Institute for Materials and Structures – Vienna University of Technology

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The Vienna University of Technology was founded in 1815 as the „Imperial-Royal Polytechnic Institute“. Currently, some 26,000 Students (19% foreign students, 30% women) study at eight faculties related to engineering and natural sciences, employing more than 4,000 staff member including 1,800 academics.

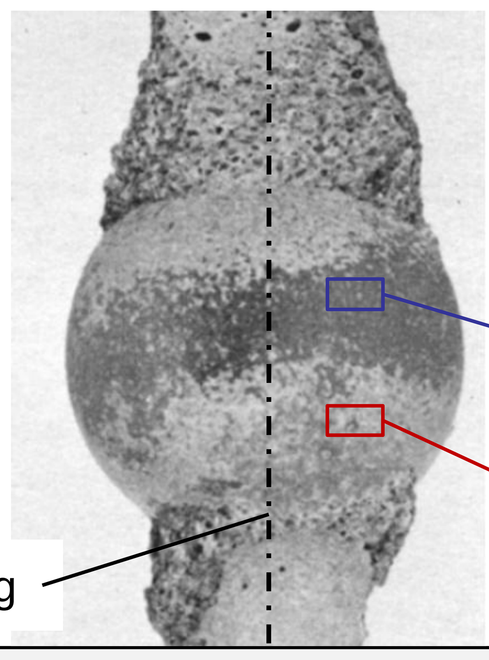
Research work at the Institute for Mechanics of Materials and Structures, at the faculty of Civil Engineering, is characterized by a synthesis of experiment, theory, and numerical simulation, in order (i) to study the mechanical behavior of hierarchically organized materials such as cementitious materials, wood, bone, and biomimetic media, and (ii) to apply developed constitutive models to structural analysis.

PARTNER PROJECT 29: Poromechanics of Cement Paste

ITZ-Induced Crack Initiation in Concrete: A Micromechanics Approach

Crack Initiation in Concrete

During monotonous increase of mechanical loads, **microcrack initiation** is observed within the interfacial transition zone (**ITZ**). These typically 15 microns thick domains [1] are **more porous** and, therefore, provide less stiffness and strength as compared to the bulk cement paste [2].
The exact location and the related failure mechanism of ITZ cracks are still unclear, but their understanding is a key for modeling the nonlinear stress-strain behavior of concrete. Noteably, the crack initiation in concrete corresponds to the **elastic limit** of the material.



Inspection of post-failure fragments after failure under uniaxial compression of concrete [3] allows for a posteriori identification of two possible failure mechanisms for ITZ cracks:

clean aggregate's surfaces
→ ITZ-aggregate separation

Residues on aggregate's surfaces
→ ITZ failure

Microscopic Failure Criteria

Relying on experimental observations two microscopic tensile failure criteria for crack initiation in concrete were developed:

ITZ-aggregate separation:

$$\boxed{f_{\mathcal{I}^{ITZ}_{agg}}(\mathbf{\Sigma}) = \max_{\underline{x}} T_r(\mathbf{\Sigma}, \underline{x}) - T_r^{ult} \leq 0}$$

ITZ failure:

$$\boxed{f_{ITZ}(\mathbf{\Sigma}) = \max_{\underline{x}} \sigma_{ITZ,I}(\mathbf{\Sigma}, \underline{x}) - \sigma_{ITZ}^{ult} \leq 0}$$

$\mathbf{\Sigma}$ . . . macroscopic stress
$\underline{x}$ . . . position vector
T_r . . . radial traction
T_r^{ult} . . . separation strength
$\sigma_{ITZ,I}$ . . . largest principal ITZ stress
σ_{ITZ}^{ult} . . . ITZ cohesion strength

