CMM-SolMech 2022 conference

S12 Plasticity, damage and fracture mechanics

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BLAST LOADING ON STRUCTURE USING ABAQUS AND DEEP NEURAL NETWORK

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In past few decades, there is increasing demand of military and government structures to be safe against the explosion and other terrorist activities and it is an interesting topic for the researchers to assess the behavior of structure and damages occur to the structure under the blast loading. The structural damage under blast loading is normally determined by numerical simulation and experimental work. Due to the high cost and difficult setup for the structure subjected to the explosion, the experimental studies are very limited. Nowadays, due to the high efficiency and cost-effectiveness of computational power, numerical simulations are widely utilized to determine the structural damage under blast loading. Also, machine learning techniques are the new way to determine structural damage. In past the machine learning techniques are utilized to determine damage due to seismic loading, however, fewer studies are found to determine structural damage due to blast loading. In the presented work, the numerical simulation of critical structure is performed in Abaqus using the built-in explosion CONWEP model to generate a dataset for the deep learning network. Various sizes of explosives, under various conditions (in air or ground) at different distances (50 meters, 100 meters, etc.) are used on structures modeled by FEM to determine the amount of damage that occurs in the structure. After performing this simulation, and obtaining results, the damage that occurs in structure is classified into three categories of green (safe to use), yellow (critical to use), and red (unsafe to used). These datasets are fed to a deep learning network, for the training of the network (70 % of data) and testing of the network (30% of data). The inputs for the network are blast wave, size of the explosion, distance from structure, condition of the explosion, and properties of the structure. Output is a classification of green, yellow, and red. The resulting trained network can be used for any type of explosion that occurs in the vicinity of the building. The trained network will take much less time as compared to the FEM model of a structure subject to blast. Eventually, it will reduce the computational time drastically and in the event of a terrorist attack, the trained neural network will provide post-event precautions that structure is safe to use or not.
Keywords: Blast Loading, Machine Learning, Abaqus, Damage Classification, Air and Ground Explosion, CONWEP model

PHASE-FIELD LENGTH SCALE MEASUREMENT BASED ON THE FRACTOGRAPHY: A CASE STUDY OF CR-AL2O3 COMPOSITES

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The phase-field simulation of fracture in heterogeneous materials, such as the metal-ceramic composites, can be conducted in two ways. One way is to distinguish between the constituent phases, and solve the phase-field problem in a heterogeneous domain. While capable of modeling the microscale fracture events, this approach is mostly restricted to small unit cell problems because the simulations need high mesh resolutions for most of the domain since the crack growth path is not known a priori. The second way is to conduct the phase-field model on the homogenized domain with the effective mechanical properties. The approach allows to predict the macroscale fracture properties such as the fracture toughness, but is incapable of capturing microscale fracture mechanisms. A critical issue arises in the determination of the length scale parameter.

To address the issue, we propose to conduct the fractography analysis, define the fracture process zone size, and use that value as the length scale parameter in the phase-field modeling. The technique is tested on Cr-Al2O3 composites fabricated by powder metallurgy at different reinforcement volume fractions and particle sizes. Mode I and mixed-mode I/II fracture tests are conducted on single-edge notched beams in four-point bending mode. The fracture surfaces are analyzed in detail by scanning electron microscopy and the fracture process zone lengths are measured. The phase-field model is then applied to simulate the macroscale fracture in the specimens, which are considered as homogeneous domains with effective elastic properties determined by the rule of mixture.

The numerical models adequately approximate the experimentally measured fracture toughness and the fracture loads of the investigated composites. It is shown that the phase-field model prediction of the crack initiation direction in the mixed-mode loading is in agreement with the results of the experiments and the generalized maximum tangential stress criterion. These outcomes justify using the process zone length as the scale parameter in the phase-field modeling of macroscale fracture in chromium-alumina and similar metal-ceramic composites.

DOUBLE SURFACE MODEL OF THE INTERMITTENT PLASTIC FLOW IN DUCTILE MATERIALS AT CRYOGENIC TEMPERATURES

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Ductile materials such as the austenitic stainless steels are the main construction material used in the cryogenic environment due to their excellent mechanical properties at very low temperatures. In these materials, during the deformation at the temperatures close to 0 K, the adiabatic shear bands occur, which is related to specific thermodynamic conditions of the weakly excited lattice. The adiabatic shear bands can be detected by the magnetic induction methods, because their formation is accompanied by the plastic strain induced diffusionless transformation from the fcc to the bcc lattice. The phase transformation leads to formation of two-phase continuum with an evolutionary microstructure. During the dissipative inelastic processes at extremely low temperatures, the shear bands gradually cover the primary material, until the available easy slip planes are entirely consumed. The α'-martensite formed during the phase transformation shows ferromagnetic properties, as opposite to the austenite. Change of the magnetic properties of the stainless steels allows for the magnetometric identification of the volume fraction of secondary phase by means of the magnetic induction method.

