ICDM3

The Third International Conference on Damage Mechanics

Tongji University July 4-6,2018

Hosted by

Tongji University

Co-Sponsored by

National Natural Science Foundation of China

The Chinese Society of Theoretical and Applied Mechanics

Architectural Society of China

同济大学 TONGJI UNIVERSITY

国家自然科学基金委员会 NSFC National Natural Science Foundation of China

中国力学学会 The Chinese Society of Theoretical and Applied Mechanics

中国建筑学会 Architectural Society of China

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Background and Aim

Since 1958, following the pioneering work of L. M. Kachanov, the theory of damage mechanics has in particular made significant progress and established itself capable of solving a wide range of engineering problems. To date, the damage mechanics is a clearly identified scientific discipline focused on studying the effect of various nano, micro and macro defects on the behaviour of materials, bridging the gap between the well-established fields of continuum inelastic deformations and the classical fracture mechanics with growing macroscopic cracks. The main objective of the conferences series entitled the n-th International Conference on Damage Mechanics (ICDMn) is to bring together leading educators, researchers, scientists, engineers and other practitioners discussing and exchanging ideas on recent advances in the field of damage mechanics. On the foundation of the International Journal of Damage Mechanics (IJDM), this conference series, held every three years, aims to become the premier international forum on damage mechanics research dissemination.

ICDM1 and ICDM2 took place in Belgrade, Serbia (June 25-27th, 2012) and Troyes, France (July 8-1th, 2015).The Third International Conference on Damage Mechanics (ICDM3) invites you to Tongji University, Shanghai, China during July 4-6th, 2018. The event will present the newest findings and depict the future development in damage and failure mechanics. The IDCM3 consists of oral and poster presentation, panel discussions and 20 mini-symposias.

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Chair of ICDM3

Jiann-Wen Woody Ju- University of California at Los Angeles

Co-Chair of ICDM3

Jie Li - Tongji University

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			Huang		
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	Shixue Liang	Tongji University		

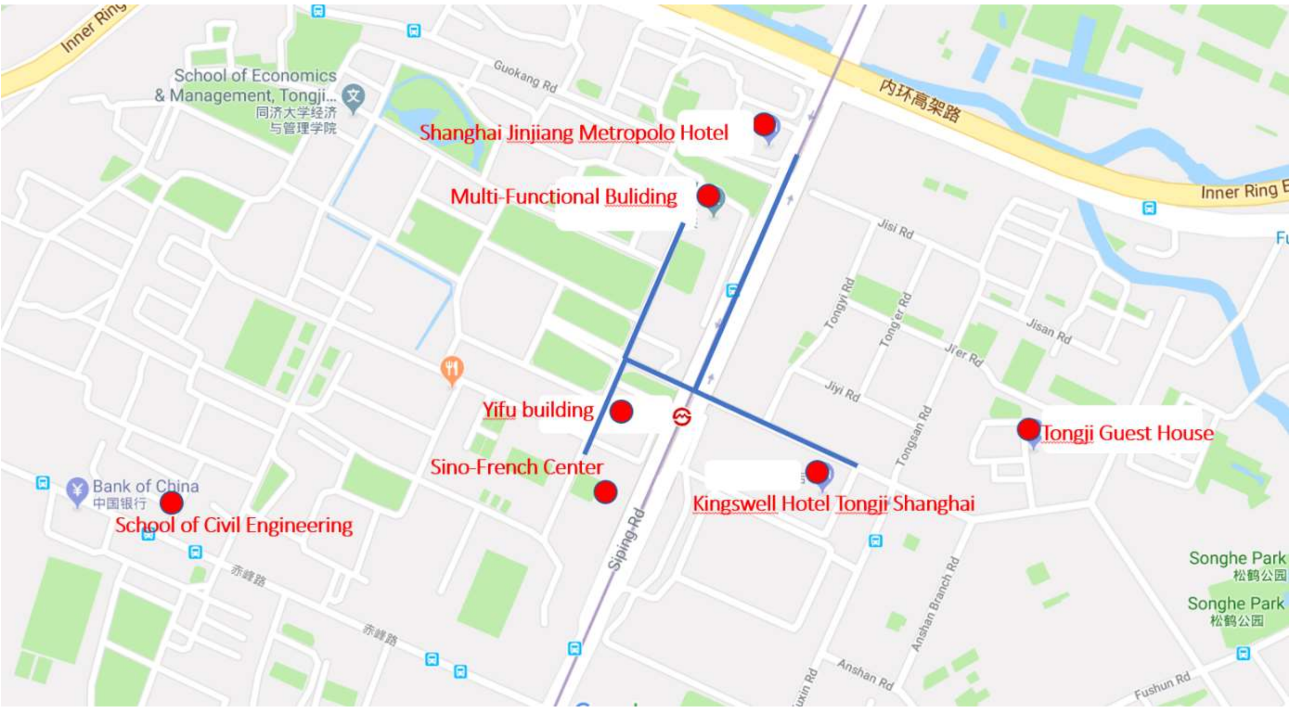
Poster Session

Poster Session will be held at the B1-floor of the Sino-French Center of Tongji University during the conference. Presenters should put up your posters on the morning of July 5th.

Conference venue

Conference venue: Tongji University

Address: 1239 Siping Road, Shanghai, China



Map of Venue

Sino-French Center

Contacts

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Program

Program: Day 1-Wednesday, 4 July 2018

Time	Venue
14:00--21:30	The 3rd floor of Kingswell Hotel
	Registration
19:00--21:00	The 3rd floor of Kingswell Hotel
	Ice Breaker/Cocktail

Program: Day 2-Thursday, 5 July 2018

Time	Venue				
	Sino-French Center Room C201				
8:20--8:40	Welcoming Remarks				
8:40--8:50	Group Photo				
	Plenary Lecture Chair(s): Jie Li				
8:50--9:30	Innovative thermo-elastoviscoplastic damage-healing model for bituminous composites Prof. J. Woody Ju - University of California at Los Angeles				
9:30--10:10	Three-dimensional fatigue fracture mechanics: bridge the gap from laboratory to engineering structures Prof. Wanlin Guo - Nanjing University of Aeronautics and Astronautics				
10:10--10:30	Coffee Break(The 1st floor of Sino-French Center)				
	Sino-French Center Room C201	Sino-French Center Room C401	Sino-French Center Room A401	Yifu Building The 1st Floor	Sino-French Center Room C301
Session 10:30--11:00	MS2: Multiscale Behavior of Damage and Failure Mechanics Chair(s): Mohammad Noori, LiZhi Sun	MS1: Advanced Local and Nonlocal Multi-Physics Modelling of Damage Behavior Coupling Chair(s): Houssem Badreddine	MS3: Damage Modelling of Engineering Structures: from Localized Cracking to Structural Collapse Chair(s): Ji Zhang	MS14: Life-Cycle Based Study And Design of Concrete-Filled Steel Tubular Structures Chair(s): Linhai Han	MS17: Damage Mechanics for Rock Mass Chair(s): Yaoru Liu
	A0885(keynote): A comparison of three different methods for the identification of hysterically degrading structures using bwbn model	A0579(keynote): Damage mechanics based evaluation of microstructural influences on cold formability of dualphase steels	A0927(keynote): Size effects on damage crack growth: fractality and scaling of fatigue threshold and fatigue limit	A0962(keynote): Life-cycle behaviour of concrete-filled steel tubular (CFST) structures: recent developments	A0270(keynote): Experimental and numerical studies on multi-peak deformation behavior of jointed rock mass under uniaxial compression
	Mohammad Noori	Sebastian Münstermann	Alberto Carpinteri	Linhai Han & Chuan-Chuan Hou	Xin Chen

Program: Day 2-Thursday, 5 July 2018

11:00--11:15	A0905: Damage evolution in fibrous composites caused by interfacial debonding	A0532: Phase field and gradient damage models: a simple and unified implementation	A0487: Experimental analysis and modelling of fatigue crack initiation mechanisms	A0959: Sensitivity analysis on the flexural behaviour of cfst trusses with geometric imperfection	A0411: Nonlinear creep damage model considering effect of pore pressure and long-term stability evaluation of bank slope of reservoir
	Jiankang Chen	Jose Cesar de Sa	Aneta Ustrzycka	Silin Chen	Yaoru Liu
11:15--11:30	A0850: Multiscale analysis of damage evolution and ultimate bearing capacity of concrete-filled steel tube structures	A0643: Texture evolution informed anisotropic plasticity model coupled with damage and fracture	A0855: Three-dimensional Grain scale hydro-mechanical coupled model based on discrete element method and pore network flow	A0969: Directional collapse of steel and cfst workshop under seismic load	A0288: Characteristics of rock fracture damage induced by shear
	L. F. Yang	Junhe Lian	Zhibing Yang	Songbo Hu	Zhihong Zhao
11:30--11:45	A0930: Experimental study on effects of shrinkage reducing admixture and moisture on the interfacial properties of new-to-old concrete	A0264: Damage prediction inside a steel overpack in presence of corrosion	A1038: Numerical simulation on tornado-induced collapse of a super-large cooling tower	A1063: Analytical behavior of cfst columns subjected to combined effect of fire and lateral cyclic loading	A0646: Boundary element analysis of fracture mechanics in gradient materials
	Renyuan Qin	Jérémy Serveaux	Shiyu Zhao	Shuai Li	Hongtian Xiao

11:45--12:00	A0892: Influence of surface energy on effective modulus of solids with periodically or-iented elliptical holes	A0583: Shakedown-ratcheting analysis of a spherical pressure vessel by anisotropic continuum damage mechanics	A0340: Analytical prediction of the response of steel fibre reinforced concrete beam elements under bending	A1050: Experimental study on partially concrete-filled steel tubular column under lateral impact loading	A0438: Evaluation criterion of the damage and cracking of rock mass based on unbalanced force
	Yuan Li	Ali Nayebi	Yifei Hao	Hanqing Liu	Zhuofu Tao
12:00--12:15	A0793: A micromechanical model to predict the electrical conductivity of multi-phase composites	A0373: Ductile damage prediction in sheet metal forming based on a nonlocal micromorphic model	A0467: The effect of void defects on the elastic properties of 3D woven composites	A0964: Experimental study on fire resistance of recycled concrete-filled steel tube columns with rectangular section	A0157: Modelling of coal under loading conditions from continuous-discontinuous method
	Dongwoo Jin	Evangelia Diamantopoulou	Yaohua Gong	Linhai Han	Jili Feng
12:15--13:30	Lunch(The 3rd floor of Kingswell Hotel)				
	Sino-French Center Room C201				
	Plenary Lecture Chair(s): J. Woody Ju				
14:00--14:40	Fully coupled constitutive equations in the framework of generalized continua for metal forming simulation Prof. K. Saanouni - University of Technology of Troyes				

	Sino-French Center Room C201	Sino-French Center Room C401	Sino-French Center Room A401	Yifu Building The 1st Floor	Sino-French Center Room C301	Tongji University Muliti-Functional Buliding Room 802

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Session	MS2: Multiscale Behavior of Damage and Failure Mechanics Chair(s): Rashid Abu Al-Rub	MS12: Short Crack Behavior and its Application MS11: Damage of Composites under Impact Loadings Chair(s): Hao Wu, Deju Zhu	MS3: Damage Modelling of Engineering Structures: from Localized Cracking to Structural Collapse Chair(s): Jiangying Chen	MS7: Damage Diagnosis and Condition Assessment of Historical Buildings Chair(s): Na Yang	MS9: Monitoring Based Structural Damage Detection Techniques Chair(s): Jianbing Chen	MS20: Damage Mechanics in Hydraulic Fracturing Chair(s): Zhiqiao Wang
14:50--15:05	A0836: A micromechanics-based phase field approach to fracture	A0571: Tolerance for nonpropagating short cracks departing from elongated notch roots	A0114: Bridging the macro to the mesoscale: developing tensorial damage models for anisotropic materials	A0600: Influence of damage on ancient timber component	A0924: Acoustic emission monitoring on flexural behavior of rc beam subjected to dynamic loading	A0376: Numerical modeling fracking in porous media by phase field approach
	Yongxing Shen	Hao Wu	Louise Olsen-Kettle	Ting Guo	Yu-Cheng Kan	Mostafa Mollaali
15:05--15:20	A0815: A hyperelastic fractional damage material model with memory	A0203: Finite element analysis on ballistic performance of bio-inspired scale-like protection system	A1068: Probabilistic model of the yielding strength for the corroded rebars	A0503: Numerical simulation of stone masonry prisms on typical ancient tibetan buildings	A0333: To monitor the fracture behavior in shaking table tests of a scale-down mockup of nuclear RC structure using acoustic emission	A1074: The Tip Region of a Near-Surface Hydraulic Fracture
	George Z.Voyiadjis	Deju ZHU	Xiangling Gao	Yuhong Jiang	Kuang-Chih Pei	Zhiqiao Wang

Program: Day 2-Thursday, 5 July 2018

15:20--15:35	A0827: Torsional fatigue failure of spring steel with small scratches	A1081: IMPACT FATIGUE BEHAVIOR OF GFRP MESH REINFORCED ECC FOR RUNWAY PAVEMENT APPLICATION	A0922: Microstructural degradation and its effects on low cycle fatigue of a directionally–solidified nickel–base super-alloy	A0522: Research on structural computing model of the traditional timber structure in the yangtze river regions with the method of structural		A1084: Numerical study of repeated fault reactivation and induced seismicity during multi-stage hydraulic fracturing
	Keiji Yanase	Yang Pan	Weiqing Huang	Chun Qing		Fengshou Zhang
15:35--15:50	A0786: Stochastic multiscale modeling for the effective properties of cementitious material	A1058: Effect of reinforcement and strain rate on the mechanical behavior of peek composites	A0400: Analysis of damage zone at macro-crack tip			A1094: Non-planar fractures initiation and propagation of during the hydraulic fracturing in gas shale
	Qing Chen	Chunyang Chen	Xu Li			Liaoyuan Zhang
15:50--16:10	Coffee Break(The 1st floor of Sino-French Center)					
	Sino-French Center Room C201	Sino-French Center Room C401	Sino-French Center Room A401	Yifu Building The 1st Floor	Sino-French Center Room C301	Tongji University Muliti-Functional Buliding Room 802

Program: Day 2-Thursday, 5 July 2018

Session	MS2: Multiscale Behavior of Damage and Failure Mechanics Chair(s): Yilong Bai	MS1: Advanced Local and Nonlocal Multiphysics Modelling of Damage Behavior Coupling Chair(s): José César de Sà	MS3: Damage Modelling of Engineering Structures: from Localized Cracking to Structural Collapse Chair(s): Shixue Liang	MS18: Multiscale Modeling of Damage and Failure in Quasi brittle Materials Chair(s): Qizhi Zhu	MS13: Thermodynamics Based Modelling of Damage Evolution, Fatigue Life and Failure Chair(s): Cemal Basaran, Joachim Nordmann	MS20: Damage Mechanics in Hydraulic Fracturing Chair(s): Fuqian Yang
16:10--16:40	A0957(keynote): Peridynamics modeling and simulation of fracture and damage of composite materials and structure under impact loads	A0955(keynote): Simulating hydraulic fracturing in carbonates using a nonlocal elastic-plastic-damage model	A1027(keynote): Study of pzt5 in domain switching under compressive loading	A0947(keynote): Micromechanics-based models for porous geomaterials with inclusion debonding	A0169(keynote): A damage mechanics theory with no curve fitting: unification of newtonian mechanics & thermodynamics	A1091: Dimensionless analysis of multi-fractures interference in volume fracturing Haiyan Zhu A1097: Experiments and regular research on the effect of natural fracture size on hydraulic fracture propagation in 3D
	Shaofan Li	Rashid Abu Al-Rub	Jiangying Chen	Wanqing Shen	Cemal Basaran	Liming Wan
16:40--16:55	A0063: Multiscale characterization of damage-healing-plasticity for granular material in concurrent computational homegenization approach	A0391: Numirical simulation of sprinback in sheet metal forming using fully coupled ductile damage and distortional hardening	A0541: On the influence of the steel-concrete bond model for the simulation of reinforced concrete structures using damage	A0951: Discrete element numerical simulation of loading rate on tested strengths of rock	A0397: Thermodynamics and multi-physical model for the effect of corrosive environment on metal	A1104: Prediction of the mechanical properties of shale based on stochastic modeling and deep learning

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	Xikui Li	Yetna N'jockMichel	LudovicJason	ChunLiu	KanssouneSALIYA	Xiang Li
16:55--17:10	A0991: Localizing gradient damage model for mixed mode fracture of concrete	A0279: Damage prediction of dp steel under different loading paths with considering lode angle dependence	A0446: Damage in frame elements subjected to cyclic loading	A0938: Micromechanics of rock damage and friction: analytical and numerical studies	A0365: A DAMAGE MECHANICS BASED COHESIVE ZONE MODEL FOR DELAMINATION AND FAILURE BEHAVIOUR OF COATINGS AT HIGH-TEMPERATURE	A1114: Numerical Calculations for the Full-Stress Hydraulic Fracturing model with and without a Fluid-Lag Zone
	Leong Hien Poh	Ke Cao	Zoran Perovic	Qizhi Zhu	Joachim Nordmann	Wenhao Shen
17:10--17:25	A0714: Numerical simulation of microstructural damage and failure of freeze-thawed concrete	A0528: Thermoelasticity coupled with quasi-brittle damage based on micromorphic heat conduction	A0520: Application of different hardening rules in constitutive model of concrete	A0943: Modeling rock with damaged virtual multidimensional virtual internal bond	A0201: Damage mechanics based approach to the analysis of fatigue behavior of butt welded joints considering weld-induced residual stress and initial damage, relaxation of residual stress and elastic-plasitic fatigue damage	A1107: Elasto-plastic damage modeling of hydraulic fracture propagation via xfem
	Yijia Dong	Weijie Liu	Ji Zhang	Zhennan Zhang	Xiaojia Wang	Qingdong Zeng

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17:25--17:40	A0608: A model for interphase damage evaluation in random particulate composites	A0370: Defining relations of damaged viscoelastoplastic media	A0387: A multi-scale analysis based stochastic damage model of concrete	A0709: A review on the microplane constitutive model of quasi-brittle materials: theory and application	A0477: Numerical prediction of long-term deformation for bridges considering basic creep, thermal cyclic creep and material degradation	A1111: EXPERIMENTAL AND NUMERICAL SIMULATION OF WATER VAPOR ADSORPTION AND DIFFUSION IN LONGMAXI FORMATION SHALE
	Lidiia Nazarenko	Mikhail Grigoryev	Shixue Liang	Cunbao Li	Qingling Meng	Weijun Shen
17:40--17:55	A0511: Experimental investigation on ductile fracture in structural steel and validation of damage factor model	A0507: Nonlocal formulation of triaxiality and lode parameter dependent continuum damage model	A0425: Effect of damage threshold in high rate severe plastic deformation in orthogonal cutting elucidated via finite element simulations	A0933: Modeling of hydraulic fracturing in anisotropic rocks with a hybrid EDFM-XFEM method	A0419: Nonlocal void coalescence formulation within an internal state variable based constitutive model for the prediction of plasticity and damage evolution in solid materials	
	Canjun Li	Yazhi Zhu	Juan Camilo Osorio Pinzon	Jianfu Shao	Luke Peterson	
17:55--18:10	A0814: Damage Evolution of Cast Steel Based on Modified GTN Model and X-ray Tomography					
	HUADONG YAN					
18:15--20:00	Dinner (The 15th floor of Shanghai Jinjiang Metropolo Hotel)					
20:00--22:00	Ceremony and Concert (The 15th floor of Shanghai Jinjiang Metropolo Hotel)					

Time	Venue				
	Sino-French Center Room C201				
	Plenary Lecture Chair(s): D. M. Šumarac				
8:30--9:10	Fundamental Issues in Continuum Damage and Healing Mechanics Prof. George Z. Voyiadjis- University of Louisiana State University				
9:10--9:50	Continuum Damage in Quasi-brittle Materials: A Review of Recent Results Obtained with the Help of Lattice Models Prof. Gilles PIJAUDIER-CABOT- Université de Pau et des Pays de l'Adour				
9:50--10:10	Coffee Break(The 1st floor of Sino-French Center)				
	Sino-French Center Room C201	Sino-French Center Room C401	Sino-French Center Room A401	Yifu Building The 1st Floor	Tongji University Muliti-Functional Buliding Room 802
Session	MS2: Multiscale Behavior of Damage and Failure Mechanics Chair(s): Lizhi Sun	MS4: Model-Based Simulation of Damage Responses to Extreme Loading Conditions Chair(s): Yan Liu, Zhen Chen	MS8: Damage of engineering materials under multi-field loadings Chair(s): Xu Long	MS15: Numerical Advances in Multiscale Failure Analysis in Geo-Engineering Chair(s): Zhijun Wu	MS3: Damage modelling of engineering structures: from localized cracking to structural collapse Chair(s): Louise Olsen-Kettle
10:10--10:40	A0688 (keynote): Multi-scale damage evolution and catastrophic rupture of heterogeneous rocks	A0858 (keynote): Damage evolution in a gar fish scale under dynamic compression loading	A0684 (keynote): Effect of electric current on creep deformation of tin	A0996 (keynote): From micro-structure evolutions to macroscopic behaviors-an example of carrara marble	A0921: Numerical investigation of ductile fracture behavior on aluminum laser welded joints HaoyunTu A0767: Corrosion damage model of bolt ball joints with corrosion damage
	Yilong Bai	Arunachalam Rajendran	Fuqian Yang	Louis N.Y. Wong	Huijuan Liu

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10:40--10:55	A0747: Computational framework for multiaxial fatigue life prediction of turbine discs under notch effect	A0698: Dynamic responses of copper under high-velocity impact of micron particles in the cold spray process	A1047: Numerical evaluation on service life of solder joint under the multi-field loadings	A0894: Instability in partially saturated granular soils: a multiscale approach	A1054: A physically stochastic fatigue damage model for concrete
	Ding Liao	Yan Liu	Xu Long	Yixiang Gan	Yanpeng Wang
10:55--11:10	A0811: A multi-level micromechanical model for elastic properties of hybrid fiber reinforced concrete	A0334: Micro Images related to the size effect on the post-peak response of concrete under uniaxial compression	A0847: Boundary element method for analysis of two-dimensional nonlinear piezoelectric semiconductor	A0298: Characteristics of permeability and damage of rock sale under the stress-seepage coupling condition	A1023: A multi-scale comprehensive simulation of two 9-story reinforced concrete shear wall models
	Jiann-Wen Woody Ju	Yuqing Liu	Qiaoyun Zhang	Wang Lu	Jingran He
11:10--11:25	A0564: Microstructural damage characterization and wave-modulus simulation of concrete materials	A0773: Deformartion behaviour of 3D printed rock-like materials with digital image correlation	A0682: Coupling effect between diffusion and deformation on stress evolution in a bilayer structure	A0842: Modeling rock failure process using an explicit numerical manifold method	A0593: An new elastic–plastic–damage model for concrete under pseudo-triaxial compression
	Lizhi Sun	Mansour Sharafisafa	Yaohong Suo	Yongtao Yang	Ji Zhang

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11:25--11:40	A0305: Multiscale random fields-based damage modeling and analysis of concrete structures	A0717: Mechanics of multi-Layer graphene and graphene/polymer based nanocomposites under extreme loading conditions	A0659: Small scale LCF experimental study of ageing Ni-based superalloy	A0759: A novel energy-virtual bond-based GPD simulation for cracks initiation and propagation in brittle solids	A0480: Influences of stress triaxiality, lode parameter and grain size on ductile fracture in micro-scale plastic deformation
	Hao Zhou	Zhaoxu Meng	Y. S. Fan	Jing Bi	W. T. Li
11:40--11:55	A0833: Local multi-scale effect on fatigue failure of weld seam	A0910: Molecular Level Deformation and Failure Transition Mechanisms in Hydrated Cement Paste at Nanoscale	A0086: A Non-Linear Ductile Damage Growth Law at High Temperature		
	Ze zhong Wei	Ram Mohan	Manoj Kumar		
12:00--13:30	Lunch(The 3rd floor of Kingswell Hotel)				
	Sino-French Center Room C201				
	Plenary Lecture Chair(s): K. Saanouni				
14:00--14:40	A unified phase-field/gradient-damage theory for the modeling of failure in solids Prof. Jian-Ying Wu – South China University of Technology				
	Sino-French Center Room C201	Sino-French Center Room C401	Sino-French Center Room A401	Yifu Building The 1st Floor	Tongji University Muliti-Functional Buliding Room 802

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Session	MS20: Damage Mechanics in Hydraulic Fracturing Chair(s): Wenhao Shen	MS6: Failures and Damages in Composite Materials and Structures Chair(s): Zhengming Huang	MS16: Damage and failure mechanics of bridge structures under extreme loading Chair(s): Zhijian Hu	MS5: Computational modeling of damage and failure in solids and structures Chair(s): Ignacio Iturrioz	
15:00--15:15	A1087(keynote): Effect of a capillary bridge on the crack opening of a penny crack	A0232: A damage criterion for riveted fiber metal laminate joints	A0589: Stochastic modelling and optimum inspection and maintenance strategy for RC girder bridges subjected to reinforcement corrosion	A0839: Mapped finite element method for the phase field approach to fracture	
		Xuecheng Ping	Tianli Huang	Yang Wan	
15:15--15:30		A0225: Experimental investigation on the stress-strain behaviors of steel-polypropylene hybrid fiber reinforced concrete under uniaxial cyclic compression and tension	A0415: Damage of masonry arch bridges-field observation and numerical simulation	A0896: A new technique for frictional contact on crack slip in the framework of the extended finite element method	
	Fuqian Yang	Biao Li	Volker Slowik	Hao Cheng	

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15:30--15:45	A1117: THE EFFECTS OF DRILL PIPE VIBRATION ON CHINA SHALE BREAKING MECHANISM WITH MICRO-PDC BIT: A LABORATORY EXPERIMENT STUDY	A0405: A damage model to predict shear behaviour of fibre-reinforced ceramic matrix tows	A0286: Investigation of PBH Connector's Capacity and Slippage	A0734: Probabilistic modeling and simulation of multiple surface crack propagation	
	Teng Wang	Daxu Zhang	Xiao LI	Yong-Zhen Hao	
15:45--16:00	A1121: Stress field evolutions with different fracturing treatments for sand-shale interbedded reservoir	A0245: The failure mechanism research of zirconium oxide particles reinforced composite material	A0250: Effect of random damage of the vehicle-track-bridge system	A0214: 3D ductile crack simulation based on h-adaptive methodology	
	Xuanhe Tang	Long Zhang	Xiang Xiao	Fangtao YANG	
16:00--16:20	Coffee Break(The 1st floor of Sino-French Center)				
	Sino-French Center Room C201	Sino-French Center Room C401	Sino-French Center Room A401	Yifu Building The 1st Floor	Tongji University Muliti-Functional Buliding Room 802