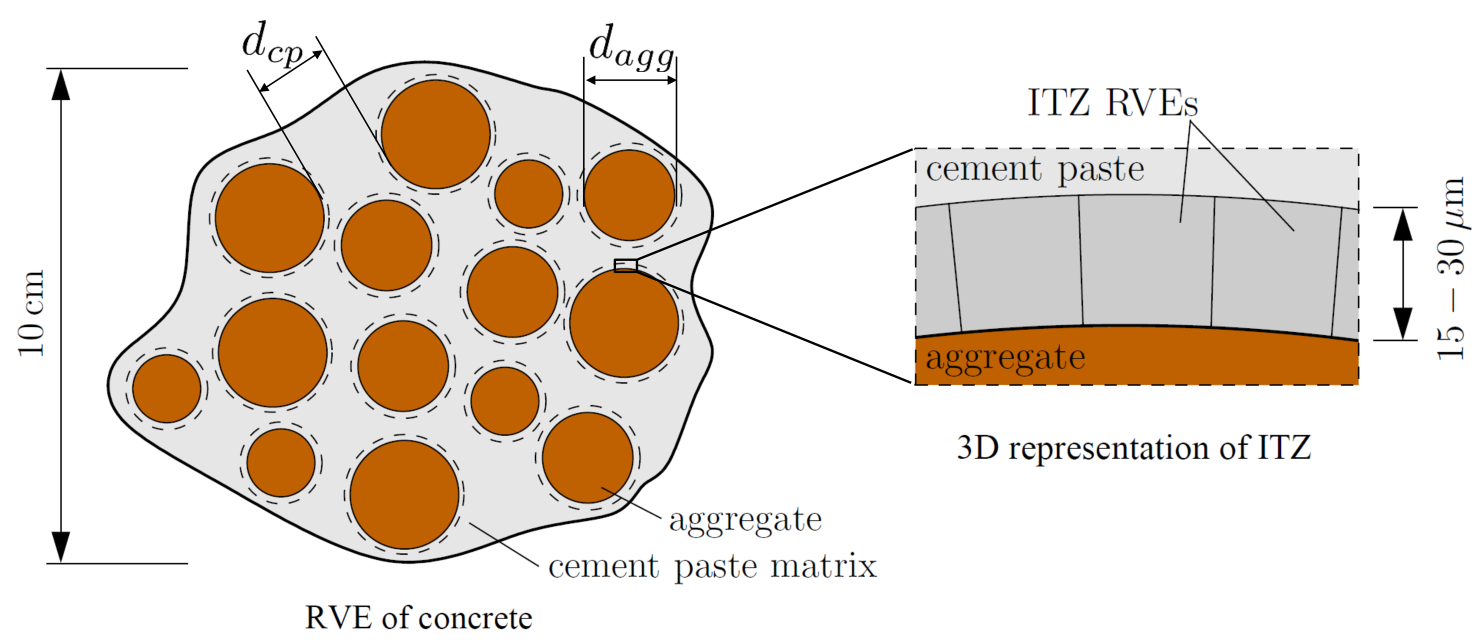
The two failure criteria are combined, in order to identify the governing failure mode for initiation of cracks:

combined criterion:

$$\boxed{f_{comb}(\mathbf{\Sigma}) = \max\left\{f_{\mathcal{I}^{ITZ}_{agg}}(\mathbf{\Sigma}); f_{ITZ}(\mathbf{\Sigma})\right\} \leq 0}$$

The failure criteria require access to traction vectors acting on aggregates' surfaces and to the stress states within the ITZs. This is provided by an analytical 2-scale **continuum micromechanics model.**

