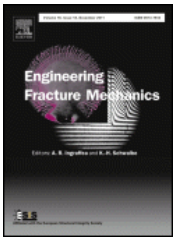

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An engineering solution for mesh size effects in the simulation of delamination using cohesive zone models

Volume 74, Issue 10, July 2007, Pages 1665-1682
Turon, A. | Dávila, C.G. | Camanho, P.P. | Costa, J.

A methodology to determine the constitutive parameters for the simulation of progressive delamination is proposed. The procedure accounts for the size of a cohesive finite element and the length of the cohesive zone to ensure the correct dissipation of energy. In addition, a closed-form expression for estimating the minimum penalty stiffness necessary for the constitutive equation of a cohesive finite element is presented. It is shown that the resulting constitutive law allows the use of coarser finite element meshes than is usually admissible, which renders the analysis of large-scale progressive delamination problems computationally tractable. © 2006 Elsevier Ltd. All rights reserved.

Three-dimensional crack initiation, propagation, branching and junction in non-linear materials by an extended meshfree method without asymptotic enrichment

Volume 75, Issue 5, March 2008, Pages 943-960
Bordas, S. | Rabczuk, T. | Zi, G.

This paper presents a three-dimensional, extrinsically enriched meshfree method for initiation, branching, growth and coalescence of an arbitrary number of cracks in non-linear solids including large deformations, for statics and dynamics. The novelty of the methodology is that only an extrinsic discontinuous enrichment and no near-tip enrichment is required. Instead, a Lagrange multiplier field is added along the crack front to close the crack. This decreases the computational cost and removes difficulties involved with a branch enrichment. The results are compared to experimental data, and other simulations from the literature to show the robustness and accuracy of the method. © 2007 Elsevier Ltd. All rights reserved.

Structural damage diagnosis and life-time assessment by acoustic emission monitoring

Volume 74, Issues 1-2, January 2007, Pages 273-289
Carpinteri, A. | Lacidogna, G. | Pugno, N.

The acoustic emission technique is applied to identify defects and damage in reinforced concrete structures and masonry buildings. By means of this technique, a particular methodology has been put forward for crack propagation monitoring and damage assessment, in structural elements under service conditions. This technique permits to estimate the amount of energy released during fracture propagation and to obtain information on the criticality of the ongoing process. In addition, based on fracture mechanics concepts, a fractal or multiscale methodology is proposed to predict the damage evolution and the time to structural collapse. © 2006 Elsevier Ltd. All rights reserved.

Representative volume: Existence and size determination

Volume 74, Issue 16, November 2007, Pages 2518-2534
Gitman, I.M. | Askes, H. | Sluys, L.J.

The concept of the representative volume element (RVE) is analysed in the present paper. For elastic materials the RVE exists and one can determine the size of the RVE. However, for other applications, such as the case of softening materials, the RVE may not exist. In the present work the RVE has been investigated for different stages of the material response, including pre- and post-peak loading regimes. Results were based on a statistical analysis of numerical experiments, where tests have been performed on a random heterogeneous material. © 2007 Elsevier Ltd. All rights reserved.

A geometrically non-linear three-dimensional cohesive crack method for reinforced concrete structures

Volume 75, Issue 16, November 2008, Pages 4740-4758
Rabczuk, T. | Zi, G. | Bordas, S. | Nguyen-Xuan, H.

A three-dimensional meshfree method for modeling arbitrary crack initiation and crack growth in reinforced concrete structure is presented. This meshfree method is based on a partition of unity concept and formulated for geometrically non-linear problems. The crack kinematics are obtained by enriching the solution space in order to capture the correct crack kinematics. A cohesive zone model is used after crack initiation. The reinforcement modeled by truss or beam elements is connected by a bond model to the concrete. We applied the method to model the fracture of several reinforced concrete structures and compared the results to experimental data. © 2008 Elsevier Ltd. All rights reserved.

High-speed photography of compressed human trabecular bone correlates whitening to microscopic damage

Volume 74, Issue 12, August 2007, Pages 1928-1941
Thurner, P.J. | Erickson, B. | Jungmann, R. | Schriock, Z. | Weaver, J.C. | Fantner, G.E. | Schitter, G. | Morse, D.E. | Hansma, P.K.