Formation of the adiabatic shear bands at the temperatures close to absolute zero is closely correlated with the occurrence of the intermittent plastic flow during the deformation of the TRIP materials. The intermittent plastic flow consists in the sudden drops of stress relative to strain, resulting from the massive breaking of the internal lattice barriers by the pile ups of dislocations, as soon as the shear stresses at the heads of dislocation pile ups are large enough. Until now, there has been no evidence of the connection between the occurrence of the phase transformation and the intermittent plastic flow. It has been experimentally shown, that the formation of the shear bands generates the phase transformation that can be measured by means of the magnetic induction methods. In order to describe the intermittent plastic flow during the plastic deformation of the metastable materials subjected to loading at extremely low temperatures, a double surface model, including the yield surface and the recovery surface, has been developed. The proposed model includes the standard type Huber-Mises-Hencky yield surface and the recovery surface, corresponding to the lower bound of the stress oscillations. The serrations, in the form of periodic drops of stress, occur between the yield surface and the recovery surface. The description of the intermittent plastic flow remains in the context of the classical, rate-independent theory of plasticity, including the associated flow rule.

APPLICATION OF UNIFIED MECHANICS THEORY TO CONSTITUTIVE MODELING OF GIGACYCLE FATIGUE

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The unified mechanics theory (UMT) introduces to the Newtonian space-time coordinate system the fifth, linearly independent axis, along which the degradation of a physical system is measured. This additional thermodynamic state index axis maps the entropy generation rate between zero and one, according to the thermodynamic fundamental equation of the material. The thermodynamic lifespan of any closed system travels between zero and one along this axis (Basaran, 2021).
In this study, a UMT based fatigue life model for metals subjected to ultrasonic vibration is developed, with the dominant entropy generating mechanisms taken into account. To validate the modeling, a series of ultrasonic vibration tests are performed on A656 grade steel samples, at a frequency of 20 kHz. It is observed that during very high cycle fatigue, the entropy generation due to thermal conduction, atomic friction generated heat, and microplasticity are about at the same order of magnitude, while microplasticity is the main contributor.
In the next step of the research, corrosion fatigue is considered. A series of electrochemical corrosion tests are conducted on A656 grade steel specimens, in a 5 wt.% NaCl aqueous solution at PH level 7. The electrochemical corrosion is performed and monitored using a potentiostat. Then a series of ultrasonic vibration fatigue tests are conducted on the previously corroded samples, at a frequency of 20kHz. The UMT is used to predict the corrosion fatigue life.
It is shown that the physically-based unified mechanics theory can predict very high cycle fatigue life very well, without the need for the traditional empirical curve fitting a fatigue damage evolution function (Lee et al., 2022).

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UNIFIED BRITTLE FAILURE CRITERIA

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Different failure criteria have been proposed and utilized. For isotropic brittle materials, the maximum normal stress criterion was used frequently, and the failure strength was obtained using a typical dog-bone shape test coupon. However, if the same material has a line crack, the normal stress criterion is not applicable any longer because of the stress singularity at the crack tip, which introduced a new material property called fracture toughness. If the same material has a notch other than a line crack, other failure criteria have been proposed. In other words, depending on the existence of any notch or crack, different failure criteria have been used even for the same material.

This paper is to present a unified failure criteria for brittle materials independent of the existence of any notch or crack. The new failure criteria are based on two set of conditions. The first condition is that the maximum stress should be equal to or larger than the failure strength which was obtained from a dog-bone specimen. This criterion determines the potential locations of failure. However, this condition is necessary but not sufficient to initiate failure. The second condition is based on the stress gradient. This condition provides the failure path. In other words, failure propagates along the path of lowest stress gradient in terms of its absolute value. When both criteria are satisfied, failure are considered to occur. Therefore, the new set of failure criteria provide not only failure initiation location but also failure propagation path. This set of criteria can be applied to the same brittle material regardless of any existence of a notch or crack.

For a specimen like a dog-bone tensile coupon, the first criterion is the controlling condition since second criterion is fully satisfied with zero stress gradient along the width of the specimen. For a specimen with a line crack, the first criterion is always satisfied because of infinite stress at the crack tip. Then, the second criterion is the controlling failure criterion. On the other hand, for a specimen with a hole, none of the criteria are satisfied obviously. Hence, both criteria must be applied. However, when the criteria were applied to specimens with various sizes and shapes of holes, the second criterion was more critical than the first criterion.

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DISSIPATIVE PHENOMENA ACCOMPANYING LOW CYCLE FATIGUE OF P91 STEEL

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High-temperature components of power plant units are often subjected to thermomechanical fatigue. In such load conditions, high-chromium steels exhibit the evolution of the microstructure which manifests in cyclic softening, observed regardless of the test temperature and the level of deformation. Additionally, during the process of frequent starting-ups and shutting-downs of the power plant units, the variable load is often stopped, while the constant load is maintained, causing creep, which changes the nature of the load and the durability of the objects [1].
This research concerns constitutive modeling of low cycle fatigue of P91 steel at variable test temperatures. To properly reflect the first two stages of material cyclic softening induced by plastic mechanisms, the thermodynamic forces related to plastic hardening were decomposed into several nonlinear components. The third stage of rapid softening is related to the development of fatigue damage.
Experimental tests revealed the influence of the testing conditions on the hysteresis loop characteristics usually used to estimate the cumulative damage level. The discrepancy is related to the lack of the stabilization period in P91 steel cyclic behavior, which causes problems with establishing comparable test conditions for different control schemes. At the same time, the dissipated energy does not exhibit sensitivity to test conditions. For this reason, a classical model of accumulated plastic strain-controlled ductile damage development was here verified with the use of an approach based on the entropy-type measure of damage evolution as the change in the material microstructure disorder state. The results indicate that dissipation-based fatigue damage modeling leads to better fatigue behavior predictions [2].
To investigate the influence of alternating creep and fatigue periods, the load programs were used in which constant and cyclic loads occurred independently. It was observed that the creep periods alternating with the fatigue load reduce the fatigue life, while the sequence of events influences the durability of samples. Therefore the commonly used linear damage summation concept, which is insensitive to the sequence of load events, may lead to significant differences between the results of simulations and experimental tests.