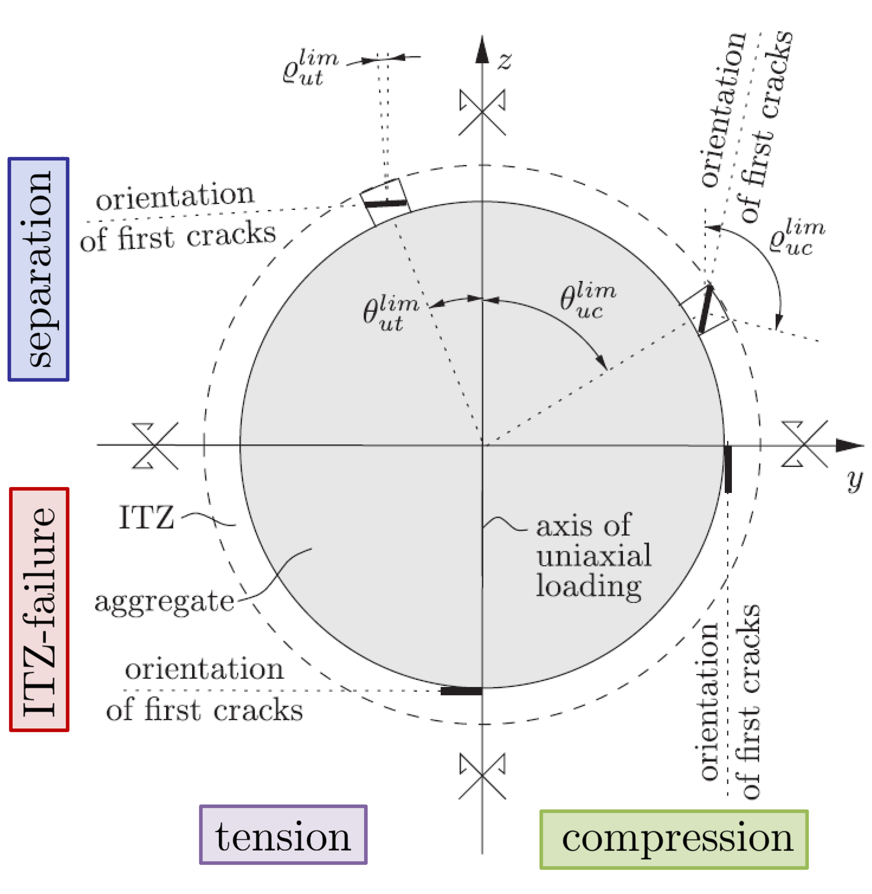
Micromechanics Model



- According to **scale-separation-principle** [4], ITZ thickness is negligible as compared to aggregate distance/diameter, $t_{ITZ} \ll \{d_{cp}\,;\,d_{agg}\}$
  → 2D interphase phase on concrete RVE
  → 3D representation on micrometer-scale
- **stress concentration relations** for elastic phase stresses

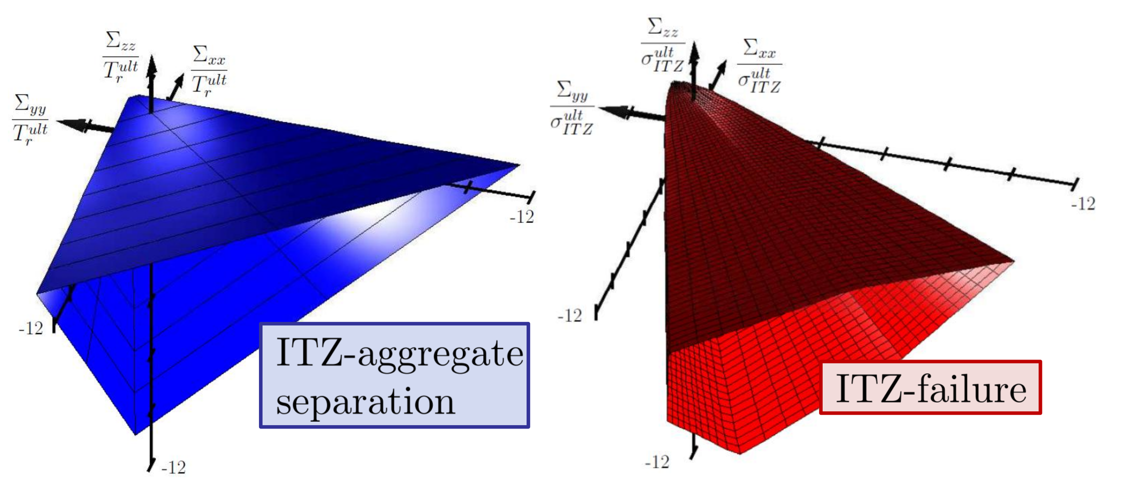
$$\boldsymbol{\sigma}_{agg} = \mathbb{B}_{agg} : \mathbf{\Sigma} \quad \ldots \text{ macro-to-micro} \quad \Rightarrow \boxed{T_r}$$
$$\boldsymbol{\sigma}_{ITZ}(\underline{x}) = \mathbb{B}_{ITZ}^{agg}(\underline{x}) : \boldsymbol{\sigma}_{agg} \quad \ldots \text{ aggregate-to-ITZ} \quad \Rightarrow \boxed{\sigma_{ITZ,I}}$$

Results: Initial Cracks



Results: Elastic Limits

Upscaling of microscopic failure criteria by applying the stress concentration relations yields **elastic limit surfaces** of typical concretes in macroscopic principal stress space. Elastic macroscopic stress states are on or within the pyramids.



Conclusions

Comparison of model-predicted elastic limits with experiments (available in the literature) imply:

- **Compression**-dominated macroscopic loadings: **ITZ failure** governs crack initiation,
- **Tension**-dominated macroscopic loadings: **separation** and **ITZ failure** are possible
- ITZ-aggregate separation strength is larger than 50% of ITZ cohesion strength

References

[1] Scrivener et.al.; Interface Sci. 12[4] 411–21 (2004)
[2] Mondal et.al.; Nanotechnology in Constr. 3. 315–20 (2009)
[3] Perry and Gillott; Cem. Concr. Res., 7 [5] 553–64 (1977)
[4] Zaoui; J. Eng. Mech., 128[8] 808–16 (2002)

Corresponding papers

Königsberger, M., Pichler, B., Hellmich, C.; *Micromechanics of ITZ–Aggregate Interaction in Concrete: Part I: Stress Concentration. Part II: Strength Upscaling;* Journal of the American Ceramic Society, 97: 535–551 (2014), DOIs: 10.1111/jace.12591 and 10.1111/jace.125606