Adatlap[1] témahirdetési javaslathoz
a Csonka Pál Doktori Iskola Tanácsa részére

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Téma címe (magyar és angol nyelven):
Vasbeton tartók repedésképei
Fracture patterns of concrete structures

A **téma** rövid leírása[4] (magyar és angol nyelven):

A vasbeton szerkezetek a beton korlátozott húzószilárdsága miatt hajlamosak repedésre. A vasbeton szerkezet tervezésének meghatározó eleme a repedések viselkedésének (a repedés irányának, megnyílásának) kontrolállása. Meglévő szerkezeteknél a repedéskép, beleértve a repedések megnyílását fontos információt hordoz a szerkezet jelenlegi és múltbeli terhelésével kapcsolatban. Jelen kutatás célja a feszítés nélküli és feszített tartók (gerendák, lemezek) repedésképeinek számítására szolgáló eljárás kidolgozása és a repedésképek elemzése.
Kizárólag kvázi-rideg anyagokkal (elsősorban beton) foglalkozunk, az analitikus és numerikus vizsgálatokhoz a rideg törés variációs alapú megközelítéséből indulunk ki, azt a betonacél és a beton közötti tapadást leíró törvénnyel egészítjük ki. A vonatkozó irodalom hangsúlyozza, hogy a variációs megközelítés kiválóan alkalmas több repedés egyidejű, egymást befolyásoló növekedésének vizsgálatára. A kutatási terv néhány egyszerű problémát vet fel, ezek az új modellel vizsgálhatóak. A problémák elemzése új adatokat szolgáltat az elmélet továbbfejlesztéséhez és segíti a tartószerkezeti szakértőket a repedésképek mélyebb megértésében.

Due to the limited tensile strength of concrete, reinforced concrete [RC] structures are prone to cracking. In the design phase of an RC structure, it is essential to controll the cracking process (i.e. direction and opening of the crack). In the case of standing structures the cracking pattern, including the opening width of the cracks carries crucial information about the present and past loading of the structure. Present proposal aims to develop a method to compute the cracking patterns of RC strurctures (beams and plates, with and without prestress alike) and study the emerging fracture patterns.
We consider solely quasi-brittle materials (mainly concrete), for the analytical and numerical analysis we build on the variational approach to brittle fracture and extend it with a law to describe the bonding between the rebars and the concrete matrix. The literature on variational brittle fracture emphesizes that the method is capable to investigate the mutually influenced growth of multiple cracks. The research proposal addresses some simple problems to be investiagted by the new model. Analysis of these problems is expected to provide new data to improve the theory and helps structural consultants in deeper understaning of fracture patterns.

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[1] Az adatlapot egy példányban *kinyomtatva és aláírva* a Szilárdságtani Tanszék titkárságára, *elektronikus változatban* pedig a Doktori Iskola titkárának (B.Kóródy Anna, korody@eik.bme.hu) kell eljuttatni. A témahirdetés elfogadása esetén az adatlap felkerül a Csonka Pál Doktori Iskola (http://www.szt.bme.hu/index.php/oktatas/csonka-pál-doktori-iskola), a témahirdetés rövid leírása pedig az Országos Doktori Tanács (http://www.doktori.hu/)honlapjára.
[2] A témahirdetés elfogadása automatikusan a témavezető akkreditációját is jelenti az azévi felvételi eljáráshoz.
[3] Kérjük, olyan elérhetőséget adjon meg, ahová biztonsággal küldhetünk hivatalos értesítéseket.
[4] A téma rövid leírása (szóközökkel) 1000-3000 leütés hosszú. A jelentkező hallgatókat bővebben tájékoztató változatot, (mely a téma fent megadott releváns nemzetközi irodalmára tételesen hivatkozik) kérjük a mellékletben megadni.