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A DOMAIN-DECOMPOSITION MD-FE COUPLING METHOD FOR FRACTURE SIMULATIONS OF AMORPHOUS POLYMERS

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Fracture of materials is essentially a multiscale problem since it originates from the propagation of microcracks which is related to processes at the atomistic or molecular scale, but subjected to macroscopic boundary conditions. Thus, atomistic-to-continuum domain-decomposition methods are appropriate for fracture simulations since they can embed an atomistically-resolved domain into a continuum domain with pre-cracks, such that the processes of the crack propagation can be investigated under macroscopic boundary conditions. Although there have been various domain-decomposition methods proposed in the past decades, most of them are designed for crystalline or amorphous glass materials and not appropriate for multiscale simulations of polymers due to the material's amorphous microstructure and complex mechanical properties. The Capriccio method [1] is a multiscale simulation method designed for amorphous polymers by coupling a particle domain treated by Molecular Dynamics (MD) simulations and a continuum domain solved by the Finite Element Method. This method has been recently extended to inelasticity [4] to capture the rate-dependent behavior of polymers under larger strains by employing a viscoelastic-viscoplastic constitutive model [3] in the continuum domain based on MD simulation results [2]. In the present contribution, the extended method [4] is further modified for fracture simulations of amorphous polymers with pre-cracks under various loading conditions.

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A MECHANICALLY MOTIVATED DAMAGE MODEL BASED ON THE THEORY OF INVARIANT TENSOR FUNCTIONS

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Ceramic matrix composites (CMCs) combine the outstanding high temperature properties of monolithic ceramics with a quasi-ductile, non-brittle mechanical behavior. Microcracks are bridged by fibres such that damage does not directly lead to overall brittle failure. Looking at the effective properties, this microstructural damage leads to a stiffness degradation on the macroscopic scale. Describing this stiffness degradation by a macroscopic material model is a challenging task and involves many effects such as the anisotropic damage initiation and evolution, transverse damage effects, damage deactivation under compression as well as residual (plastic) strains. On the other side, in view of an industrial application, a material model needs to be as simple as possible in order to enable an efficient numerical implementation as well as a straightforward and unique experimental parameter determination.

In this talk, we will present a damage model for CMCs with a special focus on the formulation of the so-called damage effect. In the literature this damage effect is either derived by applying the idea of effective stress together with some equivalence requirements between damaged and undamaged materials [1], but sometimes the motivation also remains unclear [2]. Here we will follow a more rigorous way to formulate the damage effect by making use of the representation theory of invariant tensor functions [3]. Starting from a very general damage effect equation, we reduce the number of material parameters by applying some general mechanical requirements as well as some special material symmetry conditions. In the very end, we will validate the resulting model and give a physical interpretation of the material parameters.

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PREDICTION OF DAMAGE GROWTH IN EN-AW 2024 ALUMINUM ALLOY UNDER LCF REGIME

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The paper is focused on modeling damage accumulation in the process of low-cycle fatigue of EN-AW 2024 alloy. A damage growth model was presented in a form analogous to that of the model proposed earlier for the creep process [1]. In this model, it was assumed that, in every cycle, the increase of the damage state variable is constant. This variable was made dependent on the increment of plastic strain and on nominal stresses. It was accepted that there is no growth of damage in the compressive part of the cycle. This model was successfully experimentally verified for as-received (undamaged) material using data obtained in low-cycle fatigue tests [2]. It was also adapted for determination of damage accumulation in material with creep pre-deformation. In such cases, total failure was considered as the sum of damage resulting from preliminary creep and damage accumulated as a result of cyclic loads. At the same time, the need to determine constants present in the model independently for material with differing pre-deformation history was noted. This results from a substantial change in the microstructure (average grain size and grain size distribution, precipitate size and distribution, grain boundary angle misorientation value) of the material induced by creep at elevated temperature, particularly at 200 °C and 300 °C. Good consistency of the results of numerical simulations with experimental results was obtained.

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ANTI-PLANE BRIDGE CRACKS INTERACTION IN PIEZOELECTRIC MATERIALS WITH INITIAL FIELDS

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The interaction problem of two collinear, unequal bridge cracks in a piezoelectric material with static initial fields, is studied. We formulate and solve the mathematical problem for anti-plane bridge cracks in a pre-stressed and pre-polarized piezoelectric material, assuming the initially deformed configuration of the body is locally stable. Using the boundary conditions of anti-plane bridge cracks, we get the Riemann-Hilbert problems. Nonhomogeneous linear complex differential equations having the unknown complex potential are obtained. For constant value of the applied incremental forces can be obtained the complex potentials, incremental displacement and stress fields corresponding to the third mode of the classical fracture. We determine the asymptotical forms of complex potentials and further asymptotical representations of the incremental fields. For piezoelectric materials with initial fields, we extend Sih's strain energy density criterion and study cracks propagation for a particular piezoelectric material.

Keywords: piezoelectricity, cracks interaction, anti-plane mode, initial fields.