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Session	MS4: Model-Based Simulation of Damage Responses to Extreme Loading Conditions Chair(s): Xiong Zhang, Luming Shen	MS6: Failures and Damages in Composite Materials and Structures Chair(s): Wu Xu	MS16: Damage and failure mechanics of bridge structures under extreme loading, Chair(s): Volker Slowik	MS5: Computational modeling of damage and failure in solids and structures Chair(s): Vinh Phu Nguyen	MS19: Damage and Fracture in deformation-based manufacturing and materials processing Chair(s): Rui Xiao, Xu Hong
16:20--16:50	A0239 (keynote): Multiscale finite element methods for the simulation of strain localization and crack propagation problems	A0876(keynote): Damage and failure analysis of composite structures based on the BMANC	A0442(keynote): Dynamic response of steel box girders under internal blast loading	A0267(keynote): Truss like discrete element method applied in the simulation of damage processon quasi-brittle materials	A0704: Effect of Loading History on Mechanical Properties of HDPE YiZhang A0662: Forming limit predictions of magnesium alloy sheet based on two fracture criteria
	Yonggang Zheng	Yanchao Wang	Leilei Xia	Ignacio Iturrioz	Feifan Li
16:50--17:05	A0320: Recent advances in simulating coupled thermomechanical failure evolution with the generalized interpolation material point method	A0720: Computational Multi-Scale Failure Analysis of Unidirectional Carbon Fiber Reinforced Polymer Composites under Various Loading Conditions	A0798: Damage Identification for a Continuous Bridge by Using Responses of Vehicles Moving on The Bridge	A1071: Comparative study of plastic damage models with application to RC shear wall	A0517: Damage evolution and fracture prediction in cycle bending
	Jun Tao	Yetna N'jock Michel	Zhijian Hu	Ming Cheng	Heng Yang

17:05--17:20	A0234: Damage and self-healing of cementitious composites with microcapsules	A0491: Investigating the fracture behavior of particle reinforced al alloy matrix composites by using rve-based fe simulations	A0474: Dynamic response and damage analysis of UHPC thin layer reinforced piers under vehicle impact	A0769: Damage analysis of purlin-sheeting systems during the passage of a tropical typhoon	A0455: Experimental investigation on nucleation strain under different stress state and pre-strain conditions
	Xianfeng Wang	Han Wang	Yifeng Zhang	Fan Bai	Yu Zhang
17:20--17:35	A1002: Nacre-like aluminium alloy composite plates for ballistic impact applications	A0229: Accurate estimation of the Mode I cohesive zone size of various cohesive laws	A0559: Extraction of Cable Forces Induced by Dead Loads for Cable-Stayed Bridge Condition Assessment	A1017: Micro CT Image-based Fragmentation Simulations of Concrete Under High Strain Rates up to 1000/s	A0453: The effect of pre-strain on the fracture locus
	Tingyi Miao	Wu XU	Yuan Ren	Xin Zhang	Yan Ma
17:35--17:50	A0072: nvestigation on fire resistance of steel-fiber reinforced concrete beams after impact loading	A0189: Fabrication of super-strong carbon nanotube bundles with tensile strength over 80 GPA	A0554: Prediction of Thermal Behavior on Cable Forces Based on Long-term Monitoring Data and Support Vector Machine	A0693: On the development of a micromechanically-based constitutive law for solid propellant	A0299: Determination of a combined Johnson-cook and GTN damage model for predicting the fracture of aluminum alloy extruded profiles under different stress state
	Liu Jin	Yunxiang Bai	Qiao Huang	Marion Picquart	Zhigang Li
17:50--18:05		A0630: Experimental and Numerical Study on Mechanical Property of SAP-contained Concrete under Various Curing Conditions		A0534: Nonlocal damage modeling by using the scaled boundary finite element method	A0217: A NEW FATIGUE DAMAGE MODEL FOR LIFE CALCUTION OF METAL SPECIMEN
		Shengying Zhao		Zihua Zhang	Zhixin Zhan
18:05—18:20		A0258:Study on the Damage Coupling Mechanical Behavior of Ceramic Matrix Composite		A0321: RELIABILITY ANALYSIS METHOD FOR FATIGUE DAMAGE OF DEEPWATER RISE	A0027: Optimization Design on Explosively-Formed Projectile of Multi-functional Warhead
		Yabo Wu		Jun Liu	Chang Jiang

Plenary Lectures

Jiann-Wen Woody Ju

PhD from the University of California at Berkeley in Structural Mechanics (1986). Currently distinguished Professor at UCLA and at Tongji University. Editor of the Int. J. of Damage Mechanics, Editor of the J. of Composites, Associate Editor of the J. of Nanomechanics and Micromechanics, and Editorial Board Member of the ActaMechanica. Fellow ASME, Fellow ASCE, Fellow ACI, Fellow USACM, Fellow IACM.

INNOVATIVE THERMO-ELASTOVISCOPLASTIC DAMAGE-HEALING MODEL FOR BITUMINOUS COMPOSITES

J. Woody Ju
Professor, University of California at Los Angeles, USA

ABSTRACT: Innovative strain energy based thermo-elastoviscoplastic damage-self healing formulations for bituminous pavement materials are presented for numerical simulations of experimental data. A class of elastoviscoplastic two-parameter constitutive damage-self healing models, based on a continuum thermodynamic framework, is developed within an initial elastic strain energy based formulation. An Arrhenius-type temperature term is uncoupled with the Helmholtz free energy potential to account for the effect of temperature. The governing incremental damage and healing evolutions are coupled in volumetric and deviatoric parts and characterized through the net stress concept. New computational algorithms are systematically proposed, based on the two-step operator splitting methodology. Comparisons with experimental measurements and model predictions are demonstrated.

Wanlin Guo

Ph.D from Northwestern Polytechnical University (1991), Academician of Chinese Academy of Sciences, Chair Professor in mechanics and nanoscience, founder and director of the Key Laboratory of Intelligent Nano Materials and Devices of Ministry of Education and the Institute of Nanoscience of Nanjing University of Aeronautics and Astronautics.

Three-dimensional fatigue fracture mechanics: Bridge the gap from laboratory to engineering structures

Wanlin Guo
Professor, Nanjing University of Aeronautics and Astronautics, China

ABSTRACT: The fracture mechanics theories have been developed actively for several decades, and have been successful for many specific engineering applications and serves as the fundamental for damage tolerant design of structures. In 1957, William and Irwin obtained the stress intensity factor K dominated solution of the singular stress and strain fields near crack tip in linear elastic plate, provided the theoretical basis for linear elastic fracture mechanics. In 1968, the famous J-integral dominated HRR solution for plane stress and plane strain cracked plates of power law hardening materials has long served as the fundamental of elastic-plastic fracture mechanics and similar solution has been developed for power law creeping cracked plates in 1980s. In 1986, Li and Wang solved the higher terms to the HRR solution and proposed that the J-dominated plane strain HRR solution is not enough for finite sized plates. Discussions about the higher order solutions widely attracted the attention of the fracture community in the world during 1990s and developed into constraint theories to consider the in-plane constraint effects. However, all the HRR solution based higher order solutions and constraint theories are mainly limited to two-dimensional cracked plates at the two limits of out-of-plane constraint $T_z = \frac{\sigma_{zz}}{\sigma_{xx}+\sigma_{yy}}$ =0 for plane stress and 0.5 for ideal plane strain states. In 1993, we developed the two parameter J-T_z dominated singularity solution for cracks in power law hardening materials under general out-of-plane constraints ranging from 0 to 0.5, filling the gap between the plane stress and plane strain states. We have also developed the J-T_z solution to three parameter J-T_z-Q_T solutions to consider both the in-plane and out-of-plane constraints, and recently to C^*-T_z-Q^* solution for power law creeping solids.

Based on this three-dimensional (3D) theory, we have made great efforts in the past 20 years to bridge the gap for fracture and fatigue from laboratory standard specimens to complex engineering structures. In this talking, we will address the advances in the following critical issues and introduce our most recent works along the line.

1) From 2D fracture mechanics to 3D fracture mechanics;
2) From tensile to mixed mode loadings;
3) From static/toughness to fatigue/durability;
4) From ambient to high temperature environments;
5) From empirical design to predictive design;
6) From continuum methodology to multiscale simulations.

Khemais Saanouni

PhD from University of Technology of Compiègne (France) in Solid and Structural Mechanics (1988). Currently distinguished Professor of solid and structural mechanics at the University of Technology of Troyes. Member of editorial board of 2 international journals: IJDM and IJFO, and member of organizing committee of more than 40 scientific events.

Fully coupled constitutive equations in the framework of generalized continua for metal forming simulation

K. Saanouni
Professor, University of Technology of Troyes, France

ABSTRACT: Nowadays, it is well established that when subjected to various loading paths, materials may exhibit severe strain localization inside narrow bands. One or more of these localization zones may lead to initiation and evolution of different kinds of damage and even can transform to propagating macroscopic cracks. This damage occurrence influences strongly the material behavior inside the localization zones and interacts deeply with the different involved physical phenomena (inelastic flow, hardening …) modifying severely the distribution of the mechanical fields. This talk is dedicated to the formulation of advanced fully coupled constitutive equations in the framework of generalized micromorphic continua based on the first gradient of some selected state variables. The associated numerical aspects will be briefly discussed and some applications to metal forming by large plastic strain will be shown.

George Z. Voyiadjis

PhD from University of Columbia University (USA) in Engineering Mechanics (1973). Currently the chair and the Boyd Professor of the Department of Civil and Environmental Engineering at Louisiana State University. The Chief Editor of the Journal of Nanomechanics and Micromechanics of the ASCE.Fellow ASME, Fellow ASCE, Fellow AAM.

Fundamental Issues in Continuum Damage and Healing Mechanics

George Z. Voyiadjis
Professor,University of Louisiana State University, USA

ABSTRACT: Certain fundamental issues are discussed in continuum damage and healing mechanics including introducing some new concepts. The new concepts of damageability and integrity of materials are introduced. This is followed by introducing what is called the integrity field and the healing field. These issues are abstractions at the moment but their practical applications will become clear in the future. In addition, a new exponential damage variable in introduced. Finally, the healing process is dissected into several stages that are examined. It is hoped that these new fundamental concepts will open the way for new and innovative research in damage and healing mechanics in the future.

Gilles PIJAUDIER-CABOT

PhD from Northwestern University (1987). Currently vice-president of the National Commission for the evaluation of research on radioactive wastes. Prof. Gilles Pijaudier-Cabot authored over 120 refereed papers which received over 4000 citations (h=32). He participated to 4 European projects, acted as principal investigator of over 15 industrial collaborations, and received an advanced grant from the European Research Council in 2008.

CONTINUUM DAMAGE IN QUASI-BRITTLE MATERIALS: A REVIEW OF RECENT RESULTS OBTAINED WITH THE HELP OF LATTICE MODELS

Gilles Pijaudier-Cabot
Professor,Université de Pau et des Pays de l'Adour, France

ABSTRACT: The degradation of quasi-brittle materials encompasses micro-cracks propagation and interactions, and finally coalescence in order to form a macro-crack. These phenomena are located within the so-called Fracture Process Zone (FPZ). This process has been properly described with the help of nonlocal continuum damage formulations for several decades. Issues such as the size and shape effects on fracture that have been observed experimentally could be captured with the help of such formulations. On the other side, some unresolved issues remained, such as incorrect damage initiation conditions or boundary effects. The initial formulation in which the internal length was considered to be a constant material property has been enhanced over the years in order to address such issues. Most of these proposals, however, consisted into ad-hoc phenomenological adjustments that could not be motivated by rational arguments.

This presentation aims at providing a further insight on the evolution of the correlation between damage events, or the internal length in a continuum setting, with the help of statistical analysis in lattice models that mimic the continuum response in a discrete way. These mesoscale models have been found to be much more effective than standard nonlocal models for the prediction of size and shape effects. The statistical analysis relies on the implementation of Ripley's functions, which have been developed in order to exhibit patterns in image analyses. It is shown how a correlation length may be extracted from the Ripley's function analysis. Comparisons between experimental (acoustic emission results) and numerical evolutions of extracted correlation lengths are performed and the evolution of the internal length in the continuum model is obtained.

The lecture is concluded by an illustrating example of the capabilities of the lattice model dealing with hydraulic fracturing. For this, the action of the fluid pressure on the skeleton is described by Biot's theory. Fluid flow in a lattice dual to the mechanical one is represented by considering Poiseuille's flow. The numerical model is compared to existing analytical solutions. Then, the influence of a natural joint of finite length crossed by the fracture is shown.

Jian-Ying Wu

PhD from Tongji University (China) in Structural Engineering (2004). Currently Professor at South China University of Technology (China). Awardee of Excellent Youth of the National Natural Science Foundation of China (2012) ; Winner of the National Natural Science Award of China (2016).

A unified phase-field/gradient-damage theory for the modeling of failure in solids

Jian-Ying Wu
Professor, South China University of Technology, China

ABSTRACT: Damage and fracture mechanics are two paradigms developed to deal with cracks induced failure in solids and structures through distinct methodologies. Aiming to bridge the in-between gap, we address a unified phase-field/gradient-damage theory for both brittle fracture and quasi-brittle failure under quasi-static and dynamic loading scenarios. Either calculus of variation or irreversible thermodynamics is sufficient to formulate the model, without introducing other ad hoc assumptions. For the first time the energetic equivalence between fracture and damage mechanics is established, resulting in a length-scale insensitive and discretization objective material model. Numerical aspects and benchmark validation are also presented in this lecture.

Abstracts

MS1:Advanced local and nonlocal multiphysics modelling of damage behavior coupling

A0264- DAMAGE PREDICTION INSIDE A STEEL OVERPACK IN PRESENCE OF CORROSION

J.Serveaux[1], C.Labergere[2], K.Saanouni[3], F.Bumbieler[4]

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In this paper, the behavior of a welded steel overpack subjected to mechanical loading paths applied in multiple points is studied. An elastoplastic behavior model strongly coupled with ductile damage formulated in the classical thermodynamics of irreversible processes with state variables at the macroscopic scale is used. The external surface of the overpack is subjected to generalized and homogeneous corrosion with controlled corrosion rate. A weak coupling between the homogeneous corrosion and the elastoplastic-damaged behavior is used to introduce the effect of softening due to the corrosion in material properties of the steel. The model was implemented into ABAQUS/EXPLICIT thinks to the VUMAT users' subroutine. The numerically predicted behavior and damage of overpack is presented and discussed on the light of some available experimental results.

A0279-damage prediction of DP steel under different loading paths with considering lode angle dependence

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In order to accurately predict the ductile damage of sheet metal, the consideration of damage anisotropy is necessary in order to account for complex loading path changes. One way to consider damage anisotropy with still using scalar variable consists on including the Lode angle dependency in the evolution damage low. In this paper we propose a fully coupled damage model considering Lode angle dependency in addition of stress triaxiality and micro-crack closure effect. This model is validated by predicting the damage initiation and propagation for a DP steel. An experimental data base including various tests: uniaxial tensile tests; pre-notched tensile tests with different notch radii; shear tests and other butterfly

specimens tests under different load paths, is made to identify the model parameters.. Finally through the comparison between the numerical responses and experimental results of complex cross section deep drawing tests, the validation of the given model will be proved. Then, the influence of Lode angle on damage evolution will be shown and discussed.

A0302- EXPERIMENTAL STUDY ON DAMAGE EVOLUTION OF 42CRMO STEEL UNDER RATCHETTING-FATIGUE INTERACTION

Yujie Liu[a] , Yijun Sun[b]

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In order to realize the ratcheting-fatigue damage evolution during asymmetric stress-controlling cycling , the experimental study has been carried out for annealed 42CrMo steel (cyclically stable material) and tempered 42CrMo steel (cyclically softening material) under asymmetric stress-controlling cycling. Based these cyclic experiments with various stress loading, the damage variable is defined by decline of elastic modulus. Then damage evolution of annealed 42CrMo steel and tempered 42CrMo steel are described. The characteristics of damage evolution are analyzed for ratcheting-fatigue interaction. Compared with strain-controlling test, ratcheting deformation can cause additional damage and reduce fatigue life. Furthermore, the influence of mean stress, stress amplitude and cyclic characteristic on damage evolution are discussed. Some conclusions which is helpful for constitutive model and damage evaluation are obtained.

A0370-DEFINING RELATIONS OF DAMAGED VISCOELASTOPLASTIC MEDIA

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The main physical mechanisms of degradation of the initial strength properties of structural materials (metals and their alloys) effected by fatigue and creep are considered. Based on mechanics of damaged media (MDM), a mathematical model is developed, which describes processes of viscoplastic deformation and damage accumulation with material degradation mechanisms accounting for fatigue and creep of the material, as well as for their interaction. Results of numerically modeling fatigue life of elements and parts of bearing structures are presented.

A0373-Ductile damage prediction in sheet metal forming based on a nonlocal micromorphic model

Evangelia Diamantopoulou[1] , Carl Labergere[1] , Khemais Saanouni[1]

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An advanced numerical methodology is developed for metal forming simulations based on thermodynamically-consistent nonlocal constitutive equations accounting for various fully coupled mechanical phenomena under finite elastoplastic strains in the framework of the generalized micromorphic continua. The numerical implementation into ABAQUS/Explicit is made for accurate 2D bilinear assumed strain quadrangular element in axisymmetrical configuration thanks to the VUEL users' subroutine in order to predict the isotropic ductile defects occurrence. The related numerical aspects required to solve the initial and boundary value problem (IBVP) are briefly presented in the framework of the 2D finite element method with adaptive remeshing technique. The global resolution schemes as well as the local integration schemes of the fully coupled constitutive equations are briefly discussed. Finally, some typical examples including blanking operation of cylindrical hole in a sheet with damage occurrence are numerically simulated in order to show the ability of the proposed methodology to predict the damage zones occurrence with solutions independent from the space discretization.

A0391- NUMIRICAL SIMULATION OF SPRINBACK IN SHEET METAL SHEET FORMING USING FULLY COUPLED DUCTILE DAMAGE AND DISTORTIONAL HARDENING MODEL

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In this work, thermodynamically consistent, non-associative and fully anisotropic elastoplastic constitutive model strongly coupled with isotropic ductile damage and accounting for distortional hardening are used for springback prediction of sheet metal forming. An algorithm for local integration of the complete set of the constitutive equations is developed. This algorithm considers the rotated frame formulation (RFF) to ensure the incremental objectivity of the model in the framework of finite strains. This algorithm is implemented in both explicit (Abaqus/Explicit®) and implicit (Abaqus/Standard®) solvers of Abaqus® through the users routine VUMAT and UMAT respectively. Numerical simulations of U-draw/bending forming process are made with the explicit solver of Abaqus® and the springback step is then simulated using the implicit solver of Abaqus®. The responses of the model are studied, discussed and compared with respect to experimental results.

A0507- NONLOCAL FORMULATION OF TRIAXIALITY AND LODE PARAMETER DEPENDENT CONTINUUM DAMAGE MODEL

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Lode parameter is an important factor that influences the process of ductile fracture. In this study, continuum damage mechanics is employed to describe the effects of ductile fracture on the ductile materials with respect to the strength degradation at the macroscopic scale. Based on thermodynamic principles, a new ductile damage model is proposed coupling both effects of stress triaxiality and Lode parameter to characterize the roles of stress state parameters on the microvoid growth and coalescence. The damage model is formulated by nonlocal method to overcome the pathological mesh dependency arising in regions of strain and damage localization. Considering the numerical difficulties from the large displacement problem, the arbitrary Lagrangian-Eulerian (ALE) remeshing strategy is also incorporated to avoid excessive element distortion. The results of numerical examples demonstrate the elimination of mesh independency with the aid of nonlocal regularization and ALE adaptive meshing. Parametric studies are also provided on the characteristic length in the nonlocal formulation and the other damage related parameters to illustrate the size effect and the triaxiality and Lode parameter dependency of the ductile fracture process.

A0528- THERMOELASTICITY COUPLED WITH QUASI-BRITTLE DAMAGE BASED ON MICROMORPHIC HEAT CONDUCTION

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The analysis of heat conduction using the classical Fourier model is inappropriate to reflect the phenomena at large temperature gradient under short duration, e.g. ultrashort pulsed laser heating or cryogenic engineering. To account for the spatial nonlocal effects, a group of generalized micromorphic heat equations as well as the thermoelasticity coupled with quasi-brittle damage is derived based on the generalized continuum mechanics. The new micromorphic temperature field is introduced as additional degree of freedom (dof) to carry the targeted thermal gradient effects. A new group of micromorphic balance equation involving an internal length is derived by using the principle of virtual power and the Helmholtz free energy enriched with the micromorphic temperature and its first gradient. Several existing extended generalized heat equations could be recovered from constrained micromorphic heat equations with adequate selections of the Helmholtz free energy and heat flux expressions. Furthermore, the numerical analysis is performed to examine the spatial nonlocal effects on the material responses, which is limited to thermoelasticity for the sake of simplification, against the classical Fourier heat conduction equation.

A0532- PHASE FIELD AND GRADIENT DAMAGE MODELS: A SIMPLE AND UNIFIED IMPLEMENTATION

Jose Cesar de Sa[a], Erfan Azinpour[b], João Ferreira[c]

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The extension of the phase-field concept of brittle fracture to the ductile failure modelling may be viewed as an alternative regularization of the local description of continuous damage models or as dealing with the intrinsic discontinuous characteristic of fracture on a continuous approach. The key factor lies herein is the enhancement of sharp internal discontinuity description within the fracture context via incorporation the effects of characteristic length of the material microstructure into the material constitutive model, as it is done in nonlocal gradient models. Taking this into account, an unified implementation of both models is described in the framework of existing commercial software. The analogous treatment between coupled temperature-displacement problems and regularized material models for ductile failure is explored. The implicit gradient Lemaitre damage and phase field models are implemented via coupled temperature-displacement problems. The heat conduction equation is made compatible with the diffusive contribution of such regularization models and calculations are carried out at the material point level. and, therefore, bypassing the need to establish explicitly the weak form resultant from the coupling between the momentum conservation and the evolution of the diffusive field. Throughout benchmarking examples, the proposed methodology is exposed and validated by investigating typical issues risen from the considered material models, such as mesh independency and diffusive crack zone.

A0538- NUMERICAL SIMULATION OF DAMAGE ON SHEET METAL PROCESSING

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Based on thermodynamics of irreversible processes with state variables framework, an advanced Anisotropic Fully Coupled (AFC) model is formulated with the assumption of total energy equivalence. The model is an elastoplastic model fully coupled with isotropic ductile damage. It takes into account not only initial plastic anisotropy but also induced anisotropies such as isotropic hardening, kinematic hardening and yield surface distortion at room temperature. The model includes as well a microcrack closure parameter in ductile damage that reduces the elastic damage force under compressive loading. The model is applied to the ductile damage prediction on sheet metal forming and is compared with the real life process.

A0579- DAMAGE MECHANICS BASED EVALUATION OF MICROSTRUCTURAL INFLUENCES ON COLD FORMABILITY OF DUALPHASE STEELS

Sebastian Münstermann[a], Junhe Lian[b], Victoria Brinnel[c], Felix Pütz[d], Niloufar Habibi[e]

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Due to their microstructural composition with hard martensitic islands embedded into a soft and ductile ferritic matrix, dualphase steels show an inhomogeneous strain distribution when subjected to sheet metal forming operations. This leads to the situation that damage and failure can set the limits to cold formability instead of localized and diffuse necking phenomena. Consequently, numerical approaches to quantitatively evaluate the cold formability of dualphase steel sheets have to be able to assess the concurrence situation between these two different mechanisms.

The proposed contribution will initially present a macroscopic FE simulation framework that is able to distinguish between the occurrence of localized and diffuse necking and damage initiation and accumulation. This model is a strain-based, Lode angle and stress triaxiality dependent ductile damage mechanics model that is enriched with necking criteria that are capable of describing the transition from localized to diffuse necking. The model applies a weighting scheme to cope with non-proportional strain paths. The ability of the model to predict the sheet metal formability will be demonstrated for two different dualphase (DP) steels of significantly different strength levels (DP600 and DP1000). In particular, both necking and fracture forming limit curves will be predicted and experimentally validated. The second part of the contribution will highlight the differences between the two different materials by micromechanical modelling. Based on evaluations on statistically representative microstructure models, the interaction between microstructural parameters, such as phase fractions, individual grain size distributions, spatial distributions of martensite islands or the strength mismatch of martensite over ferrite, and the cold formability of the DP steels will be quantitatively expressed.

A0583- SHAKEDOWN-RATCHETING ANALYSIS OF A SPHERICAL PRESSURE VESSEL BY ANISOTROPIC CONTINUUM DAMAGE MECHANICS

A. Surmiri[a], A. Nayebi*[a], H. Rokhgireh[b]

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In the present research, Bree's diagram (Int J. of Mech. Sci., 1989, Vol. 31, 865-892), which has been used for ratcheting assessment of pressurized equipment in ASME III NH, has been developed when the pressure vessel contains discontinuities such as voids and microcracks. Nature of these defects leads to an anisotropic damage. Anisotropic Continuum Damage Mechanics (CDM) is considered to account effects of these discontinuities on the behavior of the structure. Shakedown – ratcheting response of a hollow sphere under constant internal pressure and cyclic thermal loadings is studied by using anisotropic CDM theory coupled with nonlinear kinematic hardening. Return mapping method is used to solve numerically the developed relations. Elastic, elastic shakedown, plastic shakedown and ratcheting regions are illustrated in the modified Bree's diagram. Influence of anisotropic damage due to the plastic deformation, is studied and it was shown that the plastic shakedown region is diminished because of the developed damage.

A0590-Simple modeling of biological composites, kirigami, and viscoelastic crack propagation

Ko Okumura

Professor Ph. D, Department of Physics and Soft Matter Center, Ochanomizu University, Tokyo, Japan, okumura@phys.ocha.ac.jp

In this talk, we use simple models to provide a clear understanding of mechanical properties of different materials. We discuss biological composites, kirigami (sheet of paper with many cuts), and crack propagation in viscoelastic materials.

In certain biological composites such as nacre and spider webs, the combination of soft and hard elements seems indispensable for achieving high strength and toughness. In this talk, we discuss the mechanical superiority of such soft-hard biological composites. As a result, we provide an intuitive understanding of how their remarkable structures contribute to enhancing their fracture resistance in the presence of cracks, and how such structures are physically optimized in terms of mechanical properties.

Kirigami is a highly stretchable sheet material and has been received much attention especially because of its potential for various engineering applications such as graphene kirigami and stretchable batteries. In this talk, we show that the high stretchability emerges from a transition from in-plane to out-of-plane deformation, providing scaling laws that describe experiment well.

It is known that the velocity of crack propagation in elastomers exhibits a significant jump as the applied load is increased, which could trigger catastrophic failure in automobile tires. Physical understanding of this velocity jump is important from fundamental and industrial points of view. In this talk, we present an exactly solvable model for the phenomena to provide a clear physical understanding of the velocity jump.