A **téma** meghatározó irodalma[5]:

- Francfort G.A., Marigo J.J. 1998. Revisiting brittle fracture as an energy minimization problem. *J.Mech. Phys. Solids*, **46** p. 1319
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- Lancioni G., Royer-Carfagni G. 2009. The variational approach to fracture mechanics. a practical application to the french *Panthéon* in Paris. *J. Elasticity* **95** p. 1
- Miehe C., Welschinger F., Hofacker M. 2010. Thermodynamically consistent phase-field models of fracture: Variational principles and multi-phase FE implementations. *Int. J. Num. Methods Eng.* **83** p. 1273
- Farhidzadeh A., Dehghan-Niri E., Moustafa A., Salamone S., Whittaker A. 2013. Damage Assessment of Reinforced Concrete Structures Using Fractal Analysis of Residual Crack Patterns. *Exp. Mech*. **53**(9) p. 1607
- Wu JY., Cervera M. 2016. A thermodynamically consistent plastic-damage framework for localized failure in quasi-brittle solids: Material model and strain localization analysis. *Int. J. Solids & Struct*. **88-89** p. 227
- Ulloa J., Rodríguez P., Samaniego C., Samaniego E. (2019) Phase-field modeling of fracture for quasi-brittle materials. *Underground Space* **4**(1) p. 10

A **téma** hazai és nemzetközi folyóiratai[6]:

- International Journal of Solids and Structures (Sci)
- International Journal of Numerical Methods in Engineering (Sci)
- International Journal of Nonlinear Mechanics (Sci)
- Journal of Elasticity (Sci)
- Journal of the Mechanics and Physics of Solids (Sci)
- Experimental Mechanics (Sci)
- Scientific Reports (Sci)
- Concrete Structures / Vasbetonépítés
- Építés és Építészettudomány (Scopus)

A **témavezető** fenti folyóiratokban megjelent 5 közleménye:

- András A Sipos, PL. Várkonyi.: The longest soft robotic arm INTERNATIONAL JOURNAL OF NON-LINEAR MECHANICS **119** Paper: 103354, 10 p. (2020)
- András A Sipos, Eszter Fehér: Disappearance of stretch-induced wrinkles of thin sheets: a study of orthotropic films INTERNATIONAL JOURNAL OF SOLIDS AND STRUCTURES **97-98**: p. 275 (2016)
- Eszter Fehér, Timothy J Healey, András A Sipos: The Mullins effect in the wrinkling behavior of highly stretched thin films JOURNAL OF THE MECHANICS AND PHYSICS OF SOLIDS **119** p. 417 (2018)
- András A Sipos, Gábor Domokos, Douglas J Jerolmack: Shape evolution of ooids: a geometric model SCIENTIFIC REPORTS **8**: Paper 1758. 7 p. (2018)
- Sipos András A: A nyomott zónában nemlineáris anyagtörvényű, vasbeton keresztmetszet semleges tengelyének számítása ÉPÍTÉS-ÉPÍTÉSZETTUDOMÁNY **37(**1-2) p. 107 (2009)

A **témavezető** utóbbi tíz évben megjelent 5 legfontosabb publikációja:

- András A Sipos, PL. Várkonyi.: The longest soft robotic arm INTERNATIONAL JOURNAL OF NON-LINEAR MECHANICS **119** Paper: 103354, 10 p. (2020)
- András A Sipos, Emő Márton, László Fodor: Reconstruction of early phase deformations by integrated magnetic and mesotectonic data evaluation TECTONOPHYSICS **726**: p. 73 (2018)
- András A Sipos, Gábor Domokos, Douglas J Jerolmack: Shape evolution of ooids: a geometric model SCIENTIFIC REPORTS **8**: Paper 1758. 7 p. (2018)
- András A Sipos, Eszter Fehér: Disappearance of stretch-induced wrinkles of thin sheets: a study of orthotropic films INTERNATIONAL JOURNAL OF SOLIDS AND STRUCTURES **97-98**: p. 275 (2016)
- Domokos G, Jerolmack DJ, Sipos AÁ, Török Á: How River Rocks Round: Resolving the Shape-Size Paradox PLOS ONE **9**:(2) Paper e88657. 7 p. (2014)

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[5] Minimum 5, maximum 10 cikket vagy monográfiát kérünk felsorolni, amik között feltétlenül szerepelnie kell a legfrissebb, legismertebb eredményeknek.