A CONTINUUM DAMAGE MECHANICS MODEL FOR STATIC AND FATIGUE DEGRADATION OF FIBER REINFORCED POLYMERS

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Objective of the present study is the definition and implementation of a fatigue damage model for short fiber reinforced composites. The model is based on a linear elastic or viscoelastic base model. The base model is enhanced by introducing a damage variable acting on the Young's and shear moduli respectively. Failure of the material is assumed to be described by a Tsai-Hill type failure envelope. Based on experimental observations on the creep response of a short glass fiber reinforced polyamide 6 material, the criterion is re-written to a strain space formulation rather than the original stress space formulation. The damage evolution is assumed to be driven by the approach of a state point in strain space towards the failure envelope. Assuming that the fatigue response can be approximated by a linear representation of the S-N curve in a double logarithmic representation, a power-law formulation is derived for the damage evolution equation. The model is implemented as a user defined material subroutine into a commercial finite element program. Subsequently, the procedure is validated against an experimental data base on an injection molded short glass fiber reinforced polyamide 6 material. The data base comprises experiments on standard laboratory specimens loaded in static, fatigue and creep modes as well as more general specimens introducing general multiaxial loading scenarios. The model proves to provide accurate failure predictions under both proportional and cyclic loading.

FRACTURE IN PMMA NOTCHED SPECIMENS UNDER TORSION

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This paper presents the experimental results of fracture in flat PMMA specimens subjected to pure torsion. The specimens were weakened with V-notches with different root radii, i.e. 10, 2 and 0.5 mm. Additionally, specimens with two different thicknesses of 5 and 15 mm were used in this study. The interest in the subject stems from the small number of studies available on the torsion of flat notched elements. The conducted research provides a basis for further consideration on the fracture process, namely numerical calculations in order to learn the stress and strain field distributions and the formulation of fracture criterion used to predict this phenomenon.

Tests were carried out using a dynamic biaxial testing machine MTS 809.10. The tests were conducted under displacement control. An important stage of the experimental research was to determine the moment and crack initiation point and to observe its propagation. For this purpose, a system of two monochromatic PHANTOM cameras was used, which are used to capture images at high speed (up to one million frames per second). The material chosen for the study was Polymethyl methacrylate, a thermoplastic material gaining more and more popularity in various industries. The basic strength parameters were determined in a static tensile test, paying particular attention to the strain rate effect on the properties of this material.

The critical values of torsion angle and torsional moment at which this initiation occurred were identified. Microscopic observations of fractures were used to clearly indicate the crack initiation point - regardless of the specimen type, the crack initiation occurred at the edge of the element near the notch bottom but not in its symmetry axis. The nature of the fracture was also described, varying with the notch root radius and the specimen thicknes. The inclination angle of the crack propagation plane to the specimen symmetry axis was estimated, which in all cases was close to about 45°. Thanks to the recordings obtained from the high-speed cameras, the previously drawn conclusions were confirmed, but also the nature of the crack development was characterized.

Based on the experimental results, work is underway to model the stress and strain field distribution under critical loading conditions using the FEM. The results obtained will allow to formulate the fracture criterion for flat specimens weakened with different types of notches under torsion.

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GRADIENT DAMAGE MODELS FOR SIMULATION OF CONCRETE CRACKING IN L-SHAPE SPECIMEN

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It is well-known that the local damage model is not able to provide mesh-objective results in the simulations of concrete cracking. At the onset of strain localization the (initial) boundary value problem becomes ill-posed, i.e. the loss of ellipticity occurs for statics and of hyperbolicity for dynamics. The simulated zone of cracking is limited to the narrowest band of finite elements, hence the solution is governed by the discretization.

Cracking models can be regularized in a couple of ways [1]. In this paper a gradient enhancement of the scalar damage model is employed according to [3]. In the gradient damage models an extra averaging equation is introduced into the formulation, so that two primary fields are interpolated: the displacement vector and an averaged strain measure. Then the solution is determined by the internal length parameter and becomes insensitive to the adopted mesh. However, when this parameter is constant as in the conventional gradient damage model, an overly expanded damage zone is observed in the results. This undiserable effect can be eliminated when the internal length parameter becomes a function. Among different options of implementation of the evolving length scale, the so-called localizing gradient damage model is applied according to [4]. A decreasing function of gradient activity is selected to control the internal length scale and the width of the damage zone is reduced.

Both versions of the gradient damage model are compared using the example of L-shape concrete specimen, based on the experiment presented in [5]. The numerical study is performed for static loading as well as for different dynamic loading functions. It is shown that the resulting crack patterns depend on the loading rate, see also [2]. In the dynamic analysis of the L-shape specimen the character of failure can evolve from mode I to mixed mode.

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MODELING OF DEFORMATION AND FRACTURE OF METAL-CERAMIC MICROCANTILEVER BEAMS IN BENDING