A0597- DAMAGE PHYSICAL MECHANISMS AND MODELLING OF DUCTILE FRACTURE

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Ductile damage physical mechanisms in metallic alloys include not only void initiation, growth and coalescence but also fracture without voids, for example in thin sheets with low stress triaxiality. Classical porous plasticity models have to be coupled with other damage models. The Coulomb model is used for transgranular fracture. The coupled model is used in finite element simulations of notched tensile and shear specimens and also in fracture mechanics specimens (Compact Tension and Kahn). In aluminum alloys (Al-Mg-Si extrusion, Al-Cu-Li sheet), shear fracture in plain specimens and the transition from flat fracture to shear fracture in cracked specimens is well modeled. The balance betweeen void damage and transgranular fracrure is well captured.

A0643- TEXTURE EVOLUTION INFORMED ANISOTROPIC PLASTICITY MODEL COUPLED WITH DAMAGE AND FRACTURE

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Plastic deformation of metallic materials very often exhibits different levels of anisotropy. Various microstructure features could contribute to the plastic deformation anisotropy and among them texture is the main factor. Tremendous effort has been made on the constitutive modeling development for the anisotropic yielding and plastic deformation. However, the texture evolution induced evolution of the plastic deformation anisotropy is often overlooked in these models. It has a non-negligible influence on the accurate description of the plastic flow behavior of materials, and it is even more significant concerning the strain localization, damage and fracture, as severe plastic deformation is always companied by extensive texture evolution. Therefore, in the current study, an integrated multiscale modeling approach is established enabling bridging the microstructure-scale information, texture evolution, with the macroscale evolving anisotropic plastic behavior. The evolving anisotropic plasticity model is further coupled with a damage model to render the ductile damage and fracture behavior. Resulting from the integrated modeling approach, the interaction of the texture evolution with the development of damage and fracture is fully explored with respect to the stress state and loading history. The relation between texture evolution and ductile damage and fracture can subsequently guide the texture or microstructure design for damage tolerance materials. In the current study, the model will be calibrated and validated by bcc structure steels.

A0955- SIMULATING HYDRAULIC FRACTURING IN CARBONATES USING A NONLOCAL ELASTIC-PLASTIC-DAMAGE MODEL

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Hydraulic fracturing method is used in oil and gas industry to stimulate wells and increase oil recovery by injecting a high pressure fluid to create new fractures and enhance crack propagation in the existing natural fractures in the carbonated rocks. In this work, a coupled gradient-dependent nonlocal elasto-plastic and anisotropic damage model based on continuum damage mechanics (CDM) and laws of thermodynamics is used to simulate crack propagation in carbonated rocks due to fracking. The model contains two damage evolution laws for both tension and compression, and a yield criterion which accounts for the distinct tensile and compressive behavior of rocks under reservoir conditions. The model is calibrated and compared to experimental results for loading-unloading, uniaxial, biaxial, and mixed mode fracture for carbonates. A number of fracture patterns were simulated where geometries with single and multiple fractures at varying orientation angles and separation distances are simulated in a uniaxial compressive state of stress. Resulting crack patterns are compared with similar careful and novel laboratory experimental results for the same flaw patterns. The study shows that the ratio between the water pressure applied in the flaws and the vertical stress plays a crucial role in the magnitude and shape of the stress field around a flaw tip, and therefore in the location of tensile and shear fracture initiation and propagation patterns.

MS2:Multiscale Behavior of Damage and failure mechanics

A0039- DAMAGE COUPLED CRYSTAL PLASTICITY CONSTITUTIVE MODEL FOR METALLIC MATERIAL FAILURE ANALYSIS

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A damage coupled crystal plasticity constitutive model is proposed for the metallic material damage analysis at the scale of microstructure. A damage variable is introduced to describe the degradation of the shearing stiffness of crystal. The damage coupled constitutive equation is derived based on the conception of effective stress and hypothesis of shearing strain energy equivalence. The damage evolution equation is deduced from the thermodynamics of damaged material. The proposed model is intended to be applied for the analysis of damage evolution at grain scale for aluminum alloy specimens under uniaxial tension loading.

A0063-MULTISCALE CHARACTERIZATION OF DAMAGE-HEALINGPLASTICITY FOR GRANULAR MATERIAL IN CONCURRENT COMPUTATIONAL HOMEGENIZATION APPROACH

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The coupled damage-healing-plasticity process occurring in granular material at the macroscale is characterized in terms of meso-structural evolution of discrete particle assembly. The characterization is performed in the frame of concurrent computational homogenization approach with the global-local FEM-DEM nested analysis scheme. The meso-mechanically informed non-linear incremental constitutive relation is derived and upscaled to the macroscopic gradient Cosserat continuum. The thermomechanical framework of isothermal damage-healing and plastic process is presented. The internal state variables to describe the coupled anisotropic damage-healing and plasticity occurring at local material points in the macroscopic continuum are defined and characterized. The numerical example of strain localization problem is performed to demonstrate the applicability and advantages of the proposed multiscale characterization of coupled damage-healing-plasticity for granular material leading to failure behavior of heterogeneous geo-structures.

A0305- MULTISCALE RANDOM FIELDS-BASED DAMAGE MODELING AND ANALYSIS OF CONCRETE STRUCTURES

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This paper deals with a new treatment of the correlation concrete structure that incorporates the stochastic damage constitutive relation of concrete. Within the framework of stochastic damage mechanics, the spatial variability of concrete is modeled as two-scale stationary random fields. In micro-level, the damage evolution law of concrete is conjugated to the random field of the microscopic fracture strain. In macro-level, the strength distribution of any concrete component forms a lognormally distributed random field. The connection between the two-scale random fields is strictly established by covariance constraint. Then, taking advantage of the stochastic finite element method, the stochastic damage evolution analysis of concrete structures can be numerically achieved.

A0497-A FINITE STRAIN CRYSTAL PLASTICITY THEORY COUPLED WITH DAMAGE EVOLUTION

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For a wide range of polycrystalline metals, ductile fracture process which is a microscopic phenomenon requires an elaborate investigation on grain-level mechanisms. This work presents a finite-strain constitutive model which fully couples rate-dependent crystal plasticity with damage evolution for metal polycrystals. The model is developed within the framework of thermodynamics with internal state variables related to the irreversible plastic deformation and damage evolution. The kinematics is formulated by the multiplicative decomposition of deformation gradient into the elastic, damage, and plastic parts. Specific formulations of the Helmholtz energy and the dissipation of plastic deformation and damage is deduced respectively under the restrictions imposed by the second law of thermodynamics. The proposed model can successfully describe the interaction between the evolution of microstructure at grain level and the process of material degradation. The numerical integration of the presented model is carried out on a fictitious plastic configuration by a two-level staggered fashion. At the outside level, a trust-region approach which is global convergent is used to integrate the internal state variables related to the dislocation slip and the damage evolution. At the inside level, the Newton–Raphson iterative scheme is used to integrate the velocity gradients of plastic deformation and damage. The prescribed algorithm together with the analytical consistent tangent stiffness has been implemented into the ABAQUS finite element code by writing a user subroutine. The performance of the formulation and the robustness of the algorithm are demonstrated by numerical simulations.

A0511- EXPERIMENTAL INVESTIGATION ON DUCTILE FRACTURE IN STRUCTURAL STEEL AND VALIDATION OF DAMAGE FACTOR MODEL

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Micromechanics-based fracture models can be effective methods to predict damage fracture in steel structures. In this paper, a series of experiments, including tensile tests, cyclic tests and shear tests, are conducted to achieve multiple loading conditions. Some key theoretical issues are discussed. Based on the theoretical and experimental studies, the damage factor models for predicting ductile fracture in structural steels are proposed and the model calibration is carried out using experimental data. The comparative analysis between experiments and numerical prediction is performed. It demonstrates the accuracy of the proposed models. Due to their simplicity, the proposed models are also effective and applicable for engineering practice.

A0564- Microstructural damage characterization and wave-modulus simulation of concrete materials

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This paper presents a quantitative analysis of microstructural damage evolution of concrete materials under freeze-thaw (F-T) action using three-dimensional (3D) X-ray computed tomography (CT). The microstructural damage evolution as well as pore network (porosity, pore size, and pore distribution) are specifically investigated. The concrete microstructures of different F-T action show that the interfacial transition zone (ITZ) is most likely to be damaged first under frost attack. Pores and cracks can nucleate during the F-T action, and further accumulate and grow in the paste and aggregates, eventually leading to concrete failure. It is demonstrated that 3D X-ray CT is capable of acquiring microstructures of concrete and revealing existence of internal pores and cracks in different phases of concrete, and effective to characterize accumulated damage of concrete due to F-T action. Based on the nanoCT microstructure, we further conduct micromechanics-based numerical simulation of effective wave-moduli of concrete materials. The effects of heterogeneous aggregate size and shape are investigated on the wave-moduli. Finite element results are also compared with experimental data from smart aggregate technique to demonstrate the dependence of overall wave-moduli on material heterogeneity.

A0608- A MODEL FOR INTERPHASE DAMAGE EVALUATION IN RANDOM PARTICULATE COMPOSITES

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An approach to the modeling of progressive damage of interphases in random particulate composites will be discussed. In the model the interphases are represented by layers of springs whose stiffness parameters change as a result of damage associated with gradually increasing loading. As a result, the interphases become progressively inhomogeneous, with their properties degrading according to a postulated damage model. This, in turn, causes the effective properties of the composite to become increasingly anisotropic. To capture the effects of interphase damage on the overall properties of the composite three ideas proposed with the author's participation are utilized. One is the Method of Conditional Moments (MCM), a statistical homogenization technique developed in the past to analyze the effective properties of random composites without interphases. The second idea is the recently introduced notion of energy equivalent inhomogeneity (EEI), which replaces the particles of the composite and their interphases with homogeneous perfectly bonded particles whose properties are energetically determined in terms of the properties of the particles and properties of their interphases. The idea of the EEI allows methods devised to describe composites without interphases, such as MCM, to analyze problems with interphases. In addition, the notion of EEI permits to account for interphases with spatially varying properties, a feature critical from the point of view of their damage. The key feature associated with the combination of these two ideas is that it allows to evaluate stresses at the interphases of a statistically averaged composite. The new and the most important is the third idea concerning the development of the statistical interphase damage model. In the proposed approach dispersed micro-damage of interphases is modeled by an increasing fraction of randomly distributed destructed springs in the spring layer. This aspect of the model is directly tied to the ability of evaluating interphase stresses, facilitated by employing the MCM and the EEI approaches. Some combination of normal and tangential interphase stresses (the so-called equivalent stress) is compared to the current value of the interphase micro-strength to determine what fraction of the yet-undamaged interphase springs will be damaged. The model assumes that the interphase micro-strength is not homogeneous (statistically homogeneous), and that it is described by one-point Weibull distribution function. In view of the strong nonlinearity of the problem, all three of the employed ideas will be used in an incremental/iterative scheme. The approach will be illustrated by numerical examples. They will concern composites with spherical particles under various loading scenarios. Interphase damage evolution will be examined for each type of loading. Comparisons with the existing numerical and experimental results will be described and the relative merits of the proposed approach will be discussed in this context.

A0688- Multi-scale damage evolution and catastrophic rupture of heterogeneous rocks

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There are 3 distinct length scales involved in the damage evolution and catastrophic rupture of heterogeneous rocks: two essential ones, namely the sample size macroscopically and the grain size at micro-scale, the other is the emerging localized band. Generally, the microscopic heterogeneity can be treated in terms of mean field approximation, and this leads to a stress-strain relation with damage variable, depicting the mechanical behavior of the rocks under uniaxial and biaxial compressions quite well. However, beyond the peak load, a new length scale emerges, namely a localized band with high strains, owing to continuous bifurcation of deformation. Significantly, any width of the localized zone can satisfy all macroscopic conservations and then leads to some uncertainty in catastrophic rupture of these rocks. On the other hand, a changeable power law appears ahead of catastrophic rupture and helps us to foresee specifically the occurrence of catastrophic rupture of the heterogeneous rocks.

A0714- Numerical Simulation of Microstructural Damage and Failure of Freeze-thawed Concrete

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Concrete structures in cold region are exposed to cyclic freezing and thawing environment, during which deformation and fracture properties of concrete degrade due to internal damage. In recent years, internal microstructural damage has been observed by three-dimensional X-Ray CT techniques but its mechanical influence to the fracture property is unknown. To gain a deep understand of fracture behavior of concrete damaged by freeze-thaw cycles, the deformation and fracture processes of concrete samples damaged by freeze-thaw cycles in 3-point bending tests were modeled and simulated using micromechanics-based finite element method. Two level meso-to macro-scale finite element model was developed based on X-Ray CT images and realistic micro cracks due to freeze-thaw cycles was taken into account. The load-deflection curves and fracture energies were compared with experimental results and showed satisfactory consistency. Simulation results demonstrated that microcracks are the main reason of decrease of fracture properties.

A0747- COMPUTATIONAL FRAMEWORK FOR MULTIAXIAL FATIGUE LIFE PREDICTION OF TURBINE DISCS UNDER NOTCH EFFECT

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Hot section components like turbine discs often operate under harsh conditions with complex multiaxial loadings. According to the notch and size effect in these components, a computational framework for multiaxial fatigue life prediction of a turbine blade to disc attachment is established by coupling finite element (FE) simulation of stress gradient with Fatemi-Socie (FS) damage criterion. Specifically, FE-based parameters calibrated for stress gradient and size effect is incorporated in this framework. Through the elasto-plasticity FE analysis, a notch support extension accounting for stress gradient effect has been described based on FS criterion. Experimental data of turbine disc alloy GH4169 and field spectra of a high pressure turbine disc were introduced for model validation and comparison. Finally, using this framework, testing effect can be significant reduced according to deterministic model predictions with notch effects.

A0786- STOCHASTIC MULTISCALE MODELING FOR THE EFFECTIVE PROPERTIES OF CEMENTITIOUS MATERIAL

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A stochastic multiscale model is presented to describe the probabilistic behavior of the effective properties for the cementitious material. At the microscale level, the cement paste is represented as a multiphase composite consisting of the water, air, hydrated and unhydrated products.The volume fractions of each components are analitically calculated by the hydration degree. By upscaleing procedures, the properties of mortar and concrete are reached by multileve homogenization scheme quantitativley. By modeling the hydration degree, volume fractions and properties of constituents as stochastic, we extend the deterministic framework to stochastic to incorporate the inherent randomness of effective properties among different specimens. Maximum entropy based simulation procedures are employed to characterize the material's probabilistic behavior. Numerical examples including limited experimental validations, comparisons with existing micromechanical models, commonly used probability density functions and the direct Monte Carlo simulations indicate that the proposed models provide an accurate and computationally efficient framework in characterizing the material's effective properties.

A0793- A MICROMECHANICAL MODEL TO PREDICT THE ELECTR ICAL CONDUCTIVITY OF MULTI-PHASE COMPOSITES

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Numerous studies were conducted to incorporate electrically conductive materials in composites, in an effort to enhance the electrical conductivity of the composites [1]. This paper presents a portion of a numerical study done by the authors (Jin et al., 2018) to predict the electrical conductivity of multi-phase composites incorporating CNT and carbon fibers. The Ponte Castañeda-Wills (PCW) model is adopted in this study and extended for predicting the electrical conductivity of multi-phase composites [2-3]. By assuming various shapes and curviness of CNT and carbon fibers, the developed model predicts the electrical conductivity of composites. In addition, experimental investigation [1] and the predictions will be compared.

A0811- A MULTI-LEVEL MICROMECHANICAL MODEL FOR ELASTIC PROPERTIES OF HYBRID FIBER REINFORCED CONCRETE

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There is a demand for multi-scale micromechanical models to disclose and analyze the effects of microstructure on macro mechanical properties of hybrid fiber reinforced concrete (HFRC). This study presents a multi-level micromechanical model that involves the cement paste level, the concrete level, and the hybrid fiber reinforced concrete level to quantitatively predict the effective isotropic and elastic properties of HFRC under ambient temperatures. For the purpose of homogenization, the volume fractions of different phases at different levels are determined by means of a modified Power's model. In the multi-level micromechanical model, hydration products of clinker, sand, coarse aggregate, and hybrid fiber are comprehensively considered. A homogenization stepping framework is presented to realize upscaling from microstructural properties to the effective elastic properties of a macrostructure for HFRC. Further, several sub-stepping homogenizations are also presented to estimate the effective elastic properties of an equivalent medium with respect to the cement paste and hybrid fiber reinforced concrete. Comparisons with experimental data from extant studies are implemented level by level. Subsequently, the influences of aggregate, sand, fiber type, and hydration degree on the properties of HFRC are discussed based on a proposed multi-level

micromechanical model. Finally, the mixture ratio of steel fiber and w/c are investigated with respect to the HFRC design to obtain anticipated elastic properties.

A0814- Damage Evolution of Cast Steel Based on Modified GTN Model and X-ray Tomography

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Because structural engineers do not have adequate knowledge of the effect of micro-porosity on mechanical porosities of steel castings, excessively high safety factors are employed on cast components to ensure reliability, which lead to increased component weights and inefficient use of materials. In order to solve this problem, the effect of micro-porosity on the damage evolution and the stress state in tensile specimens is investigated by a modified Gurson-Tvergaard-Needleman (GTN) model. X-ray tomography measurements are proposed to determine the parameters in GTN model. The damage evolution is observed and recorded, and the parameters of modified GTN model are identified through counting void fraction at three damage stages of GS-20Mn5V. Compared with the uniaxial tensile experiments, the predicted results show a good agreement. The parameters determined by X-ray tomography can be applied to the research of the fracture for cast steel.

A0815- ON FRACTIONAL CALCULUS APPLICATION IN DAMAGE MECHANICS

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In this work a scalar damage model for hyperelastic materials is presented and applied for modeling the abdominal aortic aneurysm. The novelty of the proposed approach lies in the evolution law for damage variable that is formulated with the application of fractional calculus. Such a concept provides physical interpretation, that damage evolution includes memory. In other words the current intensity of damage evolution, is based on information from the past– explicit time length scale is included in the fractional operator. This new formulation introduces two additional material parameters compared with classical formulations: (i) order of damage evolution; and (ii) memory (time length scale) of damage evolution. Both parameters allow very flexible modelling of material softening observed in the experiment.

A0827- TORSIONAL FATIGUE FAILURE OF SPRING STEEL WITH SMALL SCRATCHES

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A number of components in the automotive vehicles have various types of compression coil springs. These days, because of the strong demand for better performance of automotive vehicles, the use of high-strength spring steel has been increasing. When the compression coil springs are subjected to high stress, fatigue crack sometimes propagates from small defect or scratching produced in the manufacturing process. In practice, the ability to access the effects of small defects, inclusions and inhomogeneities on the uniaxial fatigue strength has grown rapidly over the last decades. However in a wide range of actual engineering applications, the engineering components with complex geometries (e.g., suspension parts and crankshafts) are usually subjected to multiaxial cyclic loading. Given the substantial knowledge on uniaxial fatigue, it is of practical merit to propose a predictive method that can connect the fatigue strength under multiaxial loading with that under uniaxial loading. Correspondingly in this study, a series of torsional fatigue tests were systematically conducted in the high cycle fatigue (HCF) and very high cycle fatigue (VHCF) regimes. By taking advantage of parameter to represent the effect of scratch, the fatigue behavior of high-strength spring steel with different types of small artificial scratch was examined in a systematic manner.

A0833-Local Multi-scale Effect on Fatigue Failure of Weld Seam

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This paper summarizes assessment methods of fatigue fracture life of weld metal structures and analyses the local multi-scale effect of weld seam on fatigue life. From the overall to the local with different structural level, current fatigue failure analysis methods of weld seam are the nominal stress method, the structure or hot spot stress method, the notch stress method and the crack propagation method. The Overall method include the nominal stress method and the structural or hot stress method. The nominal stress method is utilized to conduct the fatigue strength design according to stress ranges and structural details, and the nominal stress range should not exceed the specified fatigue allowable stress range. The structural or hot-spot stress method is used to establish the common S-N curve with different structural details, and structural details with different hot-point fatigue stresses have proportional relationships. The notched stress method and the crack propagation method belong to the

local method. It is concluded that the fatigue failure of the welded joint starts from the local stress concentration place, and if local circulation parameters are the same, and fatigue performances are equivalent. From the analysis of above fatigue failure assessment methods, it can be seen that fatigue failure analysis of welded structures involves multi-scales ranging from meso-scale to macroscopic scale. Weld seam materials exist small defects, such as inhomogeneity of microstructure, cavities and microcracks. Under the fatigue load, the muiti-scale evolution of the kind of defect is the main factor that causes the fatigue failure of the weld seam. Based on analyses of related literatures, this article considers the influence of microscopic defects of the weld material and discusses the local multi-scale effect on fatigue life of the weld seam.

A0836-A MICROMECHANICS-BASED PHASE FIELD APPROACH TO FRACTURE

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The regularized variational theory of fracture, or so called phase field ap-proach to fracture, has gained popularity due to its ability to predict crack nucleation, propagation, and branching without extra criteria. This approach works by minimizing a total energy functional with the displacement field and phase field (0=intact material, 1=crack) as arguments, and eliminates the cumbersome geometric tracking compared with traditional discrete crack methods such as the extended finite element method. Since 2000, a few variants of this approach have been proposed to account for the unilateral constraint. In this presentation, I will first give a brief introduction to the phase field approach to fracture, and then detail our formulation for the unilateral constraint based on homoge-nization theory and micromechanics.

A0850-MULTISCALE ANALYSIS OF DAMAGE EVOLUTION AND ULTIMATE BEARING CAPACITY OF CONCRETE-FILLED STEEL TUBE STRUCTURES

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Concrete-filled steel tube (CFST) is widely adopted in engineering practice. Their mechanical models for damage evolution and ultimate bearing capacity analysis are mainly developed on the material and structure scales. However, the accuracy and efficiency of the current method are unsatisfying especially for damage evolution and ultimate bearing capacity of complex CFST structures due to lacking of component scale model as an effective bridge between the

material and structure scales. In order to overcome this problem, the material, component and structure scale models, with a self-adaptive linear iteration technique were proposed to evaluate the damage evolution and ultimate bearing capacity of CFST structures. Firstly, the fiber model for evaluating the material property of CFST was developed to investigate the material constitutive relations and to assess the influence of material heterogeneity on the damage evolution including hooking effect, gaps of concrete and initial stress of steel. Secondly, the interaction equations and homogeneous generalized yield function (HGYF) were presented for CFST components by means of the fiber model method and test database. The element bearing ratio (EBR) was then defined as the indicator for damage state of component based on HGYF. Using the proposed elastic modulus reduction strategy, the component damage state and its evolution were simulated self-adaptively according to EBR. Finally, the reference element bearing ratio (REBR) was defined to identify highly-stressed and lowly-stressed components, and the damage evolution and ultimate bearing capacity were then determined by the linear elastic iteration procedure. Due to that the material damage is covered in the simulation of component damage by HGYF-based pre-consideration, the present method does not involve the complex nonlinear damage evolution analysis of material. Hence, the proposed method links effectively the three scale damage evolution processes of material, component and structure and can achieve higher efficiency than the incremental nonlinear finite element method. This method provides a new route to simulate the damage evolution and determine the ultimate bearing capacity of CFST structures and has been applied to some CFST arch bridges.

A0885-A COMPARISON OF THREE DIFFERENT METHODS FOR THE IDENTIFICATION OF HYSTERICALLY DEGRADING STRUCTURES USING BWBN MODEL

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Structural control and health monitoring schemes play key roles not only in enhancing the safety and the reliability of infrastructure systems, but also to optimally minimize the life cycle cost and maximize the performance through the full life cycle design under natural disasters. In this paper, an effective strategy is proposed to identify general hysteretic behavior of a typical shear structure subjected to external excitations. First, the characteristics of the early version of Bouc-Wen-Baber-Noori (BWBN) model and its parametric physical implications are presented using a single degree of system. Subsequently, a time varying shear structural dynamic system is presented for different case studies. By incorporating a “Grey Box” strategy, an Intelligent Parameter Varying (IPV) and Artificial Neural Network (ANN) approach is

introduced to identify the hysteretic behavior of the generalized hysteresis structure using system identification modeling approach. Genetic algorithm (GA) and Transitional Markov Chain Monte Carlo (TMCMC) based Bayesian Updating framework are developed to identify this hysteretic structural system. Correlation analysis and algorithm efficiency are further studied to compare and evaluate the system identification results.

A0892- INFLUENCE OF SURFACE ENERGY ON EFFECTIVE MODULUS OF SOLIDS WITH PERIODICALLY ORIENTED ELLIPTICAL HOLES

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Properties of materials near a free surface are different than those in the bulk, and surface effect gets significant at nanoscale. Massive surfaces exist in heterogeneous material, so when the characterize size of the defeats in heterogeneous material shrinks to nanometers, surface effect can significantly affect their interactions and alter the effective properties and other mechanical performance. In this paper, the defeats are considered as uniform elliptical holes, and based on the surface elasticity theory, the influence of surface effect on the effective properties of nano-porous materials with periodically distributed nanosized holes through finite element calculation and theoretical analysis. Firstly, Using the user subroutine, we will incorporate the influence of surface energy through surface element and calculate the effective modulus of porous materials. Then an analytical expression is also obtained to approximate the effective bulk modulus of nanoporous materials. Finally, the analytical expression of the effective properties of heterogeneous material with surface effect can be presented by the micromechanics method and compared with the finite element results. This project will be helpful with the promotion of material properties by design of surface and its micro-structure, improve and enrich the research of multi-scale failure mechanics.

A0905-DAMAGE EVOLUTION IN FIBROUS COMPOSITES CAUSED BY INTERFACIAL DEBONDING

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Fibrous composites are widely used as structural materials. There are several damage mechanisms in these composites. In particular, the weakening effect of the interface region on the overall mechanical properties of composites plays a significant role in the damage accumulation process. For instance, the interfacial sliding or separation between inclusions and matrix has been described by the nonlinear cohesive zone model by a number of researchers. In this paper, the interfacial debonding in a unidirectional fiber-reinforced composites subjected to axial symmetric loading is investigated. The matrix material is assumed to be a viscoelastic one, and the distribution of the radii of the fibers is assumed to obey the logarithmic normal distribution. A new energy criterion for the debonding is suggested. The Laplace transform method and the Eshelby's equivalent inclusion theory are adopted to evaluate the damage evolution in the viscoelastic matrix material. The reinforcing effect due to fibers and the weakening effect due to interfacial debonding on the overall mechanical properties of the composites are studied. A newly defined volume average method is proposed to derive the macroscopic constitutive relation of the composites. The effect of the material parameters of matrix, as well as size of fibers on the critical stress for debonding and damage evolution is detailed discussed. The results obtained in this paper indicate that the macroscopic strain rate, the distribution of the fiber's radii, the Poisson's ratio of the matrix and the adhesive energy at the interface all play key roles in the overall mechanical properties of the composites.

