests up to embedment depth of 520 mm
   - calculated up to embedment depth of 2500 mm
   - stable crack growth
   - deciding is fracture energy, tensile strength minor effect
2. Nenad Bićanić (Univ. Glasgow): *"Pullout failure mechanisms in concrete"*
   - five parameter model for tensile softening
   - RILEM round robin (axisymmetric)
   - acoustic tensor analysis
   - discontinuity surface
   - pull-out of curved bar, also in 3D
3. John Nienstedt (Hilti Schaan): *"Application of FEM to anchoring technology in concrete"*

- working principles of the anchor
  - friction
  - keying
  - bonding
- failure mechanisms
- FIXANA - smeared rotating crack based FEM program, axisymmetrical
- results for headed anchors and bonded anchors

Discussion to Part I:

Rots:

- which smeared model is the best (MP, plasticity, smeared)

J. Cervenka:

- RILEM round robin
- relevance of 2D pull-out tests to the practical applications

Eligehausen:

- RILEM round robin - large scatter of results
- discrepancy of the models and practical needs: plane or axisymmetrical group of anchors near to an edge
- models - for parametric study
- MP - mesh insensitivity

Willam: 3D - axisymmetrical in pull-out

Rots: smearing of the radial crack in axisymmetry

Nienstedt:

- study + verification with experiments
- changes in the anchor design - positive or negative
- mesh sensitivity - fitting the mesh, optimization of the model

Eligehausen: improvements of crack band model

V. Cervenka: importance of crack band implementation

Part II - Basic Issues of Discrete vs. - Smeared Failure Analysis

4. Jan Rots (TNO Delft): *"Comparison of smeared and discrete solution strategies"*

- distributed fracture in reinforced concrete $\longrightarrow$ smeared model (cooling tower)
- discrete cracks (brick wall, concrete) - try to apply smeared models
- practical applications: interface element, predefined crack (engineering judgement)
- evaluation of RILEM round robin - variety of models principal conclusions:
    - large scatter (also in experiments)
    - learned a lot
- important points:
    - softening not specified, very important
    - boundary conditions
    - compression nonlinearity
    - mesh alignment
- future possibilities for benchmarks:
    - simple mode-I fracture
    - model problem: fixed material parameters
    - arbitrary FE mesh

5. Jacky Mazars, G. Pijaudier-Cabot (ENS–Cachan): *"Bridges between damage and fracture mechanics"*
    - equivalent crack - equivalent damage zone
    - equivalent crack concept (damage to fracture)
        - thermodynamic comparison: damage and fracture
        - damage - up to the peak
        - fracture mechanics - after the peak (descending branch)
    - fracture energy and nonlocal damage (fracture to damage)
        - quasi homogeneous $\longrightarrow$ bifurcation $\longrightarrow$ localization (damage parameters, characteristic length)
        - deduce fracture energy, size effect law
6. Jan Cervenka (consulting and CU Boulder): *"Discrete fracture analysis of pullout problems"*
    - RILEM round robin
    - discrete crack model with interface cohesive zone with dry friction
    - adaptive mesh adjusting
    - discrete cracks more brittle

7. Ignacio Carol (ETSECCPB–UPC Barcelona): *"Fundamental topics in smeared and discrete failure analysis"*

- critical failure condition on a plane:
  - discrete - introduction of interface element
  - smeared - multicrack approach (Q-analysis)

Discussion to Part II:

Weihe:

- difference between discrete and smeared cracks are the kinematics (interface elements) vs. continuum elements
- acoustic tensor includes kinematics (jump)
- associated and non-associated flow rules
- potential for smeared crack approach - improve kinematics

V. Cervenka:

- difference between theory and practical application
- problem are to be solved now with available methods
- future development - should follow the theory

Rots: practical point of view

Larsson:

- for practical applications, computer codes for discrete cracks become too complicated

Bićanić:

- different elements with different kinematics $\longrightarrow$ different localization behavior

Willam:

- capturing capabilities of different elements, especially in shear
- nonlocality of FEM
- weak discontinuity require alignment of traditional elements or enrichment

J. Cervenka:

- embedded crack formulation most satisfy interelement continuity

Rots:

- high-order elements
- geometrical discontinuity
- microcracking - discrete final crack (discrete phenomena)

Willam:

- question of benchmarks
- simply enough and with relevance to engineering practice

Rots: RILEM round robin - comparison of models

Eligehausen:

- simple benchmark - results known in advance
- predictive benchmarks
- reinforcement included + concrete in compression
- splitting failure
- tensile bar - large, small cover
- bonded anchor pull-out
- tests afterwards

Rots:

- both ways, predefined mesh
- displacement boundary conditions affected more as load
- problems with boundaries, slip law

Nienstedt: interests in bonded anchors

Willam: ACI benchmarks:

- Brazilian test
- concrete shear test (Iosipescu beam)
- confined compressed column + cyclic loading
- deep beams without shear reinforcement (Walraven)
- academic pull-out problem

Mazars:

- tests afterwards
- well defined boundaries, material parameters - problem
- results from material tests

Bićanić, Rots, Phillips: support this

Willam: conclusions

- benchmark should be prepared
- simple enough, realistic and practical

5 Lessons of RILEM TC-90 Round-Robin Benchmark

Anchorage technology is an important engineering field. The single headed stud pulled out from a concrete block has been extensively studied in the past with the aid of all above mentioned techniques. An anchor pull-out benchmark was proposed by RILEM TC-90 as a Round Robin problem for plane stress and axisymmetric analysis. Comparable specimens were tested afterwards and the test results were not known in advance. Examples with proposed geometry, material properties and boundary conditions were simulated by several researchers using available non-linear techniques. Some of these results were presented during the workshop.

The experience from the above Round-Robin analysis was discussed on the workshop and can be summarized as follows:

- The evaluation of the results showed the current state-of-art in the non-linear finite element modeling of concrete.
- A very large scatter of results of the different FE models was observed.
- The most important factors influencing the results were, beside the material model and FE code used, the analyst her/himself and her/his experience with non-linear modeling.
- The results of the study were significantly influenced by: modeling of the boundary conditions, the quality of the finite element mesh, and the interpretation of the underlying material assumptions (especially the softening behavior, which was not explicitly stated in the problem definition).
- Most of the solutions were obtained using smeared crack models, and therefore no objective comparison between the discrete and the smeared crack models could be drawn.
- The educational importance of the RILEM Round-Robin benchmark was stressed repeatedly. The experience from this Round-Robin study should help to prepare future benchmark problems.

The heterogeneity of the RILEM Round-Robin results indicate that the benchmark problem was too complicated for comparison of the different FE models. On the other hand, from the practical point of view, this benchmark, with a single anchor embedded into a concrete block, was too simple. The two-dimensional non-linear analysis should be extended to three dimensional problems, such as groups of anchors near to an edge of a concrete specimen.

Due to this dichotomy of opinions, two levels of validation for the non-linear material models were proposed: 1) simple benchmarks to test and validate the FE models, and 2) complex benchmarks to further engineering insight. Simple benchmarks should be modest examples with well defined and generally accepted material behavior, which should serve for evaluation of the model response under basic loading conditions. They should be used by the material model developers as well as by the potential users for testing material model properties.

The complex benchmarks should be relevant to the engineering practice, and their aim should be to limit the range of applicability of material models.These benchmark problems should be predictive, but corresponding experiments should be performed afterwards to ensure an objective evaluation of the numerical results. The pull-out of a bonded anchor, as an example for such a complex benchmark in anchoring technique, was proposed at the workshop.

The basic requirement for the future benchmarks is a "clear definition" of the problem. Special care should be taken in obtaining the material properties and description of the geometry including boundary conditions. In order to reduce the computational scatter of results, the load increment, convergence criteria and the finite element mesh should be prescribed in advance, at least for one fundamental reference case.