Mechanical testing of trabecular bone is mainly motivated by the huge impact of osteoporosis in post-menopausal women and the aged in society in terms of social and health care costs. Trabecular bone loss and impairment of its mechanical properties reduce bone strength and increase fracture risk, especially in vertebrae. It is generally accepted that in addition to bone mineral density, microarchitecture and material properties of bone also play important roles for bone strength and fracture risk. In order to overcome the limitations of standard mechanical tests delivering merely integral information about complicated samples, experiments were designed for step-wise mechanical testing with concurrent imaging of trabecular and cortical bone. In this communication we present an approach for real-time imaging of trabecular bone during compression using high-speed photography and investigate the hypothesis whether the whitening of deformed trabeculae is due to microdamage. Experiments on human trabecular bone samples from a healthy male donor revealed that failure of such samples is highly localized in fracture bands. Moreover, strongly deformed trabeculae were seen to whiten, an effect similar to stress whitening in

polymers. Scanning Electron Microscopy of the same regions of interest revealed that whitened trabeculae were strongly damaged by microscopic cracks and mostly failed in delamination. Higher resolution images uncovered mineralized collagen fibrils spanning the cracks. The whitening partially faded after unloading of the samples, presumably due to partial crack closure. Overall, high-speed photography enables microdamage detection in real-time during a mechanical test and provides a correlation to recorded stress strain curves.

Debonding along the FRP-concrete interface under combined pulling/peeling effects

Volume 74, Issues 1-2, January 2007, Pages 132-150
Pan, J. | Leung, C.K.Y.

The bonding of fiber reinforced plastics (FRP) plates or sheets to the concrete beams has been found to be an effective technique for flexural strengthening. In a reinforced concrete beam, debonding may be induced by a major flexural/shear crack in the span. Under such condition, there is relative vertical displacement on the two sides of the major crack. The FRP is then under both pulling and peeling forces, resulting in a combination of shear sliding and opening displacement along the FRP/concrete interface. In this investigation, using a novel experimental set-up, the effect of combined pulling/peeling on FRP debonding is studied. A new theoretical model for debonding analysis under such a situation is developed. In the model, the interfacial behavior is described by four parameters, with one of them, the interfacial shear strength, affected by the maximum interfacial normal stress. With a set of parameters obtained from two of the specimens, the model is able to describe the debonding behavior of FRP for various specimens with different thickness and under various degrees of peeling effect. The applicability of the proposed analytical approach to the analysis of interfacial debonding under combined pulling/peeling effects in real material systems is hence demonstrated.

Fracture mechanisms and fracture toughness in semicrystalline polymer nanocomposites

Volume 74, Issue 7, May 2007, Pages 1054-1078
Cotterell, B. | Chia, J.Y.H. | Hbaieb, K.

Polymer nanocomposites, especially nanoclay composites, have received much attention in recent years. While it is the functional properties of these composites that are the driving force, good mechanical properties are necessary in most applications. Although claims are made that the mechanical properties of nanocomposites should be excellent, in practice the mechanical properties are often disappointing. Soft or hard spherical particles can toughen semicrystalline polymers, but plate-like nanoclay particles have not produced any significant toughening action and frequently cause significant embrittlement. In this paper the toughening of semicrystalline polymers with nanoparticles, and particularly the difference in behaviour of spherical and plate-like particles is reviewed.

Constitutive modeling of void shearing effect in ductile fracture of porous materials

Volume 75, Issue 11, July 2008, Pages 3343-3366
Xue, L.