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In this paper a combined experimental and computational study of the deformation and fracture of microcantilever specimens made of chromium(rhenium)-alumina Metal-Matrix Composite (MMC) is presented, with a particular focus on the failure properties of the metal-ceramic interfaces [1].
In two-phase ductile-brittle materials reinforced with ceramic particles, the interface between the matrix and the reinforcement plays a dominant role in the overall material response to mechanical loading. Hence, the interfacial strength and fracture toughness are among the factors of primary importance in producing stronger and tougher MMCs. Micromechanical testing techniques are being more and more used to investigate the mechanical properties at the microscale, which are of primary importance for modeling. However, determination of both the interfacial strength and fracture toughness is still a challenging task. In this research we attempt to solve the problem in question by proposing an inverse numerical analysis of the results from micromechanical tests to infer the properties at the microscale. More specifically the micro force-displacement curves and deformation patterns from the bending tests are used as input data in the finite element model predicting the micro specimen behavior with a sufficient accuracy. The most essential outcome of this model is an estimation of the cohesive strength and fracture energy of the interface.
In general terms this work contributes to a better understanding of the local deformation and fracture behavior of Cr(Re)/Al2O3 MMC manufactured by powder metallurgy. The specific targets achieved encompass: (i) in-situ experimental identification of the deformation and failure modes of the FIB-milled micro cantilevers loaded by a nanoindenter, and (ii) numerical simulation of the bending experiments to predict the cohesive strength and fracture energy of the interface between Al2O3 particles and Cr(Re) matrix on the microscale.
It is shown that the dominant fracture mode of the chromium(rhenium)-alumina composite under investigation is brittle interfacial mixed-mode cracking that is quite sensitive to the amount of ceramic reinforcement in cross-sections near the specimen's fixed end. Interestingly, higher maximum forces are exhibited by specimens with more Cr(Re)/Al2O3 interfaces in that region. An extensive parametric study demonstrates that the cohesive strength and fracture energy of the interface are estimated to be 0.63 MPa and 50 J/m2, respectively.

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THEORY OF YIELD STRENGTH IN BODY-CENTERED-CUBIC HIGH ENTROPY ALLOYS

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BCC high entropy alloys show exceptional strengths up to 1900K. Fundamental understanding of the mechanisms that control strengthening is necessary to formulate theories that enable screening over the immense compositional HEA space. Supported by the recent experimental findings in NbTaTiV and CrMoNbV alloys, we show with theory that edge dislocations can control the yield strength in BCC high entropy alloys [1]. The theory of edge dislocation strengthening is based on the interaction of the edge dislocations with the random field of solutes in the HEAs [2]. Theory rationalizes and captures a broad range of experiments on BCC alloys. The theory is cast in an analytical form that is parameter-free and depends on physical quantities (alloy concentrations, lattice parameter, elastic constants, misfit volumes) that can be determined ab-initio or experimentally. The reduced theory enables screening over 10 million compositions in the whole Al-Cr-Mo-Nb-Ta-W-V-Ti-Zr-Hf alloy family to find the strongest BCC HEAs.

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FRACTURE SIMULATIONS OF ICE WITH THE PHASE FIELD METHOD

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The phase field method describes interfacial problems in different physical fields for instance solidification or fracture mechanics. Especially in the last-mentioned research field it has gained significant interest in the past decade due to its ability to predict different crack phenomena like crack initiation, crack propagation as well as crack branching. Based on a variational formulation of Griffith's criterion, the crack is represented in a diffuse way by a continuous scalar field which distinguishes between intact and broken material. In the last years the method has been expanded to viscoelastic solids, where fracture processes are highly nonlinear.

Motivated by the fracture of ice shelves we propose a phase field model for materials of a Maxwell type which have a short time elastic behavior and act like a fluid on long time scales. The finite element software FEniCS is used to implement the model and typical load situations of ice shelves are studied.

MICROPOLAR CRYSTAL PLASTICITY MODEL WITH THE GRADIENT-ENHANCED INCREMENTAL HARDENING LAW

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With the advance of nanotechnology the focus in the study of plastic deformation has shifted to submicron dimensions. As it turned out, at this level, an intrinsic length scale may have crucial impact which results in the size effects in material response. In the continuum mechanics, it is commonly accepted that, at least at micron scale, the size effects in plasticity are related to the notion of geometrically necessary dislocations (GNDs). Mathematically the concept of GNDs is associated with the incompatibility of plastic (or equivalently elastic) deformation described by the dislocation density tensor [1].

In the present work, a model of gradient crystal plasticity is examined in which the incompatibility of plastic deformation field is included in two different ways. In the first one, a more common approach is used where the accumulated incompatibility of plastic deformation is included. This is achieved by employing the Cosserat model where, under specific conditions, the gradient of micro-rotation (i.e. curvature tensor) is related to the dislocation density tensor [2]. The second way incorporates the rate of the incompatibility tensor in the incremental hardening law. The latter effect involves a natural length scale that evolves during plastic deformation and is fully determined in terms of standard parameters of a non-gradient hardening law [3].

The numerical implementation of the resulting model in the finite element method (FEM) involves six degrees of freedom per node (3 displacements + 3 micro-rotations) which is computationally beneficial compared to the models based on micromorphic approach [4]. The ability of the proposed model to predict size effects is examined and illustrated by 1D shear tests and a 3D spherical indentation problem of Cu single crystals. It has been shown that if the effect related to the rate of incompatibility tensor is predominant, then the Cosserat formulation provides only a regularization, and then the model can be used to predict size effects in spherical indentation with satisfactory agreement to experiments.

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EXPERIMENTAL AND NUMERICAL ANALYSIS OF LUEDERS BANDS AND PLC EFFECT IN AW5083 ALUMINIUM ALLOY

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Lueders bands and Portevin-Le Chatelier (PLC) effect are two types of propagative instability. Lueders bands occur when, after initial softening stage and formation of a stationary band, a plastic front forms and moves through a sample until hardening results in uniform plastic deformation. The PLC effect is characterized by serrated response in the stress-strain plot, related to moving shear bands and commonly attributed to so-called dynamic strain aging (DSA). It affects several material properties, including the yield stress, the hardening rate (and thus material ductility) and the ultimate tensile strength. The Lueders bands and the PLC effect occur in metals, for example steel and aluminium alloys, under certain strain rate and temperature conditions.