[6] Minimum 5, maximum 10 folyóirat megadását kérjük, melyek között feltétlenül szerepelnie kell a PhD fokozatszerzés szempontjából elengedhetetlen (Scopus és/vagy Sci illetve Iconda) minősítésű idegen nyelvű folyóiratoknak is. Kérjük, ezeket a periodikákat a felsorolásban jelöljék meg.

A **témavezető** eddigi doktoranduszai[7]:
(név/felvétel éve/abszolutórium megszerzésének éve/PhD fokozat éve)

- **Fehér Eszter** 2014/2017/2019

Melléklet: a téma bővebb leírása (magyar és angol[8] nyelven)

Budapest, 2019. január 23.

Témavezető aláírása

[7] Kérjük, a témavezetési tevékenységre vonatkozó adatokat abban az esetben is adja meg, ha témavezetőként a DI már korábban akkreditálta.
[8]A téma bővebb leírása angol nyelven csak akkor szükséges, ha a témavezető vállalja külföldi hallgató fogadását.

Fracture patterns of concrete structures

András A. Sipos

1. Background

As long as the well-documented elastic (or hyperelastic) models of mechanics is considered, we are constrained to the present or documented recent past states of a solid body. As far as the constitutive model is based on reversibility no clue about past states is preserved after their root cause (such as prescribed boundary displacements or external loads) is removed. Irreversible phenomena (such as creep or plasticity) make the analysis significantly harder, however these models can be in accordance with the second law of thermodynamics and imply a present state under the influence of former states (Howell et al., 2009). In other words, irreversibility makes it possible to draw (perhaps incomplete) conclusions about the history of the stress and strain fields by simply investigating the present state. This idea is one of the key tools in the practice of structural diagnostics. In contrast to the wide range of possible applications, systematic analytical studies and their comparison against controlled measurements are rare, in most of the cases some simple mechanical hypotheses or human intuition is used for verification.

In this proposal we aim to focus solely on one irreversible process: fracture of quasi-brittle materials, especially the fracture patterns of reinforced concrete (RC) structures, beams and plates with and without prestressing. Quasi-brittle fracture produces rich and not easily predictable geometrical patterns of cracks in case of a sufficiently supported body under quasi-static loading. Investigation of brittle fracture started by the pioneering work of A.A. Griffith (Griffith, 1921), and his ideas gained a wide recent interest in the context of *variational brittle fracture* (Amor et al. 2009, Bourdin et al. 2008, Francfort & Marigo 1998, Ulloa et al. 2019). Although Griffith himself took a variational viewpoint, his model required *a-priori* knowledge about the path of a single crack. The regularized elliptic energy functional in variational brittle fracture is free from such a limiting prerequisite, furthermore a Γ-convergence result (Bourdin et al. 2008) demonstrated that in the zero limit the model is identical to Griffith's. The non-zero limit, i.e. a spread damage field – which is a scalar field in the simplest case, but can be enriched as a vector or tensor field – opens the possibility to investigate *quasi-brittle fracture*. We aim to investigate the interplay between the loading history and the observable cracks via the methods of continuum mechanics. During the investigations chemical reactions of the material are neglected thus to keep consistence with the laws of thermodynamics, healing of cracks is excluded.

The idea and rigorous judgment of variational brittle fracture originates in the mathematician community, although similar ideas (which focus directly on applicability) appeared in fracture mechanics, too (Bažant, 1998). Damage is associated with a (scalar, vector or tensor) state field. In the scalar case $\alpha = 0$ represents intact (elastic) material, $\alpha = 1$ corresponds to a completely damaged state. Here a *rate-independent* viewpoint is admitted, thus crack propagation occurs through a series of quasi-static equilibrium solutions of the governing equations as the load parameter is varied. Irreversibility implies α to be nondecreasing at any point of the domain. In terms of nonlinear programming, this requirement transform the problem into a *variational inequality*. Nondecreasing α implies that during the evolution the Karuch-Khun-Tucker (KKT) conditions must be fulfilled to have a local minimizer.