Many solids, including geomaterials and commercially available metallic alloys, can be considered as a porous media. The Gurson-like model has been proposed to describe plastic deformation for such type of materials. It has attracted a great deal of attention and various modifications to this model have been proposed. The constitutive equations of Gurson-like model are governed by the first and second stress invariants and the current void volume fraction of the material. Tvergaard and Needleman included void nucleation, growth and coalescence to Gurson model in a phenomenological way [Tvergaard V, Needleman A. Analysis of the cup-cone fracture in a round tensile bar. Acta Metall 1984;32(1):157-69] - thus suggesting the so called GTN model. Meanwhile, little attention was given to the dependence of the damage evolution on the third stress invariant. McClintock et al. [McClintock FA, Kaplan SM, Berg CA. Ductile fracture by hole growth in shear bands. Int J Fract Mechan 1966;2(4):614-27] proposed damage model based on the void evolution in localized shear banding. In the present paper, a separate internal damage variable which differs from the conventional void volume fraction is introduced. The GTN model is further extended to incorporate the void shearing mechanism of damage, which depends on the third stress invariant. Numerical aspects are addressed concerning the integration of the proposed constitutive relations. A unit cell is studied to illustrate the intrinsic mechanical behavior of the modified model. Computations of the deformation in axisymmetric and transverse plane strain tension are also performed. Realistic crack modes in these simulations are achieved for the modified GTN model.

Fracture statistics of ceramics - Weibull statistics and deviations from Weibull statistics

Volume 74, Issue 18, December 2007, Pages 2919-2932
Danzer, R. | Supancic, P. | Pascual, J. | Lube, T.

It is claimed in almost every experimental work on ceramics that the strength is Weibull distributed. The literature demonstrates that this is not valid in any case, but it is up to now the backbone in the design of brittle components. An overview on situations that deviate from Weibulls statistics is presented (multi-modal flaw distribution, R-curves, etc.). It is also shown that testing specimens with different volumes may help to understand the real strength distribution. Inaccuracies that arise from using the Weibull's theory are presented. Monte Carlo simulations on the basis of the standardised testing procedure (30 specimens) clearly reveal that these deviations can be hardly detected on the basis of small samples.

Microstructure-based multistage fatigue modeling of aluminum alloy 7075-T651

Volume 74, Issue 17, November 2007, Pages 2810-2823
Xue, Y. | McDowell, D.L. | Horstemeyer, M.F. | Dale, M.H. | Jordon, J.B.

The multistage fatigue model for high cycle fatigue of a cast aluminum alloy developed by McDowell et al. is modified to consider the structure-property relations for cyclic damage and fatigue life of a high strength aluminum alloy 7075-T651 for aircraft structural applications. The multistage model was developed as a physically-based framework to evaluate sensitivity of fatigue response to various microstructural features to support materials process design and component-specific tailoring of fatigue resistant materials. In this work, the model is first generalized to evaluate both the high cycle fatigue (HCF) and low cycle fatigue (LCF) regimes for multiaxial loading conditions, with appropriate modifications introduced for wrought materials. The particular microstructural features of relevance to fatigue in aluminum alloy 7075-T651

include micron-scale Fe-rich intermetallic particles and rolling textures. The model specifically addresses the role of local constrained cyclic microplasticity at fractured inclusions in fatigue crack incubation and microstructurally small crack growth, including the effect of crystallographic orientation on crack tip displacement as the driving force. The model is able to predict lower and upper bounds of the fatigue life based on measured inclusion sizes.

A status report on delamination resistance testing of polymer-matrix composites

Volume 75, Issue 9, June 2008, Pages 2779-2794
Brunner, A.J. | Blackman, B.R.K. | Davies, P.

The development of fracture mechanics test methods for the determination of delamination resistance or fracture toughness of fiber-reinforced, polymer-matrix composites is an active area of research. The emphasis in this review is on standardisation of test methods. Recent developments leading towards new standardized test procedures will be presented, complementing and updating earlier reviews.

Ductile fracture initiation and propagation modeling using damage plasticity theory

Volume 75, Issue 11, July 2008, Pages 3276-3293
Xue, L. | Wierzbicki, T.

Ductile fracture is often considered as the consequences of the accumulation of plastic damage. This paper is concerned with the application of a recently developed damage plasticity theory incorporates the pressure sensitivity and the Lode angle dependence into a nonlinear damage rule and the material deterioration. The ductile damaging process is calculated through the so-called "cylindrical decomposition" method. The constitutive equations are discussed and numerically implemented. An experimental and numerical investigation for three-point bending tests is reported for aluminum alloy 2024-T351. Crack initiation and propagation in compact tension specimens are also studied numerically. These simulation results show good agreement with experiments. The present model can successfully predict slant fracture as well as the formation of shear lips.