Experiments concerning AW5083 aluminium alloy bone-shape samples under tension were made for three strain rates at room temperature. Displacements and thermal fields were measured simultaneously. At the initial stage of the analysis Lueders bands were visible but had only a transient character. Thereafter, strong saturation hardening and serrations characteristic for the PLC effect appeared, while shear bands were observed, which travel along the sample or disappear and reappear at a different position.

Two large strain material models are used to reproduce the experimental behaviour: first the Estrin-McCormick thermo-visco-plastic model and then the same model with a gradient enhancement. Viscosity and the gradient enhancement are added to the constitutive model in order to avoid pathological mesh sensitivity, characterized by strains localizing in the smallest volume admitted by discretization, which can occur when a classical continuum description is employed. Viscosity turns out to be essential to avoid problems with convergence. In the constitutive model the Huber-Mises yield function is used. Saturation hardening and linear thermal softening are included to represent the experimental behaviour. The full thermomechanical coupling is incorporated with thermal expansion and plastic self-heating. The thermal boundary conditions are adiabatic. All computations are executed using AceFEM and AceGen numerical packages within Wolfram Mathematica.

The results of computations are in good agreement with experimental findings in terms of global load-deformation response and in terms of temperature evolution. The Lueders and PLC bands are reproduced. However, the mode close to final failure is different in the experiment and simulations.

A DISCUSSION ON THE CONSTRUCTION OF DISSIPATIVE MICROSTRESSES IN A GRADIENT CRYSTAL-PLASTICITY MODEL

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A thermodynamically consistent model due to a finite-deformation single-crystal gradient plasticity framework proposed by Gurtin, is employed and detailed here. In the current formulation, the particular features are a rate-dependence function and a rate-sensitivity parameter which are incorporated into a dissipative gradient strengthening term. These features allow us to observe disparate rate-dependencies induced by dissipative conventional and dissipative gradient terms. The question of whether the size dependency of stress-strain results increases or decreases by increasing deformation rates can be addressed here. In this study, different interaction modes are numerically observed and receive great supports from exciting experimental works. Moreover, it can be seen that the current single-grain gradient crystal plasticity model may capture the rate dependency of size-dependent yield strengthening through particular features of the model.

LOCALIZED NECKING IN THIN SHEETS SUBJECTED TO PROPORTIONAL AND NON-PROPORTIONAL LOADING

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The prediction of ductile failure in thin sheets subjected to stretch forming operations is a technologically important problem. Under plane stress conditions, failure often occurs due to localized necking though the thickness of the sheet. It is well known that the failure strains are loading path dependent, and empirical strain-based failure criteria using the forming limits under biaxial stretching are generally not valid under complex non-proportional loadings.

Storen and Rice (1975) derived a general criterion for plastic instability in thin sheets using an imperfection band analysis. However, the Storen-Rice criterion predicts unrealistically large failure strains for rate-independent materials with a smooth yield surface and obey the normality flow rule. More realistic failure predictions are obtained using a non-associative flow rule, although the physical origin of the non-associativity is unclear.

In the present study, it is shown that the apparent non-normality of plastic flow can be explained in terms of a change in active yield surface at the onset of localization, using a multi-surface description of the effective yield behaviour in plane stress. Realistic predictions of the failure strains in thin sheets are obtained using a recently developed multi-surface porous plasticity model specialized to the case of plane stress loading; and the predicted failure strains are in qualitative agreement with experimental data for a range of values of the material strain hardening exponent. In particular, the model can predict the correct shapes of the forming limit curves under proportional loading, and the path dependence of failure under non-proportional loading conditions

SIMULATIONS OF DIFFERENT FAILURE MECHANISMS IN REINFORCED CONCRETE BEAMS WITH ISOTROPIC DAMAGE LAWS

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Although an idea of concrete material has a long history, it is still an active topic in civil engineering. New material mixes are defined with new additives, reduced cement content and/or recycled aggregates. At the same time an increase of computer hardware power and a growth of numerical methods allows for performing more detailed and/or complex simulations. Both processes together result in continuous development of new and modification of existing constitutive laws for concrete. These laws are usually highly non-linear with softening phases to capture the behaviour after the peak. Despite several alternatives available nowadays, constitutive continuum laws defined within CDM (especially with isotropic damage approach) are still the most popular choice in simulations of (large) plain concrete and reinforced concrete specimens. Due to its simplicity and relatively easy formulations, very many alternatives are available in literature. In the simplest versions, the degradation of the material is described via a single damage evolution law, while the complex stress/state is taken into account via the definition of an equivalent strain measure. More advanced isotropic damage models define independent softening mechanisms (e.g. in uniaxial tension and compression with adequate equivalent strains) with an additional procedures for final damage averaging (e.g. triaxiality factor).