A0930-Experimental study on effects of shrinkage reducing admixture and moisture on the interfacial properties of new-to-old concrete

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New-to-old concrete interfaces appear in various existing civil infrastructure whenever we need to deal with maintenance and repair. The interfacial failure often leads to surface delamination or/and spalling resulting in a reduction in the service life of the repaired structure. In order to make sure that such preventive measures are long lasting, one must pay attention to the material bonding between the applied layer and the substrate. The interfacial failure is generally caused by the incompatibility between the repair layer and the concrete substrate, because of the difference in shrinkage strain between the concrete substrate and the repair layer. The shrinkage is a natural phenomenon which can be further divided into chemical shrinkage and drying shrinkage. If there are restraints provided by the substrate at the interface, drying shrinkage of the repair material will not be able to proceed freely and will result in the development of stress concentration at the interface, which can lead to premature failure of the repair patch.

It is an effective method to reduce the interfacial stress by minimizing the shrinkage of new concrete, as the shrinkage in new concrete is much higher than that in old concrete. The shrinkage reducing admixture (SRA) is one of the most readily used admixtures in cementitious material in reducing the shrinkage, which can be adopted in the repair layer to enhance the compatibility with the concrete substrate. The working principle of the SRA is to reduce the water surface tension in capillary pore. Although many studies have proven the effectiveness of SRA on reducing the shrinkage, few results have been reported on whether it can enhance the interfacial performance of new-to-old concrete when adopted in the repair materials. Moreover, the presence of moisture has been reported as another key parameter, which governs the shrinkage of repaired material at an early age. The effect of using SRA on the interfacial property of new-to-old concrete under moisture condition needs to be rigorously investigated to ensure the integrity and durability of the repaired concrete structure. In order to capture the failure process of local debonding regions, the fracture-based approach is more favorable compared with strength-based approach. The fracture-based approach provides an initial step to understand how a local crack can result in a global structural failure. The interfacial fracture toughness can be measured to quantify the resistance to crack initiation in local regions, and to predict the crack propagation by macroscale experiment.

The objective of this study is to investigate the effect of SRA on the interfacial fracture toughness and stress induced at interface in new to old concrete. Four-point bending tests will be carried out to measure the interfacial fracture toughness for specimens conditioned under both dry and wet scenarios. Based on our experimental results, we can provide the recommendations from the material perspective and curing methodology to resist delamination and spalling failure of repaired concrete structure.

A0957 -Peridynamics Modeling and Simulation of Fracture and Damage of Composite Materials and Structure under Impact Loads

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In this work, we employ both bonded based- and the state based peridynamics to model and simulate fracture and damage of composite plates under the impact loads. During impact loadings, the composite structure undergoes complex damage and failure. It evolves interfacial or delaminate debonding, mixed with large elastic and plastic deformation. The previous approach of cohesive zone model (CZM) limited its scope on small scale yielding, while the previous bonded peridynamics only considers the elastic deformation treating the composite plates as brittle materials.

The proposed peridynamics formulation can model both delamination as well as impact induced damage and plasticity, and it provides a realistic simulation tool to evaluate facture and damage of composite plates under the impact loadings.

A0984- MODELING OF TIME-DEPENDENT PROGRESSIVE FAILURES IN QUASI-BRITTLE MEDIA BASED ON A STRESS-REDISTRIBUTION MECHANISM

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A new attempt is made to simulate progressive failure processes in heterogeneous materials like concrete, ceramic, rock and so on, by considering the time-dependence of stress redistributions arisen due to local breakages. Two mechanisms of stress redistribution are incorporated in order to embody the influence of each local breakage on the remaining specimen: (1) One is the immediate release of internal forces in the breaking element, which is assumed to happen within an infinitesimal time scale when compared with the characteristic time scale of external loadings. Such internal forces to be released are therefore suddenly applied to the remaining specimen, while the specimen is considered to take time to deform correspondingly due to material viscosity. This deformation delay is implemented by introducing a viscous force (VF) field all over the specimen. (2) The other is the gradual release of previously stored VF fields, whose characteristic time scale is assumed to be material-dependent. Here VF release is approximated as stepwise for simplicity. The proposed model is found to be capable of overcoming the unreasonably-low-ductility issue in existing lattice models. Furthermore, the force-displacement response obviously depends on the ratio of the VF releasing time to the characteristic time of external loading, which has the similar trends as experimental observations. Compared with results with no viscous effect, the failure pattern is more scattering, giving a new physical explanation to the concept of fracture processing zone.

A0991-LOCALINZING GRADIENT DAMAGE MODEL FOR MIXED MODE FRACTURE OF CONCRETE

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Nonlocal integral and/or gradient enhancements are widely used to resolve the mesh dependency issue with standard continuum damage models. However, it has been reported that whereas the structural response is mesh independent, a spurious damage growth is observed. Consequently, a wrong damage profile is predicted. The underlying cause is ascribed to the constant length scale parameter adopted in a conventional nonlocal damage model. To address this issue, a class of modified nonlocal enhancements is developed in literature, where the interaction domain increases with damage. In this presentation, we adopt a contrary view that the interaction domain in a gradient damage model decreases with damage. Physically, this represents the fact that the fracture of quasi-brittle materials typically starts with a diffuse network of microcracks, before localizing into a macroscopic crack. To ensure thermodynamics consistency, the micromorphic theory is adopted in the model development. The ensuing microforce balance resembles closely the Helmholtz expression in a conventional gradient damage model. The superior performance of the localizing gradient damage model is demonstrated for two benchmark examples in mode I and II failures respectively. For both cases, a localized deformation band at material failure is obtained. Finally, we consider several examples of concrete in mixed failure modes. It is shown that the localizing gradient damage model is able to predict accurately the failure profiles, which cannot be obtained with a conventional gradient damage enhancement.

A1007-Progressive failure analysis of deep circular tunnel based on the nonlinear power-law failure criterion using functional catastrophe theory

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A reliable prediction of the progressive failure characteristics of roof collapse in deep tunnels is still one of the most important and challenging tasks in tunnel engineering. In this paper, functional catastrophe theory is used to investigate the progressive collapse mechanisms and collapsing block shapes of deep circular tunnels under conditions of plane strain. The analytical solutions for the shape curve of the collapsing block of circular tunnels are derived based on the nonlinear power-law failure criterion and the non-associated flow rule. Moreover, criterions on progressive failure occurrence for deep tunnels are obtained. Then, the analytical predictions obtained in this paper are compared with experimental testing results. The comparisons show that our analytical predictions are consistent with the corresponding experimental testing results, thus demonstrating the validity of the proposed analytical methodology.

MS3:Damage modelling of engineering structure:from localized cracking to stuctural collapse

A0114-BRIDGING THE MACRO TO THE MESOSCALE: DEVELOPING TENSORIAL DAMAGE MODELS FOR ANISOTROPIC MATERIALS

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Two of the most challenging problems which arise in continuum damage mechanics are firstly the selection of variables to describe the internal damage and secondly the difficulty in modelling materials with significant initial anisotropy such as composites or sedimentary rocks. A severe limitation imposed by many continuum damage mechanics models is the assumption of initial isotropy in many anisotropic damage models. This may place unrealistic assumptions about the material being modelled or restrict the application of continuum damage mechanics to materials without significant anisotropy. It remains a challenge to use continuum damage mechanics to model common rocks and materials with significant initial anisotropy, for example sedimentary rocks or brittle composite materials. Many theories have been proposed and various types of damage variables ranging from scalar to vector to tensor quantities have been used. In this paper we consider anisotropic damage and the most general form for damage by using a fourth order tensor for the damage variables. We demonstrate how experimentally measured quantities can be related to the internal tensorial damage variables. We apply this analysis to experiments of initially isotropic or anisotropic solids becoming anisotropic (with a change of symmetry class or magnitude of anisotropy) under loading.

We have developed methods to identify the directionality and magnitude of the introduced damage using experimental ultrasonic measurements of damaged elastic moduli. This analysis provides a robust way to validate and advance models of general anisotropic damage evolution based on continuum damage mechanics. This represents a significant advance in the development of anisotropic damage models based on continuum damage mechanics which until now have not been able to be experimentally verified and tested.

Modelling and analysis of fracture propagation and progressive damage evolution are integral for damage-tolerant design in structural, geotechnical, mechanical, and civil engineering. In many geotechnical applications such as unconventional oil and gas extraction, carbon dioxide sequestration, nuclear waste disposal and geothermal energy extraction, the initial anisotropy of the rock can impact on the stability of structures such as cavities, wellbores, or hydraulic fractures. Anisotropy is also an important factor in producing composites with optimum utilisation of the inherent strengths of the constituent materials. Manufacturing materials with optimum strength properties is important in reducing safety margins and cutting costs. With the rapidly growing advancement in material design and the increasing reliance on unconventional anisotropic reservoirs for energy, the assumption of scalar isotropic models of damage may not suffice and this research aims to develop more accurate models of anisotropic damage for initially anisotropic materials.

A0340-ANALYTICAL PREDICTION OF THE RESPONSE OF STEEL FIBRE REINFORCED CONCRETE BEAM ELEMENTS UNDER BENDING

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The stress-strain relations of construction materials are essential for accurate prediction and analysis of structural responses. These relations are normally obtained by conducting uniaxial compressive and tensile tests of the material. For steel fibre reinforced concrete (SFRC) materials, while the uniaxial compressive tests can be easily performed, however, it is very difficult to conduct the uniaxial tensile tests. Therefore current practices either assume a tensile stress-strain relation or utilise data from bending tests ignoring the size effect of specimens to analyse and design SFRC structural elements. This study carried out uniaxial compressive and, especially, tensile tests of SFRC material for obtaining accurate stress-strain relations. Hooked-end steel fibres were used to prepare the SFRC material with fibre volume fraction of 1%. An analytical model directly from accurate stress-strain relations was proposed to predict SFRC beam elements under flexural load. Apart from uniaxial compressive and tensile tests, bending tests on un-reinforced SFRC prisms and structural beams with reinforcing bars were also conducted for validation. The analytical predictions using the current model and those available in the literature were compared with the test results. The precision and advantage of the analytical model proposed in this study were demonstrated.

A0387-A MULTI-SCALE ANALYSIS BASED STOCHASTIC DAMAGE MODEL OF CONCRETE

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The relationship between microscopic and macroscopic material properties are presented based on the multi-scale method. It is equal to say that the macroscopic damage evolution can bee obtained from the micro-cell simulation results. Then, two kinds of typical micro-cells are generated for the macroscopic tensile and shear damage evolution. In order to apply the damage evolution from the micro-cell analysis to the engineering simulations, a pragmatic damage evolution law is put forwards for the tensile and shear damage and the damage evolution parameters can be obtained. Comparison between simulation and the experimental results are given to testify the validity of the present model. It is demonstrated that the model agrees well with the experimental results.

A0400-Analysis of Damage Zone at Macro-crack Tip

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The numerical solution of an infinite elastic plate containing a macro-crack and a cluster of micro-cracks under mode I load is presented based on the Muskhelishvili's complex potential method. The stress intensity factors (SIFs) at the tips of both the macro-crack and the micro-cracks are obtained for different arrangements of micro-cracks near the tip of the macro-crack. The results show how these arrangements affect the macro-crack SIF, and the influence of micro-crack orientation, length and the distance between macro-crack and micro-cracks on the SIF of the macro-crack.

A0425-EFFECT OF DAMAGE THRESHOLD IN HIGH RATE SEVERE PLASTIC DEFORMATION IN ORTHOGONAL CUTTING ELUCIDATED VIA FINITE ELEMENT SIMULATIONS

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Orthogonal cutting processes for ductile materials imposes severe plastic deformation, which involves ductile material failure at high strain-rates and the accompanying temperature rise. Plastic constitutive model parameters, ductile damage initiation parameters, damage evolution and damage threshold are directly affected by the complicate interactions among the thermomechanical conditions during the cutting process. It is vital to determine the material failure parameters for high strain, high strain-rate and the couple temperature rise for the finite element simulation of cutting process, since reasonable parameters estimation can potentially lead to reliable solutions for cutting force, thrust force, temperature rise and residual stress among others. This study presents experimental results for damage initiation constants for various strain-rates and temperatures conditions as well as their effects on damage evolution and damage threshold. Simulations with different damage parameters are presented and compared with previous works to identify the effect of these constants in force results. Finally, temperature rise due to plastic work and damage evolution is compared with experimental data obtained for various cutting conditions.

A0446-DAMAGE IN FRAME ELEMENTS SUBJECTED TO CYCLIC LOADING

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In structural analysis, material nonlinearity, as the essential aspect of numerical procedure, should include both plasticity and damage. During cyclic loading, indicators of material behavior, such as stress-strain or moment-curvature relations are often represented in form of hysteresis. Application of hysteretic operator in elastoplastic damage analysis of frame structures is presented in this paper. Preisach model of hysteresis is used, where isotropic damage is incorporated in analytical solution for material model with two approaches. The first approach represents combination of classical continuum damage theory coupled with analytical solution for elastoplastic analysis. The second approach represents closed form analytical solution for elastoplastic damage analysis defined with Preisach model of hysteresis. Using finite element method and fiber approach, existing implementation of this model in structural analysis of trusses, is expanded to frame elements. The aim of this paper is to determine influence of various parameters of analysis and beam element formulation on results in numerical examples, where some aspects of convergence and numerical performance of analysis are presented as well.

A0467-The effect of void defects on the elastic properties of 3D woven composites

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It is unavoidable to have void defects in 3D woven composite materials, which can obviously affect the elastic properties of the materials. In this paper, void defects are divided into two parts: the void in fiber tows and matrix of the woven composites. Multi-scale analysis has been conducted to get all nine elastic moduli. Analytical equations considering void effect are proposed to predicted the elastic moduli of fiber tows. The results show that the elastic moduli of 3D woven composite are more sensitive to the voids in fiber tows than those in matrix of woven composites.

A0487-EXPERIMENTAL ANALYSIS AND MODELLING OF FATIGUE CRACK INITIATION MECHANISMS

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The present work is devoted to simulation of fatigue crack initiation in materials subjected to cyclic loading within the nominal elastic and elasto-plastic regimes. The usual approach is based on averaged stress or strain amplitudes, with numerous fatigue conditions formulated for uniaxial or multiaxial stress states. However, the process of fatigue damage growth is of local nature and the account for stress fluctuations should be included. In FCC polycrystalline metals or alloys the interaction of persistent slip bands or twin boundaries

with grain boundaries generates stress amplitude concentration leading to subsequent crack initiation. The extensive review of the microstructure effect on crack initiation was provided by Sangid. The other source of stress fluctuation is related to grain imperfection generating the localised strain concentrations. Using the potential offered by novel experimental techniques it is possible to identify physical phenomena and to study evolution of the fatigue induced degradation. In the present work the analysis of strain localization preceding crack initiation was performed by means of the optical method ESPI, namely the Electronic Speckle Pattern Interferometry apparatus using the coherent laser light. The local stress-strain response in damage zones was analyzed by applying nano-indentation tests. The proposed mathematical description of fatigue damage growth and crack initiation is based on the concept of critical plane. The damage growth on the material plane is related to evolution of surface tractions. The condition of damage accumulation is formulated after Mróz et al., introducing the grain boundary stress fluctuation function. It is assumed that, when the critical stress condition is achieved on the material plane, a damage zone is generated. Afterwards, a growth of damage zone can be described. In the steady state the process of cyclic loading is described for the period of stress variation. It was noted that the influence of edge defects on the damage evolution and crack initiation is significant. In order to account for the edge effect, the edge stress fluctuation function is also introduced. The proposed model was applied to study damage evolution under cyclic tension, with its parameters calibrated by the experimental data. Moreover, the fatigue lifetime calculations are carried out using the proposed damage accumulation model and compared with some available models.

A0520-APPLICATION OF DIFFERENT HARDENING RULES IN CONSTITUTIVE MODEL OF CONCRETE

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The majority of coupled plasticity-damage model for concrete employ the same form of hardening law for compressive/tensile yield stress. They can often get agree well with the experimental stress-strain curves while compression is dominant, but always overestimating the ductility of the concrete in tension. This paper adopts different hardening rule in order to better simulate the stress drop phenomenon for concrete in tension. The implicit return-mapping numerical algorithm is coded using UMAT and then implemented in Abaqus.

A0541-ON THE INFLUENCE OF THE STEEL-CONCRETE BOND MODEL FOR THE SIMULATION OF REINFORCED CONCERTE STRUTURES USING DAMAGE MECHANICS

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When dealing with the simulation of reinforced concrete structures, the bond model between steel and concrete can become a key point if crack properties are studied. The interface between both materials is indeed partly responsible for stress transfer and consequently for the crack spacing and openings. In the context of finite element simulations using damage mechanics for concrete, it is proposed to evaluate the influence of the relation between steel and concrete by comparing two solutions: a perfect relation for which the two material keep the same displacement at the interface ("perfect bond") and a recently developed bond model in which the sliding is allowed. The approaches are compared on three applications: a reinforced concrete tie, a bending beam and a shearing wall. The competition between damage of concrete and sliding of the bond is particularly investigated. The interest of including a fine description of the steel-concrete bond rather than a simple perfect relation between materials, regarding the simulation of local properties (crack openings especially) depends on the type of applications (loadings) and on the expected crack pattern (and/or distribution of steel). Whatever the case, solutions exist to correctly capture the crack properties, even for structural applications.

A0593-AN NEW ELASTIC–PLASTIC–DAMAGE MODEL FOR CONCRETE UNDER PSEUDO-TRIAXIAL COMPRESSION

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This study aims to develop an elastic–plastic–damage model for concrete,which is based on the yield criterion proposed by Willam.Two damage variables and two hardening variables are introduced to simulate strength and deformation characteristics and stiffness degradation effect when the concrete is in low confining pressure. A series of numerical simulations for concrete under pseudo-triaxial compression are carried out using iterative return-mapping algorithm in and compare with the experimental result.

A0619-Challenges in the scale-bridging modelling of components made of heavy-plate material

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Components made of heavy-plate material play an important role in infrastructure and industry applications such as steel constructions, bridges, pressure vessels, ships, offshore

platforms, utility vehicles and mobile cranes. Usual material thicknesses range from 10 to 30 mm while the components are mostly large-scaled, covering several meters of length and height. High strength low alloy steels (HSLA) are available for such applications. These modern grades show high strengths up to yield strengths of 1300 MPa while maintaining excellent toughness values above 100J at room temperature. Yet, these steels are only applied for a minority of the abovementioned application fields, e.g. in mobile crane design. In the overwhelming majority of application fields, there is a prevalent skepticism towards the safe applicability of these steel grades. Damage mechanics modelling may help to overcome this skepticism as it is able to precisely describe the failure behavior of high strength steels. Yet, most damage mechanics models were developed on experimental results of laboratory samples, not large-scaled components. Thus, their transfer to large-scaled components involves some challenges to be solved, such as the calibration and meshing strategy. Of special interest is the correlation of certain material properties, which were determined on laboratory samples, and the component failure behavior. This includes the scale-bridging of damage mechanics models from the millimeter-scale to the meter-scale. The proposed contribution introduces the corresponding challenges, discusses solution strategies from the literature, such as meshing strategies used in ship modelling. Moreover, lessons learned from two case studies will be presented: One study on pressure vessel modelling and one on the failure of steel constructions, both including experimental large-scale testing as well as damage mechanics failure modelling

A0638-A STUDY ON DYNAMIC BOND STRENGTH OF RC MEMBERS WITH REINFORCEMENT CORROSION

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In disaster-prone Japan, the number of the reinforced concrete (RC) structures with reinforcement corrosion is increasing, which makes it important for the evaluation of the residual load capacity of these structures to be conducted against not only the static loads but also the dynamic and impact loads. To evaluate the residual load capacity of aged RC members, it is important to reveal bond condition and strength between a corroded reinforcement bar and its surrounding concrete. This study focuses on the development of a damage-based model that can be evaluated the dynamic bond strength of RC members with reinforcement corrosion. At first, an impact push-in experiment was conducted to grasp the influence of both loading rate and reinforcement corrosion on the bond strength. Through this experiment, a damage-based model regarding the dynamic bond strength considering the loading rate effect and corrosion rate was developed. After that, a FE analysis is conducted by using the model, the validity of the proposed model was discussed by comparing the results with experiment data.

A0767-CORROSION DAMAGE MODEL OF BOLT BALL JOINTS WITH CORROSION DAMAGE.

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The durability of the lattice domes is poor in a highly corrosive environment. With the increase in service time, the aggravation of corrosion at joints will lead to the decrease of the ultimate bearing capacity of the lattice domes, and finally the overall failure of the structures. However, at present, the studies on the aggravation of corrosion at joints of lattice domes are limited both at home and abroad. Therefore a pioneering study of the damage model of the joints is performed in the paper. Based on the theory of contact mechanics, constitutive relationship of steel with corrosion damage and the load-bearing mechanism of the bolt ball joints, a corrosion damage model of joints is established through fine numerical analysis, considering different corrosion time and a large number of tension simulation calculations. Then a load - displacement curve of the process can be gotten. The stiffness changes in the whole loading process, the ultimate bearing capacity and failure mode of joints can be estimated then. Therefore the relationship between corrosion mass loss rate and joint stiffness will be obtained and finally corrosion damage model of joints is established.

A0921-Numerical investigation of ductile fracture behavior on aluminum laser welded joints

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In this paper, the Gurson-Tvergaard-Needleman (GTN) model is adopted to investigate the ductile crack propagation in aluminum laser welded joint. Based on the combined method of experimental investigation and numerical calibration, the GTN parameters are fixed. The same parameters are used to predict the ductile fracture of compact tension specimens with the initial cracks located at different weld regions. Finally, results from fracture mechanics tests are compared to numerical ones, with respect to fracture resistance.

A0922-MICROSTRUCTURAL DEGRADATION AND ITS EFFECTS ON LOW CYCLE FATIGUE OF A DIRECTIONALLY–SOLIDIFIED NICKEL–BASE SUPER-ALLOY

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Pre damage matrix consisted of exposure time and temperature was made on DS superalloy DZ125. Microstructure evolution changed with exposure time in 980°C. The low cycle fatigue (LCF) mechanical properties evaluation of exposure specimen was conducted under 850°C, 810MPa with 0.1 stress ratio. The experiment result shows that there exist isotropic coarsening of precipitates in pre-exposure DS superalloys. Pre-exposure damage effects mechanical properties of DZ125, in addition, LCF life degrades with exposure time. Pre-exposure damage effects crack-initiation/ does not effect crack-initiation of DZ125. Additionally, a continuous damage model (CDM) containing microstructure degradation damage was put forward and validated.

A0927-Size effects on damage crack growth: Fractality and scaling of fatigue threshold and fatigue limit

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The prediction of fatigue life can be performed through two different methods: the first one, based on Paris' law, relates sub-critical crack growth rate to the stress-intensity factor range, whereas in the second, based on Wöhler's curve, the applied stress range is a function of the number of cycles to failure. These two different approaches can be intimately connected through the use of incomplete self-similarity and fractal modeling, so that anomalous crack-size and specimen-size effects are considered. In the first part of the paper, generalized Paris' and Wöhler's laws are derived in accordance with dimensional analysis and incomplete self-similarity concepts, which are able to provide an interpretation to the various empirical power-laws used in fatigue problems. Subsequently, through the use of a different approach, based on the application of fractal geometry concepts, similar scaling laws are found. In other words, for Paris' law, the assumption of the invasive fractal roughness of crack profile implies the incomplete self-similarity in the problem. Vice versa, for Wöhler's curve, the material ligament is considered as a lacunar fractal set which, taking into account a cross-sectional weakening, provides the incomplete self-similarity in the problem.

In the second part of the paper, on the basis of the scaling laws previously defined, it is possible to obtain the crack-size dependence of fatigue threshold, so that the so-called anomalous behaviour of short cracks with respect to their longer counterparts can be explained. Likewise, considering Wöhler's curve, the specimen-size dependence of fatigue limit can be put forward.

In other words, the hypothesis of the invasive fractal roughness of crack profile provides an explanation for the increment in the fatigue threshold with the crack length, whereas the

assumption of the lacunar fractal ligament is able to explain the decrement in the fatigue limit which occurs as the specimen size increases. Eventually, the proposed models are compared to experimental data available in the literature.

A0981-EXPERIMENTAL AND NUMERICAL RESEARCHES ON FRACTURE OF COARSE GRAINS

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The paper presents the laboratory experiments and numerical simulation which comprise the single-particle crushing test and the one-dimensional compression test on different particle sizes that are intended to study the characteristics in the crushing behavior of the coarse grains. The Weibull statistics is applied to the soil particle and numerical the single-particle crushing tests were carried out. The results show that the smaller particle size has the larger tensile stress, and the Weibull modulus could be taken to be 3.24 for the coarse grains. And the numerical results agree with previous single-particle crushing test results. In the one-dimensional compression tests, axial stress levels ranged from 1MPa to 100MPa. It could be found that the particle size has influence on particle breakage, volume deformation and input work. The plastics behaviors of numerical modelling of the crushable aggregate are closed to the real coarse grain. The relationship between axial stress and input work could be obtained. The prediction of input work was in good agreement with the test data of the volume strain. And the algebraic expression about relative breakage index and volume deformation also can be established.

A1023-A MULTI-SCALE COMPREHENSIVE SIMULATION OF TWO 9-STORY REINFORCED CONCRETE SHEAR WALL MODELS

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Concrete structures are widely used in China. The safety of such structures subjected to earthquakes is of great importance. The accurate prediction and simulation of concrete structures is always a challenge due to the coupling of randomness and nonlinearity in the

different scales from material to structure. Therefore, a scientific thought of multi-scale comprehensive simulation including numerical and physical modeling of material scale, medium scale and structural scale was proposed. This is a novel approach to study the nonlinear behavior and reliability of concrete structures. As a part of the research plan, two 9-story 7.5m concrete shear wall models were tested in the shake table laboratory of the State Key Laboratory of Disaster Reduction in Civil Engineering of Tongji University. Meanwhile, the concrete specimens which were casted during the construction period of the two models were tested for the full stress-strain curve. By doing so the practical rather than a prior information in the material scale can be incorporated into the simulation of structural behaviors. In particular, numerical simulations of the structure by embedding different constitutive laws, including the continuous damage plasticity model, the random damage constitutive model, and the random damage constitutive model involving the effects of softening due to tension, are performed. Comparisons of the results reveal unignorably differences, showing the crucial role of constitutive law of concrete in structural behaviors, and also justifying the importance of the thought of multi-scale comprehensive simulation in capturing the performance of real-world concrete structures. A detailed discussion about the test and numerical simulation will be given in the full paper.

A1027-STUDY OF PZT5 IN DOMAIN SWITCHING UNDER COMPRESSIVE LOADING

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Piezoelectric (ferroelectric) ceramics may cause change of domain structure (i.e. domain switching) under the action of force. This kind of change directly affects the macroscopic properties of the material. In this paper, the methods of resonance frequency, hysteresis loop and X- ray diffraction are used to investigate the domain switching of PZT5 under quasi-static loading and impact loading. The quasi-static load is realized by the MTS hydraulic servo test machine, and the dynamic load is realized by the separated Hopkinson pressure bar (SHPB) measuring device. The experimental results show that the stress-strain curves of PZT5 have obvious strain rate effect, but the stress-displacement curves don't have that under impact loading. The change of PZT5's resonance frequency under quasi-static loading is much larger than impact loading. The percentage of domain switching in PZT5 increases with stress. The main factor of domain switching is stress and the loading time and strain rate are the minor factor.