The theory of critical distances

Volume 75, Issue 7, May 2008, Pages 1696-1705
Taylor, D.

The aim of this review article is to introduce the theory of critical distances, to which this special issue of the journal is devoted. The theory of critical distances (TCD) is the name which I have given to a group of theories used for predicting the effects of notches and other stress concentration features. The basic methodology is described, along with a number of variants which have developed over the years. After a brief history of the TCD, the predictive power of this group of theories is demonstrated, showing that they are capable of predicting experimental data on fracture and fatigue in a wide variety of circumstances. After some discussion regarding the fundamental scientific basis of the TCD, areas for future work in this field are suggested.

Nonlocal anisotropic damage model and related computational aspects for quasi-brittle materials

Volume 74, Issue 10, July 2007, Pages 1539-1560
Desmorat, R. | Gatuingt, F. | Ragueneau, F.

A three-dimensional damage model with induced damage anisotropy is proposed for quasi-brittle materials such as concrete. The thermodynamics framework is used, considering then a single second-order tensorial damage variable whatever the intensity and the sign of the loading. The quasi-unilateral conditions of micro-cracks closure are written on the hydrostatic stress only. Altogether with the consideration of damage laws ensuring a damage rate proportional to the positive part of the strain tensor this is sufficient to model a strongly different behavior due to damage in tension and in compression. A proof of the positivity of the intrinsic dissipation due to such an induced anisotropic damage is given. An efficient scheme for the implementation of the damage model in commercial Finite Element codes is then detailed and numerical examples of structural failures are given. Plain concrete, reinforced and pre-stressed concrete structures are computed up to high damage level inducing yielding of the reinforcement steels. Local and nonlocal computations are performed. A procedure for the control of rupture is proposed. It is a key point making the computations with anisotropic damage truly efficient.

Use of J-integral to predict static failures in sharp V-notches and rounded U-notches

Volume 75, Issue 7, May 2008, Pages 1779-1793
Livieri, P.

In the present paper, the physical meaning of JV (namely, the classic J-integral applied to either sharp V-notch) is discussed. Consider a Cartesian reference frame having the x-axis parallel to the notch bisector, each mode of JV, for a given circular path, is proportional to the correspondent mode of the classic J-integral of a virtual crack having length equal to the path radius and emanating from the tip of the V-notch. Analytical and numerical results have been performed for linear elastic materials. Additionally, in order to verify the formulations of JV, experimental result of embedded cracks of sharp V-notch was considered. Then, by introducing a characteristic path radius ρ*, assumed to be dependent only on the material properties, the JV parameter was used for the estimation of the static failure load of sharp V-notches specimens under mode I loading. Furthermore, the JVρ parameter (namely, the classic J-integral applied to U-rounded notches) was used to analyze the static failure of two new series of specimens with double U-notches made of brittle material (PMMA and PVC glass) subjected to tensile loading. This method allowed us to prove that when the ratio between the notch tip radius and ρ* is small the approach agrees with the classic J-integral, whereas when ρ* becomes small with respect to the notch tip radius, the JVρ method agrees with the classic peak stress approach.

Estimation procedure of J-resistance curves for SE(T) fracture specimens using unloading compliance

Volume 74, Issue 17, November 2007, Pages 2735-2757
Cravero, S. | Ruggieri, C.

This work provides an estimation procedure to determine J-resistance curves for pin-loaded and clamped SE(T) fracture specimens using the unloading compliance technique and the η-method. A summary of the

methodology upon which J and crack extension are derived sets the necessary framework to determine crack resistance data from the measured load vs. displacement curves. The extensive plane-strain analyses enable numerical estimates of the nondimensional compliance, μ, and parameters η and γ for a wide range of specimen geometries and material properties characteristic of structural and pipeline steels. Laboratory testing of an API 5L X60 steel at room temperature using pin-loaded SE(T) specimens with side-grooves provide the load-displacement data needed to validate the estimation procedure for measuring the crack growth resistance curve for the material. The results presented here produce a representative set of solutions which lend further support to develop standard test procedures for constraint-designed SE(T) specimens applicable in measurements of crack growth resistance for pipelines.