In the paper the performance of different isotropic laws to simulate RC beams will be investigated. Selected RC specimens will be numerically simulated to reproduce experimentally observed crack patterns and force-displacement diagrams. Both simple and advanced isotropic damage laws will be examined. In the second group formulations proposed by Mazars and others, and Pereira and co-workers will be investigated. In order to regularise the boundary value problem both a non-local theory in an integral format and a fracture energy approach will be used. The special attention will be paid to the performance of analysed constitutive laws under shear, also/mostly in the case of the longitudinal reinforcement yielding. In order to capture differences between different formulations, in-depth analysis at a material point level will be made for concrete laws under biaxial stress state. If necessary, a comparison with other continuum models (e.g. elasto-plastic one with Rankine criterion) will be also executed. As a benchmark case an experimental campaign conducted at Gdańsk University of Technology will be chosen. In this research reinforced concrete beams with longitudinally reinforcement only under four-point bending were examined. Different beam heights, span lengths and shear zone lengths were tested. Two major failure mechanisms were identified: flexural failure due to the yielding of the reinforcement in the tension zone and shear-tension/compression failure modes in concrete.

ASSESSMENT OF FRACTURE PARAMETERS IN SIMULATIONS OF CONCRETE CRACKING AT MESOSCALE LEVEL

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The current level of development of computational methods allows for accurate modelling of crack propagation phenomena in highly heterogeneous materials such as concrete. The increase in modelling accuracy implies the need to consider an even greater number of material parameters, both those that have a physical interpretation and those that have only numerical meaning. In the classical mesoscale approach, concrete is assumed to consist of a cement matrix in which aggregates, other inclusions and air voids are embedded. There is also a thin layer of the cement matrix called the interfacial transition zone (ITZ), characterized by reduced strength, which surrounds the inclusions. When modelling cracks propagation in concrete specimens at the mesoscale level, it is necessary to consider not only the real shape of the mesostructure - the arrangement and shape of grains and air voids in the cement matrix, but also the material parameters of the various phases of which the concrete is composed.

Another issue is the proper choice of both a constitutive law to describe crack propagation, but also set of fracture parameters for different phases (i.e. cement matrix and ITZs). The assumed values play an important role and they may affect the obtained response significantly. Determination of parameters for each phase is a complicated issue. There are also no uniform guidelines for testing mechanical properties for certain phases e.g. ITZs. For some simulation types it may be necessary to consider secondary effects such as friction or the loading rate. As a result several values are chosen using rules of thumb.

The aim of the paper is to investigate the influence of the choice of the fracture parameters on the obtained results. Finite Element Method (FEM) will be used with interface cohesive elements to describe cracks. 2D simulations will be performed. The determination of two principal cracks growth parameters: strength and fracture energy in both phases will be carefully studied. The special attention will be paid to the uniqueness of the assumed set of parameters derived from the compliance criterion with experiment. Two experiments with dominated mode I failure mode will be numerically simulated: a wedge splitting test and a three-point bending test. A real mesostructure will be taken into account. Results from numerical calculations (force - displacement curves and crack patterns) will be compared with experimental outcomes. The influence of the selected fracture parameters on results will be analysed. The fracture parameters identification issue will be answered.

ANALYTICAL-NUMERICAL STABILITY ANALYSIS FOR LARGE STRAIN THERMO-MECHANICAL PROBLEMS

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When a localization phenomenon, which can be caused by material, thermal or geometrical softening, occurs in the material, the classical boundary valued problem becomes ill-posed and leads to a localization band in a set of measure zero. Then the numerical solution pathologically depends on the adopted discretization and thus is incorrect. The stability conditions which are related to the onset of localization are well-described in the literature for isothermal problems which involve nonlinearities in the constitutive description (plasticity, damage) as well as large strains. In the case of thermo-mechanical coupling the interest is usually limited to thermo-elasticity or small strains or adiabatic conditions.

The aim of the research is to investigate the stability of thermo-plastic material model which can undergo large strains. Special attention is paid on the regularizing effect of the thermo-mechanical coupling as the heat conductivity can play the role of regularization in the model.

The analysis of the stability condition can be performed using two approaches. The first is to investigate the equilibrium on a discontinuity surface. The jump of the velocity gradient across the surface is then non-zero. The second approach, which is applied in this research, is the analysis of perturbations imposed on a homogeneously deformed infinite body. The perturbations for displacement and temperature fields are assumed in the form of exponential harmonic waves. The thermoplastic material is then called stable if all solutions for the wave's amplitudes are bounded. The theoretical derivation results in a complicated condition which can also be analyzed in limit cases (e.g. short wave-length limit) or for special variants of the model, for example quasi-static or adiabatic.

The fully coupled thermo-mechanical model is considered. The mechanical description involves elasto-plasticity with the associative flow rule and the von Mises yield criterion, accounting for thermal softening and strain softening or hardening. In the energy balance the heat produced during plastic deformation is considered and the model includes thermal expansion and heat conduction.

The three-dimensional material model is implemented within the numerical-symbolic package AceGen/FEM and tested for a rectangular plate in tension. The procedures for the stability analysis are developed for chosen cases. When the acoustic tensor is needed in the stability analysis, it is calculated using automatic differentiation available in AceGen. Its determinant is investigated using two methods: checking its value for a selected range of the vectors associated with the wave normal or using an optimization approach.

EXPERIMENTS AND FEA MODELLING OF CRACKING IN STEEL FIBRE REINFORCED HIGH-PERFORMANCE CONCRETE

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High performance concrete (HPC) is a quite novel material which has been rapidly developed in the last few decades. HPC exhibits superior mechanical properties and durability comparing to normal concrete. The high compressive strength (80-120 MPa) is achieved by particles packing, high binder content and self-compacting consistency. HPC can achieve also superior tensile performance if strong fibres (steel or carbon) are implemented in the matrix. Since, existence of fibres farther improves the mechanical performances of HPC such as strength, toughness and ductility, it is useful in applications in structural members (e.g. beams, columns, and beam-column joints) or when reduction of member size is desirable (e.g. extremally thin slabs/walls). Thus, there exist the unabated interest in studying how the addition of different types of fibres modifies the behaviour of HPC. Nowadays, a standard numerical approaches to model the behaviour of fibres reinforced concrete (FRC) are carried out by means of the smeared or discrete crack modelling of homogenous media with appropriately changed stress-strain relationships. Usually, a modified softening description is assumed to properly reflect the influence of fibres on fracture process.
The objective of this paper is to develop a new and efficient mesoscale modelling approach for steel fibre reinforced high-performance concrete. The main idea of presented approach is to assume the fully 3D modelling with taking into account explicitly the distribution and orientation of the steel-fibres. In order to model concrete the continuum constitutive laws with isotropic softening were used. First, a concrete damaged plasticity (CDP) model implemented in Abaqus was utilised, and alternatively a formulation coupling elasto-plasticity and damage mechanics proposed by Marzec and Tejchman was applied. For steel fibres an elastic-perfectly plastic constitutive law was adopted. The fibre distribution was randomly generated according to the amount of fibres added to the concrete mix. The effect of bond between end of the fibre and cement matrix was taken into account. As a benchmark, results obtained from experimental campaign on high-performance concrete with steel fibres of different sizes and dosages on beams and thin panels were chosen. The cracking was monitored and measured with digital image corelation (DIC). Results of numerical simulation were directly compared with experimental outcome in order to validate and calibrate FE-model and to introduce the efficient numerical modelling tool.

VISCOPLASTIC CONSISTENCY MODEL FOR CONCRETE WITH NON-ASSOCIATED FLOW RULE

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Continuum material models for concrete and other quasi-brittle materials have to capture softening behaviour. In order to prevent spurious mesh dependency and ensure the well-posedness of a boundary/initial value problem it is mandatory to augment a continuum material model with a localization limiter. The most popular localization limiters are in the form of non-local approach, either in an integral or gradient format, introducing an internal length scale parameter.
Instead of non-local approaches adding viscosity to a material model can serve as a localization limiter, see e.g. [1]. In addition, the inclusion of viscosity enables a description of dynamic strength increase in a straightforward way. It can be shown that for plastic models adding a viscous term in the case of dynamic loading (wave propagation) introduces an internal length scale parameter proportional to the value of the viscosity parameter. There are three main approaches within the viscoplasticity theory: Perzyna, Duvaut-Lions and the viscoplastic consistency models. The last approach was introduced initially by Wang [2] using the Huber-Mises-Hencky yield surface. With the Hoffman yield surface the viscoplastic consistency model has been used with some success to model static and dynamic behaviour of concrete [3].
The main drawback of the viscoplastic Hoffman consistency model in the present form is the associated flow rule. The use of the associated flow rule leads to a significant overprediction of the plastic volume changes. As a result, in case of kinematic constrains (e.g. plane strain case) the load carrying capacity of a structure can be severely overestimated. In the paper a new, non-associated version of the viscoplastic Hoffman consistency model will be presented. The plastic potential is proposed either in the standard Drucker-Prager form (with a constant value of the dilatancy angle) or in a more sophisticated ellipsoidal form similar to those used in geomechanics (with the dilatancy angle dependent on the hydrostatic pressure, allowing for both dilatancy and contraction).
The proposed model will be tested in both static and dynamic simulations. Computations for the direct tension test and unnotched beam in three point bending are performed to verify applicability of the model.

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PLASTIC FLOW INSTABILITY IN AUSTENITIC STAINLESS STEELS AT WIDE RANGE OF TEMPERATURE (4K - 293K)

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Austenitic stainless steels (AISI 304, 316L, 316LN) exhibit excellent deformability at wide range of temperatures (4K-293K) due to their fcc (face-centred cubic) structure, which make them prospective materials for different industrial applications (ITER, CERN, SpaceX's Starship or DMC DeLorean - the time machine in the 'Back to the Future' films). During plastic deformation, the austenitic stainless steels undergo the strain-induced martensitic transformation. It leads to the creation of a two-phase heterogeneous continuum where the initial austenitic γ-phase has been locally replaced by the α' martensite inclusions. Presented types of austenitic stainless steels exhibit the different tendency to strain induced phase transformation (304 high, 316L medium, 316LN limited).
The objective of this paper is to study the plastic flow instability, at wide range of temperature (4K-293K) in the austenitic stainless steel (304, 316L, 316LN), in the context of the strain-induced phase transformation and the texture formation. For these purposes, the tensile tests at cryogenic temperatures (4K and 77K) and at room temperature (293K) were carried out. The strain fields were captured by means of Digital Image Correlation (DIC). The in-situ Electron Backscatter Diffraction (EBSD), in turn, was used to characterize the nucleation and evolution of new phase. The formation of martensite α' was found to be directly related to the change of the austenite texture. The primary phase undergoes the division into two kinds of grains. The first, deforms mainly through shearing, leading to the formation of martensite α'. The second, becomes an area of plastic flow due to the use of several slip systems. The large strain in 304 results from the balanced distribution of these two types of grains. Therefore, the uniform strain distribution during uniaxial tensile test is longer observed. The 316L, in turn, exhibits a lower tendency to formation the first type of grains. As a result, macro-slip bands are generated, which leads to rapid strain localization. The lowest ductility is observed in 316LN where the second type of grains dominates, and the slips in the spatial system occur.