A1033-UNCERTAINTY QUANTIFICATION FOR STUCTURES WITH RANDOM PARAMETERS OF CONCRETE STOCHASTIC DAMAGE MODEL

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In this paper, a basic uncertainty quantification framework is established for reinforced concrete (RC) structures with the stochastic damage constitutive model. A simple one-

dimensional damage constitutive model of concrete adopted in Chinese design code is firstly introduced. Then, the embedded random parameters are statistically analyzed with a general nonlinear dimension-reduction method, aiming to simplify the application on engineering purposes. The uncertainty quantification frame work is based on a well designed 10-floors plane RC frame structure, as well as a 13-floors 3-dimensional RC frame-shear wall structure. The finite element models of these two designed structures are built with OpenSEES software, which are both verified and validated yet. Then the concrete constitutive model is considered by adopting the stochastic damage model, while the deterministic elastic model and elastic-plastic model are also taken into account for calculations as reference. The probability density evolution method (PDEM) is utilized for stochastic structural response analysis, where the stochastic ground motion process is generated by a physical stochastic model. The results indicate that there are different response properties of RC structures with the concrete stochastic damage model, compared with the other two constitutive models. Moreover, these uncertain properties quantified by PDEM can be shown vividly, which is convenient for the reliability assessment.

A1038-NUMERICAL SIMULATION ON TORNADO-INDUCED COLLAPSE OF A SUPER-LARGE COOLING TOWER

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For thin-wall and super-large hyperbolic cooling towers, wind action belongs to the predominant design loads. Under the conditions of extreme wind environments, wind-induced collapse mechanism of nuclear cooling towers must be evaluated due to the requirement of resistance for extremely low probability of failure. For this purpose, the full collapse process of a reinforcement concrete cooling tower with 215 m high was conducted using the explicit-algorithm program LS- DYNA. Surface pressure of the cooling tower under the state of a moving tornado were obtained utilizing the tornado generator and synchronous pressure-measured wind tunnel test, then the equivalent 3-D pressure was imposed on the FEM model of the cooling tower. The developing process of displacement and strain of shell layers during the collapse were illustrated, then compared with those under synoptic wind action, and with results from linear stability analysis. It can be concluded that the loss of material strength would be responsible to the failure of the cooling tower under synoptic winds and tornadoes, rather than the snap stability effect.

A1054-A physically stochastic fatigue damage model for concrete

Wang Yanpeng, Li Jie

Based on the classical rate process theory, a stochastic damage model that is suitable for fatigueloaded concrete is proposed in the framework of microscopic stochastic fracture models. Besides the often used fracture criteria that are either based on micro strength or micro strain, a new criterion which is based on energy dissipation of micro elements is built. The quantity of energy dissipation of each micro element is related not only to the external load but also to its own internal structure, and can be obtained based on mechanical analysis of crack growth on the nanoscale. Calculations have shown that the proposed model can both reproduce the nonlinearity in damage evolution and scatter in lifetime of concrete specimens subjected to fatigue loading. By the way, origin of the randomness in macro fatigue behavior of concrete seems to be correctly found for the first time. The mechanism underlying typical three-stage characteristic of fatigue damage evolution is illustrated as well.

A1068-PROBABILISTIC MODEL OF THE YIELDING STRENGTH FOR THE CORRODED REBARS

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Corrosion of the rebar is the major trigger of the durability degradation and the bearing capacity decrease that induce the crack of the cover, the degradation of the bond performance and the bearing capacity of the rebar. Therefore, the bearing capacity will be decreased and even the failure model of the RC members may change from the plastic failure to the brittle failure. Only when the variety of the yielding strength of the corroded rebar has been acquired, the degradation of the bearing capacity, time-dependent reliability, and the predication of the life-time can be predicted accurately. In this paper, the 1704 test data collected from 31 references were adopted. According to working conditions, the data were classified into three groups which were constant current accelerated corrosion(CCAC), accelerated corrosion test in simulated environment(ACTSE) and in-suit corrosion of the actual RC members(ISCA). Based on the existing research, the yielding strength of the unstainable part of the corroded rebar is the same as the normal rebar. Accordingly, the key issue is to obtain the minimum cross-sectional area of the corroded rebar for the different corrosion rate.

By using statistical analysis and distribution test, the probability distribution model of the normalized relatively minimum section K of corroded steel bars under three working conditions has been established. According to the analyzed results, it is found that the change of the mean value of KISCA is minimal with the increase of the corrosion rate, while the mean value of KACTSE decreased the most. Thereby, when CCAC and ACTSE methods are adopted to simulate the corrosion of the rebar, the normalized relatively minimum section K should be revised by the formula presented in the paper. Meanwhile, the distribution of the mean value of KISCA is more scattered when the corrosion rate increase. The presented probabilistic model of the yielding strength for the corroded bars was verified by using the confidence interval of 50% and 95%. When the confidence interval is 50 percent, more than half of the

data was in the confidence interval. Almost all of the data is in the confidence interval when the confidence interval is 95 percent. It is proved that the probability distribution model of KISCA proposed in this paper is accurate and reliable, and has good applicability.

MS4:Model-Based Simulation of damage and failure in solids and stuctures

A0072-INVESTIGATION ON FIRE RESISTANCE OF STEEL-FIBER REINFORCED CONCRETE BEAMS AFTER IMPACT LOADING

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To explore the fire-resistance of steel-fiber reinforced concrete beams after impact loading, 4 beams were tested with high-performance drop-weight test system, four point bending test machine and assembled electric furnace. The beams were first subjected to impact loadings and then exposed to fire with a constant load. During the test process, the failure patterns of beams were observed and time histories of mid-span deflections were recorded. Then, fire resistance of these beams were discussed. Based on the experiment, three-dimensional finite element numerical model considering the effects of strain rate and high temperature were established. The impact loading process was simulated firstly; and then taking simulation results as the initial state, SFRC beams subjected to both fire and constant loading was simulated with a sequentially coupled thermal-stress analysis method. Good agreement between the simulation results and the test results illustrates the rationality and effectiveness of the present numerical analysis method. It has been found that when the impact energy is less, though the surface concrete is cracked, the beam is still in an elastic stage and shows good fire resistance. Moreover, the failure patterns of SFRC under the impact load is changed from shear failure to bending failure with the increase of steel fiber dosage.

A0234-DAMAGE AND SELF-HEALING OF CEMENTITIOUS COMPOSITES WITH MICROCAPSULES

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The microcapsule-based technology has become one of the main streams in self-healing micro-cracks in concrete because of the intelligent perception and immediate repair of the damaged parts. The mechanical behaviors are the main concern for the macroscopic properties of the construction materials, which are directly related to the microstructure of the material. A novel type of organic microcapsules-based self-healing cementitious composite materials are being developed in Guangdong Provincial Key Laboratory of Durability for Marine Civil Engineering at Shenzhen University. In this study, the damage and self-healing responses of the cementitious composites with organic microcapsules are investigated through experiments on the compressive strength and the micro-porosity. The damage responses of the cementitious composite specimens are monitored under uniaxial compression. The pore structure distribution is quantitatively measured using X-ray computerized tomography (X-CT). After 7 days healing in the cabinet with constant temperature and humidity, the relevant tests for the healed status of the specimens are carried out. The relationship of the healing efficiency between the parameters of pore structure and the compressive strength is presented for different contents of microcapsules.

A0239-MULTISCALE FINITE ELEMENT METHODS FOR THE SIMULATION OF STRAIN LOCALIZATION AND CRACK PROPAGATION PROBLEMS

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Multiscale finite element methods are proposed to simulate the strain localization and crack propagation problems in homogeneous and heterogeneous materials. The kinematic descriptions of the localization and crack are considered based on a set of fine-scale meshes with the Cosserat continuum model or the strong discontinuity model. Then an enhanced coarse element strategy, in which additional coarse nodes can be dynamically added according to the propagation of shear band or discontinuity line, is developed to construct the multiscale numerical base functions that can well capture the localization or discontinuous characteristics and transform the information between the fine scale and coarse scale. The mechanical problems are then solved in a coarse-scale mesh by upscaling from the fine-scale meshes based on the developed enhanced coarse element strategy. The displacement decomposition technique is adopted to modify the downscale computations by adding the perturbation solutions and thus the microscopic displacement can also be accurately obtained. Numerical examples are carried out to demonstrate the effectiveness and high efficiency of the proposed methods. These works are supported by NSFC (11672062 and 11772082).

A0320-RECENT ADVANCES IN SIMULATING COUPLED THERMOMECHANICAL FAILURE EVOLUTION WITH THE GENERALIZED INTERPOLATION MATERIAL POINT METHOD

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To better simulate the coupled thermomechanical failure evolution, a computer test-bed is being developed within the framework of generalized interpolation material point method (GIMP). In addition to the formulation in the x-y-z rectangular coordinate systems, an axisymmetric GIMP for fully coupled thermomechanics (AxiCTGIMP) is also being formulated based on the weak forms of both conservation of momentum and conservation of energy. The loading rate-dependent thermoelasto-plasticity model (Johnson-Cook model) combined with the Johnson-Cook damage model is used for constitutive modeling of failure evolution. The model-based simulation procedure is verified and validated against available solutions and experimental data. The effects of the initial velocity on the impact induced temperature, deformation and damage distribution of the Taylor impact test are particularly analyzed. Future research tasks are then discussed based on the reported findings.

A0334-MICRO IMAGES RELATED TO THE SIZE EFFECT ON THE POST-PEAK RESPONSE OF CONCRETE UNDER UNIAXIAL COMPRESSION

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Based on X-ray microcomputed tomography (X-ray μCT) and its inner loading platform, the micro images related to the size effect on the post-peak response of concrete specimens under uniaxial compression are in-situ monitored and evaluated in this study. The two- and three-dimensional morphology during the damage evolution is respectively obtained. Furthermore, compressive strength, stress relaxation and damage variable-based size effect are quantitatively investigated. The reported findings provide the useful information required for improving micromechanics-based damage modeling of concrete in the future work.

A0362-Effects of Fluid-structure Interaction on Nonlinear Seismic Response of Deep-water High Hollow Bridge Pier

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This paper uses full fluid-structure numerical method to investigate the characteristics of nonlinear seismic responses of a typical deep-water hollow bridge pier. With the bilinear moment-curvature beam elements and 3D solid elements modeling the hollow pier and potential-based fluid elements modeling the water domain, three dimensional finite element models for the typical deep-water bridge pier are built. Through nonlinear time history analyses, seismic responses of the deep-water bridge pier under different water levels are studied for two cases where the hollow pier contact with outer water only and both outer and inner water. The numerical results indicates that when water depth is lower than half of the pier height, the effects of fluid-structure interaction have little impact on the structural nonlinear seismic responses, however, the impact becomes obvious at a higher water lever. With the increase of the water level, the curvature ductility demand and shear force at the bottom of the hollow pier are significantly enlarged, and the damage index of the bridge is amplified due to the effects of fluid-structure interaction. The existence of the inner water causes further demand of the curvature ductility which may lead to severe damages to the deep-water piers. These findings can provide valuable guidance for future deep-water bridge design.

A0568-INVESTIGATION ON PROTECTIVE PERFORMANCE OF A MULTI-LAYER FABRIC COATED ALUMINUM PLATE TO HYPER VELOCIT IMPACT

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Due to their excellent impact-resistance, anti-fatigue and energy absorption capacity, fabrics and flexible composites are frequently used in protective structures to enhance their protective capacity. For example, a multi-layer fabric coated aluminum plate is usually used in the hard-upper torso (HUT) of a space suit to protect astronauts from getting hurt by space dust, where the multi-layer fabric consists of an outer-layer fabric, a multi-layer insulation (MLI) layer and a liner layer. The MLI layer is composed of aluminized films separated by gauzes. In this presentation, the protective performance of the multi-layer fabric coated aluminum plate is investigated. To establish its ballistic limit equation, thirteen hyper velocity impact tests with different impact velocities (maximum velocity is 6.19km/s) and projectile diameters have been conducted. To provide data for impact velocity higher than 6.2km/s which is hard to be obtained by tests due to the limitations of test equipment capacity, a material point method (MPM) model is established for the multi-layer fabric coated aluminum plate and validated/corrected using the test results. An equivalent laminated plate model is established for the MLI layer to avoid discretizing its each single-layer which is too thin. The numerical results obtained using the corrected MPM model for impact velocity higher than 6.2km/s are used together with the test results to develop the ballistic limit equation. The corrected MPM model and the ballistic limit equation developed for the multi-layer fabric coated aluminum plate provide an effective tool for the space suit design

A0655-NUMERICAL SIMULATION ON WIND INDUSED COLLAPSE OF A SUPER-LARGE COOLING TOWER

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For thin-wall and high-rise cooling towers, wind load is one of the critical design loads. However, wind-induced collapse mechanism, especially extreme winds, of cooling towers has not been fully understood. Using the explicit-algorithm program LS-DYNA, a 3D finite element model of a 215m cooling tower was built, with nonlinear material models employed. Wind-tunnel experiments of wind-induced pressure under tornado wind fields were conducted, with corresponding equivalent static wind load suggested, which, along with gravity force, were slowly (quasi-static) imposed on the model, and the collapse process and the strain of different tower shell layers were obtained. The collapse process of synoptic wind field and tornado wind field were compared, and wind-induced collapse mechanism was carefully studied.

A0698-Dynamic responses of copper under high-velocity impact of micron particles in the cold spray process

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Cold spray (CS) is a promising coating technique based on high-velocity impact of micron particles. CS technique is applicable for a wide variety of materials and the original micro-structure of sprayed material can be maintained, which are great advantages over conventional thermal spray techniques. CS is now considered as a promising additive manufacturing method owing to much lower working temperature. The high-velocity impact is the kernel process during cold spraying, which involves damage, large deformation, and failure of the sprayed material and the substrate. The finite element method (FEM) has been widely applied in the investigation of cold spray process. But traditional FEM encountered many difficulties such as mesh distortion when dealing with large deformation and material failure. The material point method (MPM), which is one kind of meshfree particle methods, does not have mesh distortion difficulty and it is much easier to describe material failure in MPM framework. The MPM is applied in the simulation of impact of micron copper particles on copper substrate in this work. It is demonstrated that the extremely large deformation and metal jetting at the rim of the particle can be well described, and the final configurations agree well with the experiment results. Single and multiple-particle models are investigated to obtain possible bonding mechanism between the sprayed particles and the substrate.

A0717-Mechanics of Multi-layer Graphene and Graphene/Polymer based Nanocomposites under Extreme Loading Conditions

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There have been considerable efforts to design high performance nanocomposites that employ layer-by-layer structures, mimicking biomaterials which are robust under extreme loading conditions. Recently, multi-layer graphene (MLG), with advantage of their exceptional strength and modulus, have emerged as ideal armor materials to resist ballistic impact. In addition, due to its abundant interfacial interactions with polymer matrix, it is also an ideal building block for constructing high-performance nanocomposites. To harness the superior mechanical properties of graphene/polymer nanocomposites, it is crucial to understand the mechanical properties and deformation mechanisms of the constituents and also the interfacial mechanics between MLG sheets and polymeric matrix, starting from nano-scale.

Taking advantages of our recently developed coarse-grained molecular dynamics (CG-MD)

models of MLG, we first examine how width and thickness of MLG sheets can influence their ballistic performance. We reveal that the reflected cone wave and spalling-like failure mechanism during ballistic impact both result in easier perforation for graphitic barriers, which decreases their ballistic resistance. Next, we design a nacre-inspired layered architecture of MLG-PMMA nanocomposites. Utilizing the CG techniques and by performing deformation simulations, we characterize the interfacial behaviors of the designed system as well as identify critical sizes of MLG sheets that govern failure modes, which significantly influence the toughness. Last, we demonstrate how the layered nanocomposites outperforms their constituents under ballistic impact, by possessing wave-filtering or band-gap capability.

I will discuss all the results in the context of theoretical framework based on continuum mechanics models and CG-MD simulations, and hopefully present effective optimization strategies to design mechanically robust nacre-inspired MLG-polymer nanocomposite systems.

A0773- DEFORMARTION BEHAVIOUR OF 3D PRINTED ROCK-LIKE MATERIALS WITH DIGITAL IMAGE CORRELATION

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Understanding the cracking processes of rock is important regarding the fundamental material behavior and in engineering applications. Characterizing and predicting the deformation behavior and cracking processes in brittle rocks is necessary for accurate assessing the stability of rock structures. To investigate the cracking processes in rocks under uniaxial loading, 3D printing technology is coupled with digital image correlation (DIC) method. An intact disc specimen for Brazilian test and a notched semi-circular bend specimen for three point bending test were prepared by 3D printing technology and loaded under quasi-static uniaxial loading conditions. The tests were synchronized with a digital camera to record the images of entire loading process for deformation analysis. DIC was then applied to investigate the deformation evolution and fracturing process of the specimen under loading. To calibrate and validate the DIC parameters, namely, subset size and subset distance, strain gauges were mounted on the specimens to record the strains and to compare the results with DIC. It was seen that the DIC is capable of computing strains at any point of interest with high accuracy and can overcome limitations of conventional strain measurement methods. Also this study showed that the 3D printed powder base material can mimic real behavior of natural brittle rocks. The DIC detected the location of crack initiation, type, and propagation path and failure mode by strain and displacement contours. This study demonstrates the strong capabilities of 3DP technology and the DIC to assess the deformation behavior and cracking of rocks under uniaxial loading.

A0788-NACRE-LIKE ALUMINIUMALLOY COMPOSITE PLATES FOR BALLISTIC IMPACT APPLICATIONS

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To develop lightweight materials with high mechanical performance is a major scientific challenge in diverse applications, such as safety protection, automotive industries, and civil engineering. Nature, with millions of years of evolution, has developed biological structures that have been inspiring engineers to fabricate novel materials with optimized microstructures and excellent mechanical properties. In this work, motivated by the hierarchical structure of nacre, a multi-layered aluminium alloy (AA) 7075-T651 based composite is being developed for ballistic impact applications. The designed nacre-like composite plates consists of up to 9 layers of 100mm by 100mm. Each individual layer is made of 20 mm by 20 mm aluminium tablets of 1 mm thick, which are bonded together with a toughened epoxy adhesive [1]. Wavy surfaces are introduced to the tablets to enhance the interlocking effect between the layered tablets. To investigate the mechanical performance and the failure modes, experiments and numerical simulations were performed on the designed composite plates. The bioinspired aluminium plates with various thicknesses and wavy shapes, were tested under high speed ballistic impact ranging from 400 m/s to 700 m/s. Numerical results for 5.4-mm, 7.5-mm and 9.6-mm thick bioinspired composite plates impacted by a rigid hemi-spherical projectile at various impact velocities were compared with corresponding bulk plates. The most significant improvement was recorded for the 5.4-mm nacre-like aluminium plate, which was attributed to the larger area of plastic deformation due to the tablet arrangement. Experiments data were collected to validate the numerical simulation. We have found that the nacre-like aluminium composite plates of different thicknesses had better ballistic behavior than the monolithic bulk plates. The proposed hierarchical structure is found to improve the ballistic performance by varying the failure mode from brittle and localized

A0858-DAMAGE EVOLUTION IN A GAR FISH SCALE UNDER DYNAMIC COMPRESSIVE LOADING

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With the advent of advanced imaging techniques and nano/microscale measurements, it is

now possible to characterize biological material systems for mechanical applications. In this paper, an Alligator gar (Atractosteus spatula) exoskeleton is considered for the purpose of obtaining elastic tensor of a complex bi-layered system. The gar scale is identified as having a two-phase architecture, (1) bioapatite mineral and (2) collagen protein, forming a biological composite with two distinct layers where a stiff, ceramic-like ganoine overlay a soft, highly ductile ganoid bone. It is also comprised of many disparate length scales that provide a biological analog for potential design of flexible armor systems. The ganoine layer anchors into the bone layer using a "sawtooth" type structural feature. The structural feature, porosity, and elastic modulus were determined from high-resolution scanning electron microscopy, 3D micro-tomography, and dynamic nanoindentation experiments towards developing an idealized computational model for FE simulations. The computational analysis employed a brittle damage model to determine the influence of the structured interface has on the mechanical response. The elastic modulus was functionally graded through the thickness of the fish scale. The sawtooth geometrical interface, and the moduli gradation were explicitly modeled through a representative volume element to allow for an in-depth stress analysis. To understand how a shock wave propagates into the gar fish scale, a plate impact configuration is considered in the finite element (FE) simulation. To develop a better understanding of energy dissipation in the gar fish scale layers, a damage model that describes defect evolution in terms of porosity and microcracks was implemented into a commercial FE code, ABAQUS. The results from a plate impact simulation using this code revealed that the shock reverberations and reflections in the saw tooth region generated significant crack growth under shear loading conditions (Mode II). The analysis focused damage evolutions under compressive and shear loading only; therefore, spall type damage under tensile loading is not studied in the present investigation.

A0910-MOLECULAR LEVEL DEFORMATION AND FAILURE TRANSITION MECHANISMS IN HYDRATED CEMENT PASTE AT NANOSCALE

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Cement paste is a hierarchical, multi-scale material where molecular level features from hydration of cement clinkers and evolving microstructures play a key role on its engineering scale characteristics. The hydration of cement clinkers is a complex process in which multiple physical-chemical reactions occur resulting in Calcium Silicate Hydrate (CSH), Calcium Hydroxide (CH) mixed with unhydrated cement clinkers Tri-Calcium Silicate (C3S) and Di-Calcium Silicate (C2S), key components of Portland cement. The molecular structures of hydrated components continuously evolve throughout the service-life of the cement paste. Due to the complex hierarchical structure of the cement paste, changes in cement chemistry at the nanoscale level strongly influence the microstructural and global mechanical property evolution of cement. In the present work, molecular dynamics (MD) modeling is employed to

understand deformation and failure transition mechanisms at molecular level based on material chemistry structure of hydrated cement paste at nanoscale. Present investigations focus on material chemistry structures employed and accepted in the field to represent the nanoscale structure of CSH gel. In particular, we present molecular level deformation and failure transition mechanisms obtained under the loading conditions of: 1) Hydrostatic compression resulting in predictive material models linking pressure - specific volume, and internal energy - specific volume that are important to investigate high strain rate behavior, 2) Uniaxial compression resulting in stress-strain constitutive material behavior. Results and inferences from our findings using non-reactive and reactive energy descriptions for molecular level interactions in MD modeling will be presented. Our research findings illustrate that material chemistry features in cement paste influence their mechanical behavior; by controlling chemical reactions to result in modified material chemistry molecular structures of cement paste can effectively lead to evolving modified morphologies at microstructure scale level influencing their engineering scale properties. Our enabling modeling methodologies allow predictive development of constitutive material models and response of heterogeneous cement paste, understanding of their molecular level deformation and failure transition mechanisms, and are extendable to other such materials.

A1002-NACRE-LIKE ALUMINIUMALLOY COMPOSITE PLATES FOR BALLISTIC IMPACT APPLICATIONS

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To develop the light-weight materials with high performance simultaneously is a major scientific challenge in diverse applications, such as safety protection, automotive industries, and civil engineering. Nature, with billion years of evolution, has been inspiring engineers to fabricate novel materials with optimized microstructures and excellent mechanical properties. In this work, motivated by the hierarchical structure of nacre, a multi-layered aluminium alloy (AA) 7075-T651 based composite is being developed for ballistic impact applications. The designed nacre-like composite plates are composed of interlaced layers of 100mm by 100mmplates. For each layer, the plate is made 20 mm by 20 mm aluminium tablets of 1 mm thick and bonded with a toughened epoxy adhesive [1]. The wavy surfaces are introduced to the tablets to enhance the interlocking effect between the layered tablets. To investigate the mechanical performance and the failure modes, experiments and numerical simulations were performed on the designed composite plates, in which the aluminium plates with various thickness and waviness, under high speed ballistic impact ranging from 400 m/s to 700 m/s. Numerical results for composite plates of 5.4-mm, 7.5-mm and 9.6-mm thick bioinspired composite plates were compared with corresponding bulk plates under the impact of a rigid hemi-spherical projectile under the same impact velocities. The most significant improvement was recorded for the 5.4-mm nacre-like aluminium plate, which was attributed to the larger area of plastic deformation due to the tablet arrangement. Experiments data were collected to validate the numerical simulation. We have found that the nacre-like aluminium composite plates of different thickness had better ballistic behavior than the bulk ones. The proposed hierarchical structure is found to improve the ballistic performance by varying the failure mode from brittle and localized failure in the bulk plate to more diffuse failure in the composites.

MS5:Computational modeling of damage and failure in solids and structures

A0056- DAMAGE SIMULATION OF SINGLE CRYSTALS UNDER CYCLIC LOADING USING CRYSTAL PLASTIC FINITE ELEMENT METHOD COMBINED WITH DAMAGE MECHANICS

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The crystal plastic finite element method（CPFEM） is used to simulate the mechanical behavior of single crystals under cyclic loading. A damage concept is introduced to describe the failure process of grains in material. Damage coupled crystal plasticity constitutive equations and damage evolution equations are established for modelling the failure process of a single crystalline metal. This model is applied for simulating the damage process of single crystals by using UMAT in ABAQUS. The influence of lattice orientation on the damage performance is also investigated.

A0206-Study on the effect of variable friction coefficient over fretting fatigue using damage mechanics based approach

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The variation of friction coefficient is described using a simplified function according to the experiment result. Then, this variation is considered in the fretting fatigue analysis, which is numerically implemented based on the damage-coupled elastic-plastic constitutive equations and fatigue damage evolution equations. The predicted life is compared with experimental data. The effects of variation of friction coefficient on the contact stresses, fretting scar, fatigue damage evolution, and fatigue life are also investigated.

A0214-3D DUCTILE CRACK IMULATION BASED ON H-ADAPTIVE METHODOLOGY

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In this article, we propose a 3D h-adaptive methodology to simulate the initiation and propagation of cracks in ductile materials during metal forming processes. The behavior of the material is modeled using an elasto-plastic model proposed by Hooputra et al. in 2004[1]. The crack is represented by an element deletion process in which the volume reduction is compensated by a node relocation process. The mesh is refined by a bisection technique with respect to size indicators depending on plastic strain and damage variable. The state variable fields are transferred by an original hybrid field transfer procedure which makes uses of both finite element and meshless techniques. An improved information point selection strategy is proposed in order to enhance the robustness of the meshless based diffuse interpolation method. Emphasis is given on the limitation of numerical diffusion and preservation of extrema values of the fields. The length of each loading step is adapted in order to guarantee that the sizes of deleted elements is smaller than a minimum threshold size of the mesh. This minimum size is identified as one of the intrinsic material parameter. The efficiency and the robustness of the methodology is validated with examples and results are compared to experimental data.