Optimising FSW process parameters to minimise defects and maximise fatigue life in 5083-H321 aluminium alloy

Volume 75, Issues 3-4, February 2008, Pages 341-354
Lombard, H. | Hattingh, D.G. | Steuwer, A. | James, M.N.

This paper presents a systematic approach to optimising FSW process parameters (tool rotational speed and feed rate) through consideration of frictional power input. Frictional power governs the tensile strength and the fatigue life in this 5083-H321 alloy through its effect on plastic flow processes in the thermo-mechanically affected zone (TMAZ) of the weld. Although, a close relationship therefore exists between tensile strength and fatigue performance, this arises from their joint dependence on the occurrence of certain defect types that are apparently specific to certain strain hardened aluminium alloys that are FS welded. These defects are related to plastic flow processes and have a strong influence on crack paths in FS welded 5083-H321 alloy. Weld residual stresses have been extensively measured using synchrotron X-ray diffraction strain scanning and are governed by heat input into the weld. There is no clear relationship between peak values of residual stresses and fatigue performance. The work indicates that rotational speed is the key parameter governing tool torque, temperature, frictional power and hence tensile strength and fatigue performance.

Evaluating mixed-mode stress intensity factors from full-field displacement fields obtained by optical methods

Volume 74, Issue 9, June 2007, Pages 1399-1412
Yoneyama, S. | Ogawa, T. | Kobayashi, Y.

A method for evaluating mode I, mode II and mixed-mode stress intensity factors from in-plane displacement fields using the method of nonlinear least-squares is proposed in this paper. Along with stress intensity factors, crack tip location and rigid body displacement components are determined simultaneously from both displacement components obtained using full-field optical methods or numerical methods. The effectiveness is validated by applying the proposed method to mixed-mode displacement fields obtained through digital image correlation, displacement fields obtained by analysis using elasto-plastic finite element method, and displacement fields around a fatigue crack obtained by electronic speckle pattern interferometry. Results show that the proposed method can extract stress intensity factors from the displacement fields both accurately and easily. Furthermore, they can be determined even if the material at a crack tip exhibits small-scale yielding. It is expected that the proposed method is applicable to various fracture problems during experimental and numerical evaluation of structural components.

Cohesive zone length in numerical simulations of composite delamination

Volume 75, Issue 16, November 2008, Pages 4774-4792
Harper, P.W. | Hallett, S.R.

Accurate analysis of composite delamination using interface elements relies on having sufficient elements within a softening region known as the cohesive zone ahead of a crack tip. The present study highlights the limitations of existing formulae used to predict numerical cohesive zone length and demonstrates modifications necessary for improved accuracy. Clarification is also provided regarding the minimum number of interface elements within the cohesive zone. Finally, appropriate values of numerical interfacial strength are examined. The results presented will aid the application of mesh design techniques that both preserve numerical accuracy, whilst minimising computational expense.

Anisotropic ductile fracture of Al 2024 alloys

Volume 75, Issue 12, August 2008, Pages 3692-3706
Steglich, D. | Brocks, W. | Heerens, J. | Pardoen, T.

The anisotropic fracture of the 2024-T351 aluminium alloy is investigated using a micromechanics-based damage model accounting for the effect of the void aspect ratio and void distribution. The 2024-T351 Al alloy contains precipitation free bands in which most void nucleating particles are located. The presence of these bands, which are parallel to the rolling direction, primarily controls the distribution of damage and overall fracture anisotropy. The primary void nucleating particles also present a preferential elongation in the rolling direction. These key microstructural features have been determined using quantitative characterisation methods. The effects of void shape and void spacing on the fracture behaviour are elucidated by means of FE cell calculations. FE simulations of cylindrical notched round bars loaded in different orientations are made and compared with experimental data, allowing a better understanding of the damage process as well as the limitations of the modelling approach.

Local strain energy density and fatigue strength of welded joints under uniaxial and multiaxial loading

Volume 75, Issue 7, May 2008, Pages 1875-1889
Lazzarin, P. | Livieri, P. | Berto, F. | Zappalorto, M.

In the notch stress intensity approach to the fatigue assessment of welded joints, the weld toe is modelled as a sharp V-notch and the local stress distributions in plane problems are given on the basis of the relevant mode I and mode II notch stress intensity factors (N-SIFs). These factors quantify the magnitude of asymptotic stress distribution obeying Williams' solution. If the V-notch opening angle at the weld toe is constant and the mode II is not singular, the mode I N-SIF can be directly used to summarize the fatigue behaviour of welded joints. In all the other cases, varying the V-notch angle or including multiaxial loading

conditions (where typically both Mode I and Mode III stress distributions are singular), the synthesis can be carried out on the basis of the mean value of the strain energy density over a well-defined volume surrounding the weld toe or the weld root. By using this scalar quantity, two fatigue scatterbands are obtained for structural steels and aluminium alloys, respectively. The material-dependent radius RC of the control volume (area) is carefully identified with reference to conventional arc welding processes. Sometimes the weld toe radius is found to be very different from zero. The local strain energy approach can be extended as it stands also to these cases, providing a gradual transition from a N-SIF-based approach to a Kt-based approach.

An embedded crack model for finite element analysis of concrete fracture

Volume 74, Issues 1-2, January 2007, Pages 75-86
Sancho, J.M. | Planas, J. | Cendón, D.A. | Reyes, E. | Gálvez, J.C.

This paper presents a numerical implementation of cohesive crack model for the analysis of concrete fracture based on the strong discontinuity approach. A simple central force model is used for the stress vs. crack opening law. The only material data required are the elastic constants and the mode I softening curve. The additional degrees of freedom defining the crack opening are determined at the crack level, thus avoiding the need of performing a static condensation at the element level. The need for a tracking algorithm is avoided by using a consistent procedure for the selection of the separated nodes, and by letting the crack embedded in the finite element to adapt itself to the stress field while the crack opening does not exceed a small threshold value. Numerical simulations of well known experiments are presented to show the ability of the proposed model to simulate fracture of concrete.

Fracture analysis and improved design for a symmetrically bonded smart structure with linearly non-homogeneous magnetoelectroelastic properties

Volume 75, Issue 10, July 2008, Pages 3161-3172
Li, Y.-D. | Lee, K.Y.

The mechanical model was established for the anti-plane interfacial fracture problem of a symmetrically bonded smart structure with linearly non-homogeneous magnetoelectroelastic properties. The system of Cauchy singular integral equations for the interfacial crack was derived by Fourier integral transform. The numerical solutions of the Cauchy singular integral equations were obtained by the Lobatto-Chebyshev collocation method put up by Erdogan and Gupta. The mechanical strain energy release rate and the total energy release rate were chosen as fracture parameters to discuss the effect of the non-homogeneity parameter on the extension force of the crack. A conclusion was drawn that, to reduce the weak-discontinuity of the interface in the magnetoelectroelastic structure would be beneficial to decrease the extension force of the interfacial crack. Based on this conclusion, a new improved design was suggested for the symmetrically bonded linearly non-homogeneous magnetoelectroelastic composite. The enhancement of the capability of the improved structure to resist interfacial fracture was validated by comparison between the improved and unimproved structures for their fracture responses.

An interface element for the simulation of delamination in unidirectional fiber-reinforced composite laminates

Volume 75, Issue 9, June 2008, Pages 2597-2615
Balzani, C. | Wagner, W.

Unidirectional fiber-reinforced composite laminates are widely used in aerospace industry for a great variety of structural parts. In order to enhance the exploitation of material reserves, there is a need for the integration of progressive damage scenarios in the design phase. Due to their hazardous effects on the load-carrying capacity of composite structures, this work focusses on the simulation of delaminations. A finite element based on a cohesive zone approach is developed. Two constitutive laws are proposed. One is characterized by linear degradation after delamination onset, the other is governed by exponential softening response. The damage process is history-dependent leading to an irreversible stiffness degradation in damaged zones. The practicability of the proposed model and the assets and drawbacks of the two material laws are shown by some numerical examples.