Numerical codes that handle full irreversibility are rare (Rabczuk 2013), in most of the cases global optimization with a frozen damage field over a threshold in α is applied. Let this approach be called *limited irreversibility*. Placing the problem into the regime of bifurcation theory can help to exceed this shortcoming. To establish equilibrium paths of the problem, based on the works of Poore (Poore 1987,1990) continuation of the equilibrium set is possible from a known state. A numerical method to exploit this idea and carry out continuation for problems involving irreversibility has been already developed.

2. Research goals

We aim to investigate simple problems which seems to be adequate to a detailed analysis. They include experimental, numerical and analytical pieces of work.

2.1 Cracking patterns of reinforced concrete beams with and without prestressing

Load-displacement relations and crack widths in RC structures are extensively studied, both in experiments and theoretical works. Systematic investigation of cracking patterns is rare in the literature, however, some recent experiments deserve attention (Farhidzadeh et al. 2013). Study of beams with prestress is even more scarce (Ebrahimkhanlou et al. 2019). The first goal of the proposed research is comparison of fracture patterns for RC beams at different levels of the prestress.

Q#1 Study the literature for well-documented experiments in which the fracture pattern as well the loading history is given in detail. Using some appropriate numerical package (Atena, Code-Aster or Abaqus) compare numerical and experimental results. Draw conclusions about the difference caused by prestress.

2.2 A unified phase-field model of reinforced quasi-brittle fracture

Variational brittle fracture is free from any a-priory ansatz on the geometry and size of the cracks in the specimen. In the case of a RC structure it is obvious, that before opening a crack, which is intersected by one or more rebars, the bonding between these rebar(s) and the surrounding concrete should vanish. Hence, a discontinuity in the displacement field is needed in a complete model. In the regime of variational brittle fracture, it seems a straightforward step to introduce a field that is associated with the bonding between the concrete and the rebars. Such an enriched model is expected to provide acceptable predictions on the crack patterns of RC structures.

Q#2 Building on the results of Q#1 we aim to introduce a unified phase-field model, in which not solely the fracture, but also the interaction between the rebars and concrete is modeled with an appropriately defined scalar field.

2.3 An inverse model to (partial) reconstruction of former stress-fields

The main shortcoming of cracking simulations, especially in 3D is the high computational need, even on contemporary computers. This shortcoming holds for variational brittle fracture, too. Here, typically a very dense finite element mesh is used to have an acceptable prediction on the damage field, which exhibits high gradients in the vicinity of fracture surfaces (Rabczuk 2013, Schillinger et al. 2015) Here we aim to study the interplay between stress trajectories and fracture patterns. Either a stress-function approach or a direct evolution of the stress trajectories are expected to trigger the computation of the cracking pattern.

Q#3. Investigate the possibility of a stress-function formalism of quasi-brittle fracture with reinforcement. Study the evolution of the evolution of the principal stress trajectories.

We expect, that such a crack-pattern oriented approach could be used to address the inverse problem, namely the (partial) stress-field reconstruction from observed cracking patterns. This is with an upmost importance for practical engineering: the large number of concrete structures with a significant lifetime and sometimes serious decay requires a systematic method of assessment, which without doubts call for a systematic study of their cracking patterns.

Q#4. Introduce an inverse model for partial reconstruction of former stress fields based on the observed fracture pattern of quasi-brittle materials.

Depending on the interest of the student, either all questions (Q1-Q4), or a subset of them would be investigated during the four years of study. Fluent English, expertise with concrete structures (including the relevant EC2 European Standard) and finite element modeling is essential. Background in experimental work and/or mathematical analysis is preferable.

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