A0267-TRUSS LIKE DISCRETE ELEMENT METHOD APPLIED IN THE SIMULATION OF DAMAGE PROCESS IN QUASI-BRITTLE MATERIALS

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In the present work a version of lattice method is used to represent a quasi-brittle material submitted to different kind of solicitation. The brief description of the model is carried. A specimen in Planar Strain condition is considered. Over this specimen is applied boundary condition that produces a constant strain state over the specimen. The results in terms of energy balance, acoustic emission and final configuration are presented. Finally the advantage of this approach is point out.

A0321-RELIABILITY ANALYSIS METHOD FOR FATIGUE DAMAGE OF DEEPWATER RISE

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In view of the fatigue damage caused by the flow-induced vibration of deepwater riser, a three-dimension nonlinear dynamic model of deepwater riser subjected to the combined action of internal and external flow is established. Through the riser vibration analysis in time domain, the stress time histories of riser key points are obtained. Incorporated with the rain

flow counting method, S-N curve and Miner linear cumulative damage model, the fatigue life prediction model of deepwater riser is set up. Combined with Wirching method, the reliability analysis of deepwater riser is realized. The validity of the fatigue damage reliability analysis method is verified by a typical case.

A0338-METHODOLOGY RESEARCH ON SEISMIC PERFORMANCE ASSESSMENT BASED ON DAMAGE FOR RC FRAME STRUCTURE

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A seismic performance assessment method basing on material damage for reinforced concrete structure is proposed. Two pseudo-static experiments are introduced, and the experimental procedure is simulated by “Opensees” program, and the result agrees well with experiment. Moreover, a model for RC frame is built and incremental dynamic analysis (IDA) is adopted on it to analyze the seismic fragility. It is available to evaluate performance states of RC frame basing on material level.

A0435-DEVELOPMENT OF THE MICROSCTRUCTURE IN NAFION MEMBRANE

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Coarse-graining molecular dynamics simulations were carried out for deformation and fracture problems in nafion membrane. The effects of temperature and molar mass on deformation behavior were qualitatively investigated. Temperatures below the glass transition point were examined. The temperature effect was found to be consistent with all-atom simulations and experiments. On the investigation of molar mass effect, it was revealed that complex entanglement of massive molecules can prevent voids from growing.

A0534-NONLOCAL DAMAGE MODELLING BY USING THE SCALED BOUNDARY FINITE ELEMENT METHOD

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The semi-analytical method named scaled boundary finite element method (SBFEM) is extended to model the damage evolution in both 2D and 3D. Combined with an integral-type nonlocal model, the proposed approach can effectively eliminate the mesh sensitivity concerning the strain localization. By using an automatic mesh generation algorithm based on

quadtree (2D)/octree (3D) decomposition, the number of degrees of freedoms (DOFs) is reduced considerably. Several benchmarks are modelled to verify the effectiveness and robustness of the proposed approach, and the results are consistent with those of the literatures.

A0693-ON THE DEVELOPMENT OF A MICROMECHANICALLY-BASED CONSTITUTIVE LAW FOR SOLID PROPELLANT

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Throughout their lifecycle, propellant grains undergo several types of mechanical loads induced by thermal cycles. Yet, a crack initiation would lead to an increase of the combustion surface, causing a serious incident at firing. To avoid such hazards, a constitutive law describing the material behavior is used to carry out a mechanical design and find proper grain geometry. Propellant expresses a nonlinear viscoelastic behavior [1]. Finding a model able to provide the nonlinear part is still challenging. To ensure a certain mechanical integrity to the grains, current models are conservative, which lowers performance. To develop a more appropriate constitutive law, origins of the nonlinearities have been investigated. When submitted to a macroscopic strain, propellant microstructure is known to present debonding between polymeric matrix and reactive fillers [2]. This microscopic damage is responsible for the activation of different mechanisms. Numerical models and experiments emphasized friction and vacuolization as major contributors to macroscopic nonlinear effects. Introducing these new mechanisms in the homogeneous model can lead to more accurate previsions of the propellant response. A representative volume element made up of a rigid filler immersed in polymeric matrix has been chosen. It also integrates interface vacuolization and friction. Based on the elastic and infinitesimal strains hypotheses, homogenization is now being performed in order to highlight the coupling between microscopic and macroscopic variables. Based on the result, a viscoelastic, nonlinear phenomenological model will then be developed and implemented into a finite element code. Application on an industrial case will eventually demonstrate the new law contribution to safer and more efficient propellant grain designs.

A0734-PROBABILISTIC MODELING AND SIMULATION OF MULTIPLE SURFACE CRACK PROPAGATION

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In a LCF regime, the failure of KSA30 steel is dominated by multiple surface crack propagation and coalescence. Specifically, its final failure is characterized by linking several neighboring cracks to form a critical crack. This process often shows a stochastic nature on crack propagation and coalescence. According to this, a probabilistic procedure for modeling

multiple surface crack propagation and coalescence is established based on Monte Carlo simulation with experimental measurements. Specifically, surface crack density and length distribution were measured from LCF replica tests of KSA30 steel. Through probabilistic modeling of crack growth, the procedure calculates the probability of coalescence of any two cracks with allowance for their interaction and the local plastic deformation at the crack tips. Using this procedure, it can predict the remaining usage life of engineering components from the initial state to critical cracks by propagation and coalescence of dispersed defects.

A0740-Defect Induced Buckling and Failure Behavior of Boron Nitride Nanotubes under Combined Axial Compression and Torsion

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The buckling and failure behaviors of defective boron nitride nanotubes (BNNTs) under combined axial compression and torsion are studied using molecular dynamics simulation. The structural defect considered is the Stone-Wales (SW) defect formed by rotating one B-N bond of the hexagonal atomic ring. We investigate a pair of armchair and zigzag BNNTS with similar geometries, to evaluate the differences of interactive buckling loads, and to compare the different effects of SW defects on failure responses between two types of nanotubes. By determining the interaction buckling curves, it is shown that the present of structural defects results in decreases of interactive buckling loads and postbuckling equilibrium paths, and the armchair BNNTs are more sensitive to defects as compared to zigzag nanotube behaves. The local collapse on the wall of BNNTs induced by SW defects is observed, leading to mechanical energy relaxation by onset of buckling and the following failure behaviors. It is worthy to note that the defect location strongly affects the failure behaviors of BNNTs under combined loading conditions. The significant differences between the effects of SW defect located near one end of the nanotube as well as on the middle part are carefully studied.

A0769-DAMAGE ANALYSIS OF PURLIN-SHEETING SYSTEMS DURING THE PASSAGE OF A TROPICAL TYPHOON

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The paper describes damage evaluation for a typical purlin-sheetings during the passage of one tropical typhoon hazards. Starting with the fatigue damage assessment for the screw connections between the purlin and sheeting, the Miner damage rules were employed to carry out the calculations. Thereafter, the damage of rotational restraint for the purlins could be regard as one type of damage induced by the fatigue of the claddings. Based on the purlin mechanical models considering the restraint rotational restraint effect, the residual strength of the purlins were obtained. The influence of several characteristics of the typhoon which mainly included the ultimate wind speed, the duration, and the directions were all considered

for de design typhoon. This research could be a basement for the time-dependent reliability assessment for the light steel structures after the wind related hazards.

A0839-MAPPED FINITE ELEMENT METHOD FOR THE PHASE FIELD AP-PROACH TO FRACTURE

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The phase field method to fracture has attracted widespread attention due to its ability to simulate crack initiation, propagation, merging and branching without extra criterion. However, the singularity around the crack tip deteriorates the optimality of convergence of the phase filed method. Thus we apply the mapped finite element method proposed by Chiaramonte et al. [International Journal for Numerical Methods in Engi-neering, DOI: 10.1002/nme5486] to the phase field approach for fracture. The method is based on approximating a much smoother function in a parameterized domain by map-ping the solution around the singularities, which can reach an optimal convergence rates. More important is that combining the mapped finite element method with the phase field method can eliminate the mesh dependence, since the phase field adopts a smeared de-scription of the cracks.

A0896-A new technique for frictional contact on crack slip in the framework of the extended finite element method

Hao Cheng

The traditional XFEM (eXtended Finite Element Method) encounters some challenges in the problems of frictional contact because the contact forces acting on the interface of cracks are hardly to be determined. In this paper, the simulation for frictional contact on crack slip in the framework of the XFEM is proposed. Coulomb's frictional model is introduced as the frictional constitutive model. The detecting points are sowed on the interface to detect the contact states of the cracks and to interpolate the displacement of the grid node. The formulations of the contact forces and the penalty terms are established in the framework of the XFEM. Moreover, a specimen containing two pre-existing flaws under uniaxial compression was conducted. In this experiment, image processing technique is introduced to deal with the pictures of real-time process of the specimen, which are captured by the high-speed dynamic recording system. The results from the proposed numerical method are in good agreement with the data from experiment.

A1010-EVALUATION OF ENERGY RELEASE RATE ASSOCIATE WITH CRACK KINKING

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It is important to determine energy release rate associated with crack kinking. Several kinds of solution are available but their validity is not confirmed so far. In this paper, energy release rates for kink cracks under mixed mode loading are computed by either calculating the energy difference before and after crack kinking or evaluating the J integral for the kink crack, thus we can present more accurate energy release rate formula for crack kinking. A more precise evaluation of energy release rate associated with stress intensity factors for crack kinking is proposed by calculating the energy difference before and after crack kinking to review the previous solutions and check the validity.

A1017-MICRO CT IMAGE-BASED FRAGMENTATION SIMULATIONS OF CONCRETE UNDER HIGH STRAIN RATES UP TO 1000/S

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This study investigates the dynamic failure of concrete under compression of high strain rates by mesoscale finite element (FE) modelling based on X-ray computed tomography (XCT) images. 93 XCT image slices are converted to 2D FE models consisting of aggregates, mortar, interfaces and pores. The JHC model and the node-split method in LS-DYNA are used to capture the whole crushing and fracture process under compression of high strain rate from 10 s-1 to 1000 s-1. The predicted compressive dynamic increase factors (CDIF) well match those from experiments and empirical data. The lateral inertial confinement and the meso-structure are found to be the main mechanisms for dynamic strength increase.

A1071-Comparative study of plastic damage models with application to RC shearwall

A comparative study on finite element simulation of reinforced concrete shearwall is performed with consideration of two kinds of plastic damage models. One of them is the well-known concrete damage plastic model (CDP) embedded in ABAQUS. The other is the damage energy release rate based damage model, which is implemented by using the user subroutine interfaces (UMAT) provided by ABAQUS. Based on the same uniaxial damage evolution curve and stress softening curve, the two plastic damage models are veri-fied by simple element tests and a set of cyclic benchmarks. It is shown that both of them provide the almost identical stress-strain curves for simple uniaxial tension and compression tests. However, it is quite different when it comes to cyclic loading condition. The UMAT model exhibited, in general, a higher accuracy for both the cyclic element test and the single concrete shear wall test. As for CDP model, it is suffered from the overestimation in the value of plastic strain, which causes unreasonable unloading stiffness and in-accurate hysterical cycles.

MS6:Failures and Damages in Composite Materials and Structures

A0189- FABRICATION OF SUPER-STRONG CARBON NANOTUBE BUNDLES WITH TENSILE STRENGTH OVER 80 GPA

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Carbon nanotubes (CNTs) are regarded as the strongest materials discovered. When assembled into fibers, however, the strength of CNT fibers are usually impaired by defects, impurities, random orientations and discontinuous lengths of CNTs. Fabricating CNT fibers with strength reaching that of single CNTs has been a challenge for decades. Here we show the fabrication of centimeters long CNT bundles (CNTBs) with tensile strength over 80 GPa using ultralong defect-free CNTs. The tensile strength of CNTBs is controlled by the Daniels effect due to the nonuniformity of the initial strains in the components. A synchronous tightening and relaxing strategy is proposed to release the nonuniform initial strains of the CNTB components. For CNTBs consisting of a large number of components with parallel alignment, defect-free structures, continuous lengths and uniform initial strains, the tensile strength can be over 80 GPa, which is far higher than that of any other strong fibers ever fabricated.

A0225- Experimental investigation on the stress-strain behaviors of steel-polypropylene hybrid fiber reinforced concrete under uniaxial cyclic compression and tension

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This paper presents experimental investigation on the stress-strain behaviors of steel-polypropylene hybrid fiber reinforced concrete (HFRC) under uniaxial cyclic compression and tension. The results showed that hybrid fibers have significant effects on the cyclic compressive and tensile mechanical behaviors of concrete. Based on the test results, analytical formulas for plastic strain and damage evolution laws under compression and tension are respectively proposed. Furthermore, a damaged plastic constitutive model for HFRC is developed and then verified by test results in literature.

A0229- Accurate estimation of the Mode I cohesive zone size of various cohesive laws

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The cohesive zone model is widely used with finite element method for delamination analysis of composite materials and structures. To obtain mesh objective result, there should be at least 3-5 finite elements in the critical cohesive zone. Therefore, accurate estimation of the cohesive zone size is extremely important in the finite element analysis of damage and fracture. In this paper, the cohesive zone model for an orthotropic double cantilever beam specimen is studied by using the weight function method. The weigh function is derived from two dimensional elasticity analysis of the orthotropic double cantilever beam. The cohesive zone sizes of various cohesive laws for the double cantilever beam are given in this paper, which are consistent with those determined from finite element analysis. The present method is simple and accurate in determining the cohesive zone size, and therefore providing a useful tool for the finite element modeling of delamination of composites.

A0232- A DAMAGE CRITERION FOR RIVETED FIBER METAL LAMINITE JOINTS

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Fiber metal laminates (FMLs), composed of alternating layers of metal sheets and fiber reinforced composites, have been widely used in aerospace and automobile industries. FMLs have excellent fatigue, damage resistance and impact properties, are possible to be inspected after impact threats, and easy to machine and form. Although the FMLs are often riveted to the frameworks, most researches are limited to the stiffness characteristics of FMLs and the influences of pin holes on the damage of laminates, and the damage mechanism of riveted FML are still unclear. A damage criterion based on the 3D Hashin damage theory, the Johnson-Cook model and the Traction Separation Laws is established to predict the coupling damages of fiber layers, metal layers and interfaces in riveted FMLs. The damage prediction model is verified by the experiments. The effects of pretighting force of rivets, FML categories, and sizes and positions of rivet holes on damage behaviors of FMLs are also investigated. The present model can be treated as a design criterion for riveted FML joints.

A0245-THE FAILURE MECHANISM RESEARCH OF ZIRCONIUM OXIDE PARTICLES REINFORCED COMPOSITE MATERIAL

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This paper studied the failure mechanism of the nano zirconia particle reinforced epoxy composite material. The tests of tension, compression, and fracture toughness were carried out on zirconia contained specimens of 10 different levels that ranges from 0wt.% to 20wt.%. The results show that, with the increase of zirconia particle content, both the tensile and compress modulus increase, the compress strength decreases, the tensile strength and the fracture toughness increase first, and then decrease at 8wt.%. The acoustic emission data and SEM photos showed that the zirconia content has an effect on the total time of each damage stage and characteristics of damage signal, the skeleton theory and interface bonding enhancement theory are the active mechanism of tension condition, the synergistic effect of "silver lines-screw anchor" mechanism and "silver lines-shear zone" mechanism are the active theory of fracture toughness. The Simulation results of unit cell model with different zirconia contained were agreed well with the experiment. The research indicated that in a certain limit, the zirconia particle would enhance the material properties.

A0258- Study on the Damage Coupling Mechanical Behavior of Ceramic Matrix Composite

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Off-axial tensile test and alternate tension-shear test were carried out on the ceramic matrix composite. Based on the off-axial tensile test, the damage coupling mechanical behavior was studied by comparing the effect of off-axial angel on the damage evolution and mechanical properties. The damage coupling effect was analyzed quantitatively according to the alternate tension-shear test, meanwhile, the effect of initial tensile(or shear) damage on the subsequent shear(or tensile) damage evolution was also obtained. Finally, the constituent model considering damage coupling was proposed by using damage mechanics.

A0273- TENSILE DAMAGE BEHAVIOR OF TWO-DIMENSIONAL BRAIDED C/SiC COMPOSITES

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In order to study the tensile damage behavior and the mechanical properties under low frequency cyclic loading of two-dimensional braided C/SiC (2D C/SiC) composites, their tensile loading/unloading behavior was investigated through experiments and a micro-

mechanical approach. The damage mode and damage evolution mechanism of the material during loading were analyzed by AE (Acoustic Emission) characteristic parameters, and the stress-strain relation of the initial loading, unloading and reloading was obtained by the method of the micro-mechanical model of unidirectional continuous fiber reinforced ceramic matrix composites. The relationship between the matrix crack number with the stress change and the failure judgment condition of the composite are obtained by using the fracture statistic method. The model was applied to 2D C/SiC composites through stress transformation. For monotonic loading specimens, the matrix Weibull modulus and interfacial shear resistance were obtained by orthogonal test and least square method, and the modulus of fiber Weibull was obtained by controlling the failure strength of the material in accordance with the experimental results. The tensile cyclic loading/unloading stress-strain curves of 2D C/SiC composites determined by the above parameters agree well with the measured curves.

A0363- PROGRESSIVE FAILURE ANALYSIS OF COMPOSITE LAMINATES BASED ON THE MICRO-MECHANICS OF FAILURE AND NON-LINEAR SHEAR BEHAVIOR

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This paper presents a multi-scale non-linear progressive damage modeling strategy to investigate the failure mechanisms of composite laminates. The non-linear shear response of the T300/CYCOM970 lamina was derived by monotonic and cyclic loading and unloading tensile tests on [+45/-45]2S laminate coupons. A progressive damage model considering the non-linear shear behavior based on the micro-mechanics of failure criteria and the continuum damage mechanics was developed. This model was implemented in commercial finite element software ABQUS by a UMAT subroutine. The tensile behavior and the ultimate strength of open-hole tension specimens with different lay up were predicted with this model. A reasonable good agreement was achieved between numerical predictions and experimental results.

A0405- A DAMAGE MODEL TO PREDICT SHEAR BEHAVIOUR OF FIBRE-REINFORCED CERAMIC MATRIX TOWS

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A model based on a single continuum damage state parameter determined by the ratio of the current matrix crack density and saturated density, has been developed to predict the shear

behaviour of a unidirectional fibre-reinforced ceramic matrix composite (CMC) tow. The model considers the influence of matrix cracking using Weibull distributions of damaged matrix shear strength. The nonlinear shear stress-strain response of a CMC tow, predicted by the damage model, has been used in a macro-scale analysis to evaluate its fidelity.

A0491- INVESTIGATING THE FRACTURE BEHAVIOR OF PARTICLE REINFORCED AL ALLOY MATRIX COMPOSITES BY USING RVE-BASED FE SIMULATIONS

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Owing to the combination of high strength, low density, and good ductility, particle reinforced metal matrix composites (PR-MMCs) are widely used in the area of aerospace, automobile, etc. Compared to traditional metallic materials, PR-MMCs show different fracture behaviors due to the strong interaction of the particle and the matrix and the evident difference of mechanical properties. In this work, the damage evolution and fracture behavior of in-situ TiB2 particle reinforced 7XXX Al alloy matrix composites are studied by using mesoscopic finite element simulations. The heterogeneous microstructure of the considered material is mapped into representative volume elements (RVEs) with highly fidelity meshing. Furthermore, the mesoscopic Gurson–Tvergaard–Needleman (GTN) model is employed to describe the damage evolution and plastic behavior of the matrix, while a brittle fracture criterion combining with a hypo-elasticity assumption is used to describe the mechanical behavior of the TiB2 particle, and these two phases are assumed to be bound tightly. Two different deformation modes, namely, uniaxial tension tests corresponding to the scenario of positive stress triaxiality and compression tests corresponding to the scenario of negative stress triaxiality are enforced on the RVEs. By means of these modellings, focuses about the deformation heterogeneity and the interaction between the particle and the matrix can be fully investigated, including (a) the effect of the particle on the strain localization, the formation of shear bands, and the initiation and growth of voids in the matrix; (b) the influence of the morphology of particles on the damage evolution and crack propagation of PR-AlMCs; (c) the interface debonding between the particle and the matrix during the deformation process. This work therefore explores the role of the reinforce particle on the damage evolution of heterogenous metal matrix composites, and serves as a physically motivated basis for the development and modeling of fracture and failure of PR-AlMCs.

A0630- Experimental and Numerical Study on Mechanical Property of SAP-contained Concrete under Various Curing Conditions

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When superabsorbent polymers (SAPs) are added to concrete for the sake of improving its durability, one goal to be achieved is to keep its strength from being impaired. After being cured under three different RH, concrete specimens containing SAPs are subjected to compressive load tests. The more severe strength reduction is observed under water curing than drying curing. A two-scale modelling of RVE of a cement paste with SAP inclusions is then set up based on the kinetics of water migration. This model substantiates the experimental discovery that exposure to open air is more favorable than moist curing with respect to compressive strength. As a conclusion, hygral conditions at curing plays an important role in damage mechanics of cement-based materials.

A0720- Computational Multi-Scale Failure Analysis of Unidirectional Carbon Fiber Reinforced Polymer Composites under Various Loading Conditions

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A computational multi-scale analysis based on representative volume element (RVE) modeling and molecular dynamics (MD) simulations is developed to investigate the failure mechanisms of unidirectional (UD) carbon fiber reinforced polymer (CFRP) composites. The average properties of the 200-nm thickness interphase region between fiber and matrix are investigated through MD simulations and an analytical gradient model. The results indicate that there exists a stiffened interphase region compared to the bulk matrix which influences composite response significantly. Specifically, we show that a traditional two-phase model with no interphase fails to capture the stress-strain curve compared to the experimental data. However, by adding the interphase region, the modified three-phase RVE model significantly improves the accuracy of simulation results. Furthermore, a coupled experimental-computational micromechanics approach is adopted to calibrate and validate the cohesive relationship of the interface between the fiber and interphase region, to capture the failure strength of the composites realistically. Finally, different failure mechanisms for specimens subjected to the transverse tension, compression, in-plane and out-of-plane shear are investigated in detail with our multi-scale computational model. The results show that the failure modes of UD CFRP composites are complex and multiple failure mechanisms co-exist depending on the loading conditions, agreeing well with our experimental analyses.

A0801- Study on Low - velocity Impact and Compression Failure of Composite Foam Sandwich Panel

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Low velocity impact often results in small permanent indentation(residual dent)in the panel due to the impact head, accompanied by crushing damage at the bottom and around the impacted layer. If the core layer is brittle, the debonding at the panel-core interface will occur as a result of the rapid rebound of the panel upon removal of the impact load. In addition, due to the poor impact resistance and interlayer performance of the composite sandwich structure, under the action of low-velocity impact load, fiber fracture, matrix cracking and face-core debonding can easily occur in the panel, resulting in a decrease in the carrying capacity of the sandwich structure. There are four main methods to study residual strength after impact: softening inclusion method, sub layer buckling method, opening equivalent method and damage accumulation method. At present, most scholars' research on post-impact damage is based on man-made assumption about the initial damage and then the residual strength is studied, which will lead to large errors in the calculation results.

In this paper, the surface deformation and energy absorption of the composite foam sandwich structure after low-velocity impact and the bearing capacity of the compression after-impact structure were numerically simulated and experimentally studied. Firstly, the finite element method was used to simulate the low velocity impact process of the composite foam sandwich panel. The damage of the laminated structure panel is judged by the Hashin criterion. The simulation results show that the tensile failure of matrix on the outer panel is the main failure mode during process of impact. The greater the impact of energy is, the larger the destruction area of the outer panel is. In addition, the energy absorption behavior of both the panels and the foam were compared, which is founded that the foam absorbs a lot of energy, and the remaining energy is basically absorbed by the outer panel. Secondly, the axial compression calculation was carried out using the model with impact damage and undamaged condition. The failure load and damage of the structure were recorded. The influence of the impact energy on the residual strength after compression is analyzed, demonstrating that the bearing capacity of the structure with impact damage is greatly reduced.

A0876- Damage and failure analysis of composite structures based on the BMANC

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Composite materials have been extensively employed in engineering. How to evaluate damage and failure behaviors of a composite structures is a critical issue in their engineering applications. In this work, a micromechanics elastoplastic model based user subroutine, the Bridging Model for Analysis of Composites (the BMANC), is developed. With the BMANC, users

can do linear or nonlinear mechanical analysis on complex composite structures, as long as mechanical behaviors of constituent materials are provided. Furthermore, since the micromechanics bridging model implemented is analytical, the computation efficiency of a finite element model with the BMANC is much higher than a traditional micromechanics finite element model. Besides, the BMANC can incorporate multiple constituent materials in one laminate element, making it applicable for various of complex composite structures, e.g. fiber-epoxy-metal hybrid composites. Damage and failure analysis of several kinds of composite laminates is made by finite element models with the BMANC. The prediction results are validated with corresponding experiment data.

MS7:Damage Diagnosis and Condition Assessment of Historical Buildings

A0503-NUMERICAL SIMULATION OF STONE MASONRY PRISMS ON TYPICAL ANCIENT TIBETAN BUILDINGS

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Because of traditional construction techniques in Tibet, most ancient Tibetan buildings are in the danger of heavy critical dead load. When stone masonry is subject to heavy vertical load, masonry is likely to be destroyed because of the unstable strength of stone masonry. So we need to know the behavior of stone masonry suffering pressure. Beijing Jiaotong University conducted a compression test of stone masonry prisms to study the mechanic behaviors. This paper proposes a numerical model to simulate this test and analyze the damage mechanics.

A0522-RESEARCH ON STRUCTURAL COMPUTING MODEL OF THE TRADITIONAL TIMBER STRUCTURE IN THE YANGTZE RIVER REGIONS WITH THE METHOD OF STRUCTURAL DYNAMICAL CHARACTERISTIC TEST – A CASE STUDY OF GANXI'S FORMER RESIDENCE

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In order to study the structural computing model of traditional timber structure in the Yangtze River regions, and to provide the calculation basis of aseismic performance and wind-resistant performance of this type of buildings, JingDai Building in Ganxi's Former Residence is taken as an example, the structural computing models with the methods of finite element analyzing and structural dynamical characteristic test were studied. First, by using SAP2000, the structural model considering infilled wall effect and the structural model without considering infilled wall effect were established respectively to analyze their dynamical characteristics. Then, the structural dynamical characteristic test was carried out on site, and the result was compared with the result of finite element analyzing. Finally, the integral stiffness revising model and the equivalent frame-diagonal strut model of this type of traditional timber structure were put forward to be suitable for structural analysis of wind-resistant performance and aseismic performance.

A0600-INFLUENCE OF DAMAGE ON ANCIENT TIMBER COMPONENT

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Most ancient timber buildings have been built several hundred years or even more than a thousand years ago, which have been subjected to earthquake, environmental and operational loading. Because of the effect of natural external forces such as corrosion and the degradation of the properties of structural materials, most ancient timber buildings show great degree of damage, which lead to decrease of the bearing capacity of the timber structural component. In this paper, the influence of different damage factors on the mechanical properties of a timber member is analyzed.

MS8:Damage of engineering materials under multi-field loadings

A0086- A Non-Linear Ductile Damage Growth Law at High Temperature

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Continuum Damage Mechanics model is commonly used for the prediction of ductile fracture. For numerical simulation of ductile fracture in impact or high temperature problems, the damage growth law that incorporates the effect of high temperature is needed. Experimentally, it has been observed that the damage growth decreases with temperature. However, the damage growth law at high temperature is not easily available in the literature. In the present work, a damage growth law at high temperature is proposed for steel

A0380- SIMULATED ANALYSIS AND EXPERIMENTAL INVESTIGATIONS ON WEAR RESISTANCE CHARACTERISTICS OF HOT BLANKING DIES FOR HIGH STRENGTH STEEL BASED ON EDGE QUALITY

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Hot stamping parts of B1500HS steel , as they can not only achieve the goal of car body lightweight but also ensure the high strength requirement, are widely used in various automotive components. But punching and trimming at ordinary temperatures are very difficult after hot stamping in order to obtain the required shapes and sizes of hot stamped parts. Meanwhile, laser cutting also has some disadvantages of low efficiency, high cost and short precision because of secondary positioning. However, hot blanking of high strength steels can improve the quality of parts, shorten the cycle-time and reduce cost because hot punching and trimming process are completed during the period of hot stamping, under the condition of good plasticity and low hardness of steel sheets before martensite formation. Therefore, it has practical significance to research on the hot stamping with thermal blanking process. In this paper, numerical simulation models for hot blanking parts of B1500HS steel were established by ABAQUS to analyze the influences of different parameters on the fracture surface quality, including die materials, clearances and original temperatures. And for verification, the computed results show good agreement with experimental results. The wear and tear of B1500HS hot blanking dies with four different materials or three original clearances was studied through 3000 times stamping experiments. By tests and simulations,

the appropriate die materials and die clearances of high strength steels hot blanking were determined.

A0463- STRUCTURAL DAMAGE MECHANISM OF SETTLING BEHAVIOR OF RED CLAY BASE ON MULTI-SCALE METHOD

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This paper presents an experimental investigation on settling behavior at macroscale and microscale of red clay. First, macroscale and microscale testing was conducted through dynamic triaxial test and mercury intrusion porosimetry (MIP), respectively. Second, the porosity was defined a damage variable D to build an equation of microscopic structure damage evolution base on damage theory and porosity development function. The damage-elastic-plastic constitutive model of red clay was established. The structural damage mechanism of settling behavior of red clay was proved.

A0634- DAMAGE AFFECTED DISCONTINUOUS PLASTIC FLOW

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DPF is usually observed in fcc metals and alloys strained in cryogenic conditions. Such materials like copper and its alloys, aluminium alloys and in particular, different grades of stainless steel are applied in particle accelerator installations (including superconducting magnets, interconnection systems or detector elements). These elements are often subjected to cyclic loads as well as to intensive irradiation at near-0K temperatures, which lead to evolution of local micro-damage fields and finally to inevitable failure. The physically based constitutive model of DPF, coupled with both types of damage can be helpful in design of superconducting accelerator components.

A0659- Small scale LCF experimental study of ageing Ni-based superalloy

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Turbine blades made by Ni-based superalloy in aerospace engine are exposed to severe service conditions. The LCF property is significantly important for the safety service of turbine blades. In this paper, the stress controlled low cycle fatigue behaviors at 810MPa, 850°C of aging Ni-based superalloy DZ125 were investigated in order to study the effect of aging on the LCF property. Thin walled specimens of small scale were manufactured for imitating the

service condition of turbine blades made from directionally solidified Ni-based superalloy. The ageing specimens showed lower fatigue life compared with samples without heat treatment. Furthermore, the fracture mode of small scale ageing and non-heat treatment specimens were analysised with standard round bar specimens. Finally, the damage caused by high temperature exposure was estimated based on the fatigue data. The aim of work is to elucidate the influence of microstructural damage in service stage on LCF life of DZ125 and build an experimental platform for thin walled specimens with small scale in order to estimate the mechanical properties and service lives of turbine blades in laboratory level.

A0682- Coupling effect between diffusion and deformation on stress evolution in a bilayer structure

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The coupling between diffusion and deformation plays an important role in determining the integrity of electrodes in lithium-ion battery (LIB). In this work, the coupling between diffusion and deformation is incorporated in the equations of mass transport and mechanical equilibrium in the framework of linear elasticity for the stress analysis associated with diffusion-induced stress and stress-limited diffusion. The time-dependent terms in both the diffusion equation and the equation of mechanical equilibrium are taken into account in the analysis in contrast to most works in literature, which approximates the deformation as quasi-static. Numerical method is used to solve the fully coupled, nonlinear differential equations for a bilayer structure mimicking the structure of electrode/current collector in lithium-ion battery. Two different boundary conditions corresponding to galvanostatic and potentiostatic charging operations, respectively, are used. The spatiotemporal evolution of dimensionless concentration and displacement are analyzed as a function of the ratio of the diffusivities and the ratio of the thicknesses. The numerical results reveal the nonlinear deformation behavior of the bilayer structure due to the coupling between diffusion and deformation, which likely determines the structural integrity of lithium-ion battery.

A0684- Effect of electric current on creep deformation of tin

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With the development of electromechanical structures and electronic devices toward the nanometer scale, high current carrying capacity is needed for electronic interconnects and conductor lines. This tendency is true in the future high-power IC chips and power packaging. As a result, electric currents of high current densities can seriously affect device’s reliability and potentially cause electromechanical failure of electronic interconnects and conductor lines. The aggressive scaling-down of electronic devices imposes new challenges to

understanding the electromechanical response of electronic interconnects and to improving the performance and reliability of micron and nano electronic devices.

This work is focused on the effect of electric current on the creep deformation of tin. The tensile creep of pure tin-strips is performed in the temperature range of 323-423 K and under the stress range from 1.93 to 13.89 MPa. During the tensile creep test under the action of constant load, a direct electric current in the range from 1260.16 to 3780.47 A/cm2 is passed through the sample concurrently. Steady state creep is observed for all the tests. The power law model is used to calculate the stress exponent and activation energy. The steady-state creep velocity increases with increasing temperature and tensile stress. Under the same tensile stress and same chamber temperature, the steady state creep velocity increases linearly with the square of current density. There is no significant effect of electric current on the stress exponent and activation energy for the experimental conditions. The effect of electric current on the surface morphology of the tin-stripes is also examined. The concurrent action of electric current and mechanical loading accelerates the surface damage of the tin-stripes.

A0729- A NEW method for determining the Fatemi-Socie parameter k and multiaxial fatigue life prediction

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For engineering components subjected to complex loadings like multiaxial loadings, how to estimate its fatigue damage and life accurately is of great importance for ensuring the structural integrity of these components. In this respect, the Fatemi-Socie damage criterion has shown wide applications for fatigue life prediction of materials/components under different loading conditions. Within this criterion, the normal stress sensitivity parameter k is usually treated as material constant. However, k is not a constant and varies with usage life. In this regard, current approaches for determining k have been investigated, and a new method is put forward by elaborating k as a function of the maximum shear strain amplitude, which attempts to provide a robust method for multiaxial fatigue life prediction. Experimental data of GH4169 and TC4 alloys under proportional and non-proportional fatigue loadings are utilized for model validation and comparison.

A0847- BOUNDARY ELEMENT METHOD FOR ANALYSIS OF TWO-DIMENSIONAL NONLINEAR PIEZOELECTRIC SEMICONDUCTOR

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Based on the initial nonlinear constitutive equation of the piezoelectric semiconductor and the well-developed boundary element method, a new iterative method for two-dimensional piezoelectric semiconductor is proposed. The proposed method is verified by analyzing a piezoelectric semiconductor plate under multi-field loads and comparing with finite element method. Two kinds of typical contact problems in piezoelectric semiconductor (Ohmic contact and Schottky contact) can be recognized as the boundary value problems and are solved by the presenting method. By using the sub-domain boundary element method, the central crack problem is analyzed.

A1047- Constitutive behaviour and life evaluation of solder joint under the multi-field loadings

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With the miniaturization and lightweight development of electronic equipment, people are demanding higher density, smaller size and better user experience. To achieve a satisfactory reliability for severe application purposes such as aerospace industry, lead-containing solder materials shows great superiority in the aspects of mechanical capacity under the operating condition with such an electrical-thermal-mechanical loadings. More importantly, life prediction and reliability assessment of the solder joint become a critical problem. The purpose of this paper is to study the service life prediction of the solder joint by the 63Sn-37Pb solder alloy under the multi-field loadings. Firstly, the mechanical properties of solder material are calibrated by using uniaxial tensile tests for dog-bone specimens at the strain rates applicable to the working scenarios. In order to reproduce the constitutive responses observed in experiments, the constitutive model in terms of user defined material model is proposed for the finite element commercial software ABAQUS. Secondly, by establishing the actual joint model for the finite element simulations in ABAQUS, the failure mechanism of SAC305 solder joints under the action of thermal power is investigated and the coupled electrical-thermal-mechanical loadings are taken into account. In the post-analysis, the temperature distribution, current density and thermal stress are obtained for the SAC305 solder joint. Lastly, the distribution of the induced stress and plastic strain are evaluated to find out the location with the weakest point in the solder joint which is also dominating the predictions for its service life based on Manson-Coffin model. By varying the loading parameters such as the input current density, the environmental temperature and the dimension ratio of solder joint, a comprehensive parametric study is performed to obtain the dominant factor of service life for solder joint under complicated working conditions. The findings is summarized in an analytical form which is meaningful to conveniently elucidate the practical design criterion of electronic packaging structures of high-power electrical devices.

MS9:Monitoring based structural damage detection techniques

A0333-TO MONITOR THE FRACTURE BEHAVIOR IN SHAKING TABLE TESTS OF A SCALE-DOWN MOCKUP OF NUCLEAR RC STRUCTURE USING ACOUSTIC EMISSION TECHNIQUE

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Acoustic Emission (AE) monitoring and analysis technique were introduced to evaluate the fracture behaviour of a 1/25 scale-down RC structure during the shaking table tests. The mockup, based on a simplified structure design of nuclear power plant reactor building, was composed of primary/secondary containments and floor slabs of different scale-down thickness. Serial tests with AE monitoring were conducted on the 5x5m Tri-Axial Seismic Simulator in the NCREE Lab. Micro/inner fracture due to shaking force created numerous ultrasonic AE events received/recorded through the AE instrument. The monitored results could chronicle these damages, and relate them with seismic data, such as the corresponding accelerations and displacements during the test. In this paper, the fracture behaviour and material condition of the mockup under gradually increased resonant loading was shown using AE technique. Experiment results of seismic loadings based on Chi-Chi earthquake were also presented here with AE analyses. Through the use of AE monitoring, quantitative study on shaking table test could be promised.

A0924- ACOUSTIC EMISSION MONITORING ON FLEXURAL BEHAVIOR OF RC BEAM SUBJECTED TO DYNAMIC LOADING

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This paper presents the characteristics of acoustic emission (AE) behavior of the reinforced concrete beam subjected to static/dynamic flexural loading in a four point bend test. The AE signals corresponding to crack propagation on both flexural zone and shearing zone were simultaneously observed and analyzed. Three loading rates of 0.5 Hz, 1.0 Hz and 2.0 Hz were used in the cyclic loading test in MTS. The test results provide useful information in assessing the safety of reinforced concrete structure subjected to seismic loads, in particular, in the post-yielding stage.

MS10: Composite/Structure Interface: Modelling and Simulation

A0805- Experimental and Numerical Study on Interface Adhesive Honeycomb Sandwich Structure

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Bonded honeycomb sandwich structure is a kind of special structural composite material, which is consisted of honeycomb core inserted between two thin skins or panels with adhesive bonding. Due to its good stiffness and strength, it has been widely used in aerospace structures, satisfying the special requirements on quality and performance. For example, honeycomb structures are commonly used in the primary structure of commercial aircraft, military fighter and helicopters. In addition to the choice of the materials, mechanical property of the adhesive between the skin and the honeycomb core, the peel strength being a key indicator, is also important to assure the quality and bearing capacity of honeycomb sandwich structures, and epoxy and polyimide are commonly used as adhesive materials. When the external load applying on the sandwich structure exceeds a certain allowable range, the structure will be destroyed. Because of the fragile bonding between skin and honeycomb core, the interface damage is most likely to occur. In this failure mode, adhesive layer peel stress plays a dominant role, resulting in a substantial reduction of the carrying capacity of the overall honeycomb structure. Currently, standard methods for assessing peel properties between the skin and honeycomb core interface are roller peel test (ASTM D1781), float roller test (GB /T 7122) and 180° peel test (GB / T 2790). In general, it is appropriate to adopt the 180° peel method to detect peel strength when it comes to honeycomb aluminum plate with stronger bonding interfaces.

180° Peel experiment was designed and performed to estimate the peel strength parameters and failure modes of the interface adhesive honeycomb sandwich structure filled with Styrofoam. First of all, the paper designs and manufactures aluminum-lithium alloy honeycomb core and skin samples bonded with adhesive according to the adhesive bond strength test standards, there are three conditions in the experiment of the aluminum-lithium alloy honeycomb core / skin adhesive interface, the core layer was 0% filled,90% filled and 100% filled with Styrofoam. Secondly, 180 ° peel test was conducted using the designed fixtures so as to compare the peel strength and failure form of the adhesive layer in different filling forms. The peel strength was calculated by recording the peel force-length curve and observing the destruction of the interface during the experiment. Simultaneously, local strain field, especially the critical region of the breakage point, is obtained by digital image correlation (DIC). The DIC can accurately capture the strain distribution of the honeycomb core during the peeling process and further monitor the carrying capacity of the sandwich structure with different filling rates. The results show that failure mode of the honeycomb structure with no filled Styrofoam is the cohesive failure of the adhesive, while failure mode of the honeycomb structure filled with Styrofoam is adhesion failure, and the results of numerical analysis are in good agreement with the experiments.

MS11:Damage of Composites under Impact Loadings

A0146- DISPLACEMENT-BASED DAMAGE ACCUMULATION FUNCTION FOR SRHSHPC FRAME COLUMNS

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Displacement-based damage accumulation function for steel reinforced concrete high strength high performance concrete (SRHSHPC) frame columns is presented based on experimental and numerical analysis. According to the results of tests under low cyclic reversed horizontal loading, the influence of axial compression ratio, shear span ratio, stirrup ratio and concrete strength on the strength attenuation is firstly ascertained. The finite element model is then developed to investigate the effect of various parameters on damage through pushover analysis, and the damage–drift relationships were discussed. Following, the damage function of SRHSHPC columns, whose expected predominant failure mode is flexure, was established, using the inter-storey drift ratio as the independent parameter. As the predominant failure mode of SRHSHPC column shifts from flexure to shear, a damage function for critical shearing SRHSHPC columns were developed. Based on a combination of the above function and existing damage model, the damage accumulation function and the material failure criteria were given. Comparing with the results of exciting literatures, the function is valid. All these may contribute to the seismic performance evaluation of SRHSHPC columns, and to the further analysis of SRHSHPC frame structures.

A0203- Finite element analysis on ballistic performance of bio-inspired scale-like protection system

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In this paper, a scale-like protection system, which consists of two-layer structural composite scales, was introduced and modelled by using finite element analysis software LS-DYNA . The results show that with the increasing of overlapping angle of the scales, the impact velocity of bullet at vertical direction decreased faster, especially when overlapping angle is larger than 90^{o}. The maximum deformation of the protection system decreased with the increasing number of Kevlar layers. The frictional coefficient between adjacent scales has little influence on the protective performance of the protection system.

A0674- Evaluation of Progressive Damage Models for Low-velocity Impact Failure Simulation of Carbon Fiber Composite Laminates

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This paper intends to investigate the efficiency of commonly-used failure criteria and damage evolution models and the interactions of different combinations in low-velocity impact failure simulation. Five typical criteria (Maximum stress, Hashin, Hou, Tsai-Wu and Puck) and three different damage progressive methods (non-linear exponential softening model, fracture energy based model with equivalent strain, fracture energy based model with equivalent displacement and stress) were selected for predicting intralaminar damage of composite lamina. Bilinear cohesive model was employed to capture the delamination damage. The finite element simulations were performed in ABAQUS/Explicit and the progressive damage models were established as the user-defined subroutines VUMAT. For model validation, experiments from Bouvet et al. (2013) [i] on T700GC/M21 laminated plate with reference layup $[0_2,45_2,90_2,-45_2]_s$ with 25J impact was selected and compared reasonably well with numerical results. Finally, the force-displacement, force-time curves as well as the damage area obtained at different failure modes were compared to evaluate the capabilities of the damage models. The results of this work can provide guidance for numerical failure assessment and further engineering application of these models.

A0679- Loading rate effect on mixed mode interlaminar fracture toughness

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Interlaminar fracture toughness is an important property for fiber reinforced polymer composites, especially for the application in aerospace engineering. This work investigates the rate-dependent mixed-mode interlaminar fracture behavior for a unidirectional carbon/epoxy composite over a wide range of loading rate from 0.008 mm/s to 20 m/s. The mixed mode bending (MMB) specimen was used under quasi-static condition. Dynamic tests were conducted on mixed mode flexure (MMF) specimens, through assigning asymmetry dynamic loading using a self-developed electromagnetic Hopkinson pressure bar. Hybrid numerical-experimental method was used to calculate the dynamic J integral. Node-release method is adapted to simulate the crack propagation process along the interface. And the

dynamic crack-propagation toughness was measured as a function of crack tip speed using high sensitivity strain gages.

A0880- An Experimental and Numerical Investigation on Damage Resistance Assessment of 3D Braided Composites

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Damage resistance properties of 3D multi-directional braided composites and traditional laminates were comparatively studied between four kinds of 3D braided composites and laminates by low velocity impact experiments according to ASTM D7136. All the specimens were made by the same type of carbon fiber and epoxy-resin using the same fabrication process, and the fiber volume fractions were between 47.4%-57.2%.Two types of low velocity impact experiments were carried out, including different types of composites under the same impact energy and the same composites under different impact energies. And a non-destructive inspection (NDI) methods were used to detect the damages in the composites after impact.

Conclusions were obtained according to the comparison of damage area and damage length. The damage resistance of 3D braided composites is much better than that of laminates. And the 3D 5 directional composite has the best damage resistance among 3D braided composites. For 3D braided composite the inflection point of impact energy was about 30J.In order to assess the damage resistance and predict the damage process of 3D braided composites, a numerical model was also proposed based on FEM software Abaqus, which takes different damage moods into consideration, such as fiber failure, matrix failure and shear cracks. The relative errors of damage length and damage area between simulation and experimental results are less than 15%, which indicates that the model is reasonable.

A1058- Effect of Reinforcement and strain rate on the mechanical behavior of peek composites

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Polyetheretherketone (PEEK) is a kind of high-performance thermoplastic polymer, known to own high strength, high elastic modulus, good impact resistance, high toughness, easy processing compared to other composite resins. With these advantages, PEEK composites have a great potential for aerospace application. In this paper, three types of samples (PEEK, PEEK reinforced with 30% of short carbon fibers and 30% of short glass fibers) are

investigated under a variety of strain rates from 1000 s^{-1} to 3000 s^{-1} by a Hopkinson bar system. For tensile tests, the yield strengths of pure PEEK, Carbon/PEEK and Glass/PEEK composites are independent of the strain rates. However, the fracture strain and the energy absorption capability of the three materials are very sensitive to strain rates. For compressive tests, he yield strength of pure PEEK increase with the increase of strain rate. After reinforced with short fibers, the strength of PEEK composites increase a lot while the fracture strain of them decrease obviously. The digital image correlation (DIC) technique is employed to measure the strain. The fracture process is recorded by a high speed camera. And the fracture surface is investigated in-situ in the scanning electron microscopy (SEM), which is combined with a microscale numerical model to find an explanation of the fracture mechanism of PEEK with short fibers.

A1081-Impact fatigue behavior of GFRP mesh reinforced ECC for runway pavement APPLICATION

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Concrete pavement is easy to crack and generate the chunks, which may destroy the engine of the airplane and maintenance cost is very expensive. Engineered cementitious composites (ECC) is ductile with microcracks, but its strength is low. Glass Fiber Reinforced Polymer (GFRP) mesh imbedded in ECC could improve the strength. This paper investigates the impact fatigue behaviour of ECC and GFRP mesh reinforced ECC under 5 different impact loads (1.61 MPa, 1.88 MPa, 2.10 MPa, 2.41 MPa and 3.60 MPa), the concrete specimens were also tested for comparison. The experimental results show that GFRP mesh reinforced ECC has improved impact fatigue behaviour than ECC specimens. The concrete specimens were all broken in few times, but the GFRP mesh reinforced ECC specimens were all not broken when has been impacted for 30000 times. The impact fatigue behaviour of EM-10 was the best of all the specimens, which is a desirable pavement material comparing to the ordinary concrete and ECC.

MS12:Short crack behavior and its application

A0571- TOLERANCE FOR NONPROPAGATING SHORT CRACKS DEPARTING FROM ELONGATED NOTCHROOTS

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It is well known that it is impossible to guarantee that structural components are really free of cracks smaller than the detection threshold of the non-destructive method used to identify them. Nevertheless, most components are still designed against fatigue crack initiation using procedures that do not recognize such cracks. Consequently, their “infinite life” predictions may become unreliable when cracks are introduced in them by any means, either during their manufacture, or else during their service lives, and not quickly detected and properly removed. However, while large cracks may be easily detected and dealt with, small cracks may pass unnoticed, even in careful inspections. Therefore, structural components that must last for very long fatigue lives should be designed to be tolerant to undetectable short cracks. Indeed, continuous work under fatigue loads cannot be guaranteed if any crack may or might propagate during their service lives. Since most structural components designed for long lives work just fine, in spite of not recognizing such cracks, they certainly are somehow tolerant to undetectable or to functionally admissible short cracks. However, the question es alone, but such a problem can be avoided by adding proper short crack concepts to their “infinite” life design criteria. This work proposes such a damage-tolerance requirement to quantify the behavior of short cracks that depart from form elongated notch roots. Finally, it is shown that predictions made using the proposed model, which uses only well defined mechanical properties and requires no adjustable parameters, are supported by convincing experimental data, which is based on Direct Current Potential Drop (DCPD) Technique.

A0750- MULTISCALE SEGMENTATION MODEL OF SHORT FATIGUE CRACK GROWTH

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There are microstructurally small crack (MSC) and physically small crack (PSC) at the stage of fatigue short crack, which is predominantly controlled by microstructural characters and mechanical mechanism, respectively. The distinctive feature of segmentation has made the traditional models inefficient. Based on the theory of strain energy density, the material, loading and geometry transitional functions are defined in the model and physically reasonable expression of crack driving force is formulated in the framework of segmentation. Subsequently, typical aeronautical material is adopted to perform the short fatigue crack test.

Predicted results of the multiscale segmentation model are compared with the fatigue test results of the material, demonstrating that the proposed model can reflect the multiscaling features for short fatigue crack growth.

MS13:Thermodynamics Based Modelling of Damage Evolution, Fatigue Life and Failure

A0169- A Damage Mechanics Theory with No Curve Fitting: Unification of Newtonian Mechanics & Thermodynamics

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The field of classical mechanics is based on Sir Isaac Newton's work in "The Principia," published in 1687. In this work, Newton introduced the world to three universal laws of motion, which describe the relationships of any object, the forces acting upon it and the object's resulting motion. It is these three laws that make up the foundation for classical mechanics, and all subsequent theories of mechanics are derived from them. But Newtonian mechanics still cannot account for the past, present or future of any aspect of a physical body or its governing equations.

Around 1850, Rudolf Clausius and William Thomson (Kelvin) formulated both the First and Second Laws of Thermodynamics. Because the field of thermodynamics governs the past, present and future of all physical bodies, the aging process and life span of any physical body can be modeled in accordance with the thermodynamics laws. Still, thermodynamics alone cannot convey the response of a physical body under an external force at any given moment – something classical mechanics equations are able to achieve.

Being able to accurately predict the life span of physical bodies, both living and non-living, has been one of humankind's eternal endeavors. Over the last 150 years, many unsuccessful attempts were made to unify the fields of classical mechanics and thermodynamics, in order to create a generalized and consistent theory of evolution of life-span of inorganic and organic systems. The objective has been to map out the aging process of a physical body using classical mechanics equilibrium equations while also predicting its life span. Most past attempts were based solely on the use of physical experiments, which would reveal the aging rate and life span of any physical body first. The experimental data is later be used to create a life-span expectancy model by curve fitting, like in the damage mechanics theory proposed by L. M. Kachanov.

Authors, will report a new unified mechanics theory that can now predict the aging and life span of any physical body based purely on mathematical calculations and without the need for any prior life-span degradation testing or curve fitting phenomenological damage mechanics models.

A0201- DAMAGE MECHANICS BASED APPROACH TO THE ANALYSIS OF FATIGUE BEHAVIOR OF BUTT WELDED JOINTS CONSIDERING WELD-INDUCED RESIDUAL STRESSESAND INITIAL DAMAGE, RELAXATION OF RESIDUAL STRESSESAND ELASTIC-PLASTIC FATIGUE DAMAGE

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A damage mechanics based approach is applied for the study of fatigue behavior of butt welded joints. Weld-induced residual stresses, which are employed as the initial state in the fatigue damage analysis, are determined through a simulation of weld process using a sequential coupled thermal-mechanical finite element analysis. The initial damage induced by weld process is also considered using a plastic damage model. An elastic-plastic damage model is introduced to investigate fatigue damage evolution of welded joints subjected to cyclic loading. Furthermore, the relaxation of residual stresses with the increasing number of cycles under the different level of loads is investigated. The predicted fatigue lives are compared with the experimental results from the literature.

A0365- A DAMAGE MECHANICS BASED COHESIVE ZONE MODEL FOR DELAMINATION AND FAILURE BEHAVIOUR OF COATINGS AT HIGH-TEMPERATURE

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A Cohesive Zone Model is derived within the framework of continuum thermodynamics for pure Mode I opening. The separation is additive decomposed into elastic and inelastic part. For the evolution of inelastic separation a power-law in combination with a damage law is used to consider tertiary creep, additionally. Thereby, the damage evolution is related to energy release rate and inelastic opening rate. In the next step this model is specified for isothermal conditions and applied to a Four-Point-Bending-Test at high-temperature to describe failure of an iron aluminide coating, which is coated onto an aluminium beam. Additionally, this model is applied to the interface between substrate and coating to describe delamination of the coating after failure or cracking, respectively.

A0397- THERMODYNAMICS AND MULTI-PHYSICAL MODEL FOR THE EFFECT OF CORROSIVE ENVIRONMENT ON METAL

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In various industrial sectors, some metal parts of more or less complex shape have to be carefully dimensioned to resist with time to thermo-mechanical stresses, but also to a more or less aggressive environment. When a metal structure must withstand thermo-mechanical stresses over very long periods, the problem arises to take also into account the degradation of these mechanical properties by the presence of gas such as hydrogen, which can diffuse into the material and weaken it. The presence of oxygen could also be considered, which generally oxidizes its surface. The degradation of materials subjected to such aggressive environments put significant challenges for engineering. To achieve such a goal, it is necessary to model and predict at least the diffusion of hydrogen and/or oxygen, which generates indirectly a degradation of mechanical properties, in order to improve the reliability and predictivity of models.

Based on the thermodynamics of irreversible processes under small strain hypothesis, a fully coupled thermo-elasto-visco-plastic-damage theory is formulated, which includes both kinematic and isotropic hardening, and takes into account the diffusion of several species in metals. At our knowledge, this is the first time that a coupled theory for species diffusion and thermo-elasto-visco-plastic model takes into account simultaneously ductile damage and both kinematic and isotropic hardenings. Specie is supposed to diffuse in both lattice (normal interstitial lattice sites) and trapping sites (microstructural trapping sites such as dislocation cores, grain boundaries, and interfaces between the matrix and various second-phase particles). In order to take correctly into account of different coupling effects, the diffusion fluxes vectors depend not only on the gradient of chemical potential, but also on the gradient of temperature (thermodiffusion) and on the gradient of pressure (barodiffusion). The heat flux also depends not only on the gradient of temperature, but also on the chemical potential gradient of each specie, according to the thermodynamics of irreversible processes.

Because our model takes into account the damage, it will have an effect on the diffusion. This is why we consider in the model the damage as traps for diffusing species. The number of moles (per unit of reference volume) of trapping sites is therefore defined as an increasing function of damage.

This model is implemented into Abaqus/Standard using the Uel user subroutine for application to the effect of corrosive environment on metallic alloys, such as TA6V after welding.

A0419- Nonlocal Void Coalescence Formulation within an Internal State Variable Based Constitutive Model for the Prediction of Plasticity and Damage Evolution in Solid Materials

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A nonlocal approach for predicting damage evolution in solid materials has been implemented within a continuum based internal state variable constitutive model. Specifically, a functional form for void coalescence, an inherently nonlocal phenomenon, is developed using spatial gradient and Laplacian operators to account for void sheeting and impingement effects. The intervoid ligament distance, itself a function of void number density and size, is shown to inversely correlate to the void coalescence rate. Therefore, a causal relationship between the nonlocal void coalescence phenomenon and local void nucleation and growth phenomena is established within the internal state variable constitutive model framework.

A0477- NUMERICAL PREDICTION OF LONG-TERM DEFORMATION FOR BRIDGES CONSIDERING BASIC CREEP, THERMAL CYCLIC CREEP AND MATERIAL DEGRADATION

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The long-term deformation of bridges is determined by intrinsic properties and external loads, so the deflections of girder are often seriously underestimated without fully considering these complex factors. In order to predict the multidecade deflections accurately, the coupled effects of basic creep, thermal cyclic creep, damage and tendons relaxation are considered in this paper. Meanwhile, an Arrhenius-adjusted age is applied to the material properties and viscous prestress relaxation based on the fine temperature distributions. For improving the calculation efficiency further, some numerical measures are taken into account: (1) A elastoplastic damage concrete constitutive based on damage energy release rate is introduced, as well as a spectral decomposition-based return-mapping algorithm; (2) The rate-type method for static creep is also applied to transfer viscoelastic stress-strain relation into Kelvin chain with the application of a rheology model; (3) With the aid of Duhamel similarity theory, the annual temperature boundary is rapidly equivalent in the thermo-mechanical coupled analysis. Subsequently, the long-term behavior of a large-span prestressed concrete bridge is analyzed finely. Compared to the inspection reports, the deflection at the midspan and the temperature variation on the top of box girder are all in agreement with the numerical results. And the result also shows that the coupling effect of the above factors is responsible for underestimation of long-term deformation. The irreversible strain induced by cycle thermal loads increases with alternations of seasons.

MS14:Life-cycle based study and design of concrete-filled steel tubular structures

A0959- SENSITIVITY ANALYSIS ON THE FLEXURAL BEHAVIOUR OF CFST TRUSSES WITH GEOMETRIC IMPERFECTION

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Initial geometric imperfection, which may largely affect the strength and stability behaviour of structures, is inevitable in practice. For concrete-filled steel tubular chord to hollow steel tube brace truss (CFST truss for short), imperfection might be seen in both steel and concrete. Previous studies mostly considered the certain level of imperfection throughout the CFST truss, while this paper further develops the nonlinear analysis formwork with sensitivity analysis of different imperfections. The nonlinear model is validated by previous experimental data. Both initial steel and concrete imperfection obtained from elastic buckling analysis and statistical analysis are introduced into the numerical model, together with the interactions between these materials. The flexural behaviour of such composite trusses with different initial geometric imperfections are investigated and compared, based on which the design recommendation is proposed.

A0962- VIBRATION PROPERTIES OF CONCRETE-FILLED STEEL TUBES (CFST)

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This paper studies the vibration properties of circular concrete-filled steel tubular (CFST) members and their potential applications in determining the flexural stiffness of CFST and detecting steel-concrete interface debonding. Modal testing was carried out to extract the first few modes of natural frequencies and mode shapes. The test results were compared with the numerical modelling results to calibrate the flexural stiffness of CFST. The influence of debonding at the steel-concrete interface on the vibration properties of CFST members is discussed and the possibility of employing such effects to detect the potential debonding in CFST structures is investigated.

A0964- EXPERIMENTAL STUDY ON FIRE RESISTANCE OF RECYCLED CONCRETE-FILLED STEEL TUBE COLUMNS WITH RECTANGULAR SECTION

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Results from eleven fire resistance experiments of RCFST (recycled concrete-filled steel tube) columns are presented, including nine axial compression and two eccentric compression specimens with different concrete material property and load ratio. Temperature distribution, axial and lateral deformation, and damage mode are observed. Effect of load eccentricity, load ratio and recycled concrete property on fire resistance is discussed. Results show that the similar damage mode occurred both for axial compression and eccentric compression columns with different load ratio, concrete strength and substitution rate of recycled concrete. Load ratio and load eccentricity have noticeable influence on the fire resistance of RCFST columns. Higher substitution rate of recycled concrete will lead to a little lower fire resistance of RCFST columns.

A0966- NUMERICAL ANALYSIS AND DESIGN OF SPECIAL-SHAPED CFST STUB COLUMNS UNDER AXIAL COMPRESSION

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The paper presents numerical investigation and design of axially loaded special-shaped CFST stub columns. CFST columns with triangular, D-shaped, 1/4 circular and semi-circular sections are becoming increasingly attractive to designers owing to their aesthetic appearance. Numerical models have been developed using the finite element (FE) package ABAQUS, and verified against experiments. The FE models have been proven capable of replicating the key test results, the full experimental load–deformation histories and deformed failure modes. Upon on validation of the FE models, load-deformation responses and interaction behaviors have been investigated through carefully designed parametric studies and design recommendations on key parameters including steel grade, tube thickness and concrete strength have been suggested accordingly. In addition, the experimentally and numerically generated results have been used to evaluate accuracy of the current international design provisions given in the Chinese code, European code and American specification.

A0969- DIRECTIONAL COLLAPSE OF STEEL AND CFST WORKSHOP UNDER SEISMIC LOAD

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This paper presented a numerical study on the collapse behaviour of steel and composite workshop subjected to the El Centro seismic load in order to address the increasing demand.

The aim of this investigation was to develop a rigorous methodology that could identify the directions of collapse and evaluate the efficacies of lateral stability systems that were designed to alter the direction of collapse. A series of criteria were initially determined via FEMA356 and nonlinear dynamic pushover analyses. Meanwhile, the results of nonlinear dynamic transient analyses of steel workshop models with or without lateral stability systems were obtained and proceeded. Finally, the reliability as well as accuracy of modelling results was discussed before a decent conclusion being drawn.

A0971- EXPERIMENTAL STRESS CONCENTRATION FACTORS OF CFDST CHORD TO CHS BRACE T-JOINTS

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This paper presents a preliminary experimental investigation on the stress concentration of composite T-joint consists of circular concrete-filled double-skin steel tubular (CFDST) chord and circular hollow section (CHS) brace. The brace is subjected to axial tension or compression during the test. The experimental parameters include the loading type, the chord to brace diameter ratio and the hollow ratio of the cross section. Stress concentration factors (SCFs) and strain concentration factors (SNCFs) are obtained from the test. It is found that the SCFs near the saddle point of the chord are higher than other positions. Generally, SCFs increase with the increase of the parameters of cross-sectional hollow ratio and radius to thickness ratio of chord tube.

A0988- BEHAVIOUR OF CONCRETE-ENCASED CONCRETE FILLED STEEL TUBULAR COLUMN TO REINFORCED CONCRETE BEAM JOINT SUBJECTED TO FULL-RANGE FIRE

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Concrete-encased concrete filled steel tubular (CFST) column consists of an inner CFST component and an outer reinforced concrete (RC) component. This kind of composite member is gaining popularity in high rise buildings. The structural members may be subjected

to fire during their whole life cycle. Since concrete-encased CFST column has good fire performance, it is probable that concrete-encased CFST could survive a full-range fire including heating and cooling stages. This paper experimentally investigates the behaviour of concrete-encased CSFT column to RC beam joint subjected to the full-range fire including heating and cooling. The test results, including failure modes, temperature developments and deformation versus time relationships, were reported and discussed. These results were further compared with previous research on fire performance of CFST column to steel beam joints with external ring connections.

A1050- Experimental study on partially concrete-filled steel tubular column under lateral impact loading

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The paper reports the results of an experimental investigation on the behavior of partially concrete-filled steel tubular (PCFST) column under lateral impact loading. A total of six specimens with two type of concrete-filled ratio (50% and 75%) were tested under a lateral rigid-hammer impact at different impact velocities (5 and 8 m/s) and boundary conditions (cantilever and fixed-simply-supported). The impact load was applied at the typical vehicular impact location, i.e. near the base. The impact force, reaction force and the deflection versus time curves was measured. The impact velocity and the boundary condition had significant effect on the dynamic responses and the observed damage. The distribution of main diagonal cracks was influenced with the concrete-filled ratio. In addition, the simply-supported columns failed in shear mode with one main diagonal crack originating from the base of the column to the impact point. The cantilever columns failed in with flexural cracks.

A1063- ANALYTICAL BEHAVIOUR OF CFST COLUMNS SUBJECTED TO COMBINED EFFECT OF FIRE AND LATERAL CYCLIC LOADING

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This paper illustrated the analytical behavior of concrete filled steel tubular (CFST) columns under the combined effect of fire and lateral cyclical loading. A finite element model (FEM) was developed based on the ABAQUS platform and accuracy of which has been verified by test data. Based on the verified FEM, the effect of different loading paths of combined fire and lateral cyclical load was investigated. A full range analysis on moment (M) versus curvature curve (φ) relationship of post fire CFST column was illustrated. The contact stress between concrete and steel in CFST columns under post fire cyclical load was presented.

MS15: Numerical Advances in Multiscale Failure Analysis in Geo-Engineering

A0298-CHARACTERISTICS OF PERMEABILITY AND DAMAGE OF ROCK SALT UNDER THE STRESS-SEEPAGE COUPLING CONDITION

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Rock salt is the optimal surrounding rock of underground energy storage, so its damage is directly related to the impermeability and stability of the storage. In this study, the gas permeability tests of pure rock salt under different stress conditions were carried out to obtain the characteristics of permeability of rock salt during the deformation process. The results revealed the influence of stress states on the permeability. With the confining pressure increasing, the permeability decreased significantly. Then CT scanning technique was used to analyze the microscopic damage characteristics of the damaged rock salt under the stress-seepage coupling conditions. The distribution characteristics of porosity, crack area, crack volume and crack quantity of damaged rock salt were obtained. Based on the microscopic damage characteristics, the damage variable was calculated by definition. The damage variable showed a significant confining pressure effect that the damage variable decreased with the increase of confining pressures. Meanwhile, the damage characteristics had great influence on the permeability of rock salt.

A0701-THERMAL FRACTURE MODELING OF 2D FUNCTIONALLY GRADED MATERIALS BY THE NUMERICAL MANIFOLD METHOD

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Attributing to the use of bi-cover systems, the numerical manifold method (NMM) is very suitable to solve various crack problems. In this work, the NMM is further developed to analyze 2D thermal fracture of the functionally graded materials (FGMs). The discontinuity of temperature and displacement fields across adiabatic crack faces is naturally captured. As for the singularity of thermal flux and stresses at the crack tip, it is accurately represented through the incorporation of associated asymptotic basis in the cover functions. The thermal stress intensity factors (TSIFs) are computed using the domain form of the interaction integral. The accuracy of the proposed method is examined through several numerical examples and the results conform well the available reference solutions.

MS16: Damage and failure mechanics of bridge structures under extreme loading

A0250-EFFECT OF RANDOM DAMAGE OF THE VEHICLE-TRACK-BRIDGE SYSTEM

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With the rapid development of high-speed railway construction in the world, the damage problem of the bridge gird and its upper track structures in railway has attracted more and more attention. In this paper, considering the random damages in the railway bridge and track structures, the characteristics of the random dynamic responses varying with their damages in the vehicle-track-bridge (VTB) system are systematically analyzed based on the probability density evolution method (PDEM). Firstly, a random VTB model with the random damage parameters is established and its random motion equations are derived based on the principle of virtual work. Then, the representative parameter sample sets of the random VTB system can be choose and initial probability distribution can be determined by using the number theory method (NTM); and the random dynamic responses and their characteristics varying with the damage of VTB system are analyzed based on the PDEM. Finally, the representative numerical example is applied and some conclusions for the effects of the random damages are presented.

A0253-BENDING PERFORMANCE OF CIRCULAR CONCRETE-FILLED STEEL TUBULAR MEMBERS WITH A NOTCH IN STEEL TUBE

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Bending tests under cyclic loading of the concrete-filled steel tubular (CFST) members with artificial notches were conducted in this paper to investigate the effects of material imperfection of steel tubes. The deflection-length curve, strain responses and load-displacement responses were discussed in detail with a parametric study, which includes the notch location, orientation and size. The results indicate the notched CFST specimens had lower flexural capacity than the intact CFST specimens. Under the condition of equal size of the artificial notches, the reduction of the flexural capacity of the transverse notch is larger than that of the longitudinal notch. In the same orientation of the notches, as the notch size increasing, the flexural capacity of CFST specimens decreases in a certain extent.

A0286-INVESTIGATION OF PBH CONNECTOR’S CAPACITY AND SLIPPAGE

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The PBH shear connector is a type of shear connector specifically promoted from PBL (perforated steel plate connections). To investigate the PBH Connector's Capacity and Relationship of Load-slippage, both numerical simulation and factorial tests were conducted with consideration of four factors, including concrete strength, hole space and diameter, and diameter of stirrups. Specially, a new simulation method was proposed to study the behavior of steel-concrete composite interface in the numerical model. Both numerical and experimental results agree well for stress distribution and slippage tendency. With statistic analysis of data retrieved from the experiments, the effect indices of PBH shear capacity were quantified. In addition, empirical formulas for PBH capacity were developed based on shear-friction theory, dimensional consistency and failure modes. And each of the application scope of the empirical calculation equation of load bearing capacity was given.

A0415-DAMAGE OF MASONRY ARCH BRIDGES – FIELD OBSERVATION AND NUMERICAL SIMULATION

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Although historic masonry arch bridges are comparatively durable and robust structures, modern-day traffic loads or extreme loading conditions may cause severe damage and shorten the remaining service life span. A concept for the safety evaluation of existing masonry arch bridges based nonlinear finite element simulations has been developed and applied to several existing structures of this type. The adjacent soil is incorporated in the respective finite element model and the smeared crack approach is utilized for the masonry allowing to realistically reproduce characteristic crack patterns observed at existing bridges. Possible causes for visible cracks may be identified. Other advantages of using a crack model are the opportunities to formulate failure criteria based on crack lengths and to directly consider pre-existing cracks in the finite element model. For the masonry under compression, an elastic-plastic model is used. To limit tensile stresses and to reduce unrealistic stress concentrations in the adjacent soil, plastic material behavior is assumed and the Drucker-Prager yield criterion is adopted. The analysis concept could be validated by destructive load tests at a disused masonry arch bridge. In these destructive tests, the bridge was subjected to a total load of more than five times the designated service load.

A0442-DYNAMIC RESPONSE OF STEEL BOX GIRDERS UNDER INTERNAL BLAST LOADING

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Steel structures like steel box girders have been widely employed in modern bridge engineering. The damage and failure characteristics for steel girders under inner blast loads have not yet been investigated sufficiently due to its complicated confinement effects and reflections. In order to study the damage mechanism of steel box girder under inner blast loading, CEL (fluid-solid coupling) algorithm and physical tests are conducted to simulate the dynamic response of stiffened steel plates. The numerical outcomes are compared and validated with the experimental results. With consideration of elastoplastic behavior for the structure, failure modes of steel box girders under inner blast loading are characterized with the validated numerical method. The influence of steel plate thickness is also investigated and the optimized steel plate thickness is proposed for anti-blast resistance design of steel box girders.

A0474-DYNAMIC RESPONSE AND DAMAGE ANALYSIS OF UHPC THIN LAYER REINFORCED PIERS UNDER VEHICLE IMPACT

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Ultra-high performance concrete has been widely concerned and applied in engineering because of its high durability and mechanical properties. The use of UHPC thin-layer reinforced piers has the strong tensile properties and greater ductility. In this paper, LS-DYNA software is used to establish a typical vehicle impact piers model. The dynamic response and damage of traditional reinforced concrete piers and UHPC thin-layer reinforced piers under different impact loads are analyzed and compared. From the perspective of damage and energy, the impact resistance of UHPC thin-layer reinforced piers is discussed, which can provide reference for anti-collision design of bridge pier.

A0554-PREDICTION OF THERMAL BEHAVIOR ON CABLE FORCES BASED ON LONG-TERM MONITORING DATA AND SUPPORT VECTOR MACHINE

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Aiming to avoid the wiggling in response of interest covered by temperature effects, it is meaningful to identify the thermal response, which is the precondition for the research of damage detecting or condition assessment. This paper presents the modeling of the temperature effects on cable forces for the 3rd Nanjing Yangtze River Bridge, which is equipped with long-term monitoring sensor system. Based on the one year measurement data

obtained from the sensors installed in the 3rd Nanjing Yangtze River Bridge, it is found that linear regression model is proper to fit the correlation of the ambient temperature and the cable force. Based on the existing linear regression coefficients, it can be concluded that the regression coefficients of the longer cables are relative bigger than the shorter ones'. For sake of obtaining the thermal behavior of those stay cables without efficient monitoring data, the artificial neural networks model and supported vector machine model are applied to predict the unknown liner regression coefficients. Based on the theoretical derivation formulation and practice experiences, cable force, cable inclined angle, sectional area, cable length are selected as the input variables. Then, a total of 35 samples are divided into two parts: 30 samples as the training data set and the other 5 samples as the validation data set. For the artificial neural network model, one single hidden layer model is adopted and a trial-and-error method is performed to optimize the number of neurons in the hidden layer. After a preliminary test, it is found that the best performance is achieved at five neurons in the hidden layer. For the supported vector machine model, the defined radial basis function is adopted as kernel functions and an exhaustive grid-search with exponentially growing and is then conducted to obtain the optimal models. The best values of and are 128 and 1.0, respectively, whose cross validation mean squared error is 0.086211. Comparison of the performance of the artificial neural networks and the supported vector machine models, it is concluded that the SVM model performs much better prediction capability than the artificial neural network model for both training and validation data set.

A0559-EXTRACTION OF CABLE FORCES INDUCED BY DEAD LOADS FOR CABLE-STAYED BRIDGE CONDITION ASSESSMENT

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Cable forces induced by dead loads will be redistributed when damage occurs in the bridge structures. Thus, dead load-induced cable force is an alternative indicator to imply the condition of the whole bridge structures. However, it is impossible to measure dead load-induced cable forces directly. This paper presents a method to extract dead load-induced cable forces from complicated monitoring data under random vehicle loads. The maximum and minimum cable forces induced by vehicle loads were calculated based on the influence line obtained from the updated finite element (FE) model. Based on the idea that the selected cable is bound to experience the most unfavorable vehicle loading conditions as long as the bridge serviced for enough time, it is reasonable to assume that the maximum and minimum monitoring cable force data correspond to the most unfavorable vehicle loading conditions. The equation is established based on the ratio of the maximum and minimum vehicle load-induced cable forces under above two cases and the dead load-induced cable forces will be derived. The SA-E15 stay cable of the 3rd Nanjing Yangtze River Bridge is taken as an example

to demonstrate the feasibility and advantage of the proposed method. There is only 0.2% of the possibility that errors occur when the calculated results of the proposed methods do not confirm to the dead load-induced cable forces during the bridge closure period. To avoid contingency the authors select another 4 stay cables to verify the accuracy of the proposed method. And the biggest relative error rate is 0.27% among all the 5 stay cables. Thus, it can be concluded that the proposed method is exact enough to extract dead load-induced cable forces, which -provides enough precision for engineering application.

A0589-STOCHASTIC MODELLING AND OPTIMUM INSPECTION AND MAINTENANCE STRATEGY FOR RC GIRDER BRIDGES SUBJECTED TO REINFORCEMENT CORROSION

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This paper presents a method for stochastic modelling of reinforcement corrosion depth and optimizing inspection and maintenance strategy for the reinforced concrete (RC) girder bridges due to reinforcement corrosion. The reinforcement corrosion depth is considered as a stochastic process with uncertainties, and the Gamma process is adopted to simulate the propagation of reinforcement corrosion depth in RC girder bridges. From the stochastic modelling for fatigue crack growth, the probability of failure caused by reinforcement corrosion is predicted over the service life of RC girder bridges. The remaining service life of RC girder bridges is determined by comparing the reinforcement corrosion depth with its predetermined threshold. Furthermore, the probability of detection is adopted to consider the uncertainties in detecting reinforcement corrosion depth by using existing damage detection techniques. Based on the decision tree model, a multi-objective optimization problem is proposed and solved by a genetic algorithm to determine the optimized inspection and maintenance strategy for the RC girder bridges due to reinforcement corrosion. The optimized strategy is achieved by minimizing the life-cycle cost, including the inspection, maintenance and failure costs, and maximizing the service life after necessary intervention. The number of intervention during the service life is also taken into account to investigate the relationship between the service life and the cost for maintenance. The results from a 30m span RC girder of the Guangxi Tieshan Port Bridge show that the proposed method can provide a useful approach for cost-effective inspection and maintenance strategy for RC girder bridges subjected to reinforcement corrosion.

A0609-FAST RELIABILITY EVALUATION OF BRIDGES UNDER STOCHASTIC TRAFFIC LOADS BASED ON WIM DATA

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To provide proficient information for engineers to make quick decision, a fast reliability evaluation approach via static effect of stochastic traffic flow based on WIM data is proposed. The proposed approach is time-saving because it doesn't have to solve the dynamic equation through iteration. Based on daily WIM data, an upgraded CA model designed to load the influence line is developed to simulate the traffic flow, which can simulate all kinds of vehicle behaviors, such as speed reduction, acceleration and lane-changing, and it is also adaptive to load all kinds of bridges with any span. Dynamic effect is considered by introducing an impact factor. A software strategy to calculate the fracture reliability is developed via Matlab.

A0617-MODAL IDENTIFICATION OF SUSPENSION BRIDGES BASED ON LONG-TERM MONITORING DATA ON DIFFERENT TIME SCALE AND DAMAGE BASELINE DATA ANALYSIS

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To provide an accurate information for damage identification, a software aiming at continuously analyzing the modal parameter for a long period is developed. This software can analyze the modal parameters on different time scale, providing the distribution of analysis error and changes under nature factors. Long term monitoring data of Nanjing Fourth Yangtze River Bridge is analyzed by this software on different time scale. Identification errors of different time scale is analyzed, which provides the distribution information for damage identification. Another software aiming at parametric analysis of bridge damage is also developed, which contains three damage detection methods based on modal parameters. A numerical example of Nanjing Fourth Yangtze River Bridge is developed to analyze the baseline data of damage by this software, which provides the baseline of damage identification.

A0798-DAMAGE IDENTIFICATION FOR A CONTINUOUS BRIDGE BY USING RESPONSES OF VEHICLES MOVING ON THE BRIDGE

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While identifying bridge damages by using bridge responses - known as direct method, usually requires numerous sensors instrumented on the bridges to get accurate results, indirect method which only needs few sensors on the moving vehicles is much cheaper， high efficient and accurate. The mode shapes of the bridges are extracted from the vehicular responses moving on the bridges by using Short-Time Fourier Transform and a damage index based on the extracted mode shapes is used to identify the bridge damages. One novelty of this paper is applying this method to a continuous bridge, which has been rarely studied. To reduce the influence of bridge surface irregularities on the accuracy of the identification results, two trailers are dragged by a tractor and sensors are instructed on the two trailers axle locations. Numerical tests under different vehicle speeds considering data noise are conducted and verify the effectiveness and robustness of this method.

MS17: Damage mechanics for rock mass

A0157-MODELLING OF COAL UNDER LOADING CONDITIONS FROM CONTINUOUS-DISCONTINUOUS METHOD

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The failing process of coal sample under loading conditions is investigated by using both laboratory experiment and 3D finite-discrete element method in the present paper. The cohesive zone model was used to characterize nucleation, growth and propagation of cracks, while the potential contact detection and interaction of fractured solids were examined by means of the penalty method in ABAQUS software, where the parallel computation was employed to accelerate the calculations. Uniaxial and Brazilian tests were performed in the laboratory to obtain the mechanical properties of the coal such as Young's modulus, fracture energy, cohesive strength, friction angle, uniaxial compression and shear strength. Further, these properties were carefully calibrated prior to being taken as input arguments in the continuous-discontinuous modelling. All the simulating results were basically in agreement with that obtained from the tensile tests in laboratory. This study shows that such computational mechanics of discontinua can be employed to gain powerful insight into the failure mechanism of coal, which could also be a useful tool to clarify the collapse mechanism of coal block caving in mining engineering design and rock test scheme optimisation.

A0270-EXPERIMENTAL AND NUMERICAL STUDIES ON MULTI-PEAK DEFORMATION BEHAVIOR OF JOINTED ROCK MASS UNDER UNIAXIAL COMPRESSION

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Understanding mechanical behavior of jointed rock masses is of great importance to the design of structures built in and on it. In this paper, the dependence of strength and deformability of jointed rock masses on the two joint geometrical parameters, namely, joint inclination angle and joint continuity factor, has been investigated systematically through physical model tests. Except for traditional single-peak deformation behavior (Type I-strain softening), three different multi-peak deformation behaviors (Type II-general strain softening with oscillations, III-yield platform-strain softening and IV-yield platform-strain hardening-strain softening) were observed for jointed rock models under uniaxial compression. The

corresponding damage mechanisms, such as closing/opening of pre-existing joints and cracking process of the rock matrix were further studied through particle flow modeling package PFC2D. By using the smooth joint contact model and calculating the overall mechanical response of joint system (such as the joint aperture, number of closed joints, and forces acting on the joints, etc), the role of joint strength mobilization on mechanical response of the jointed rock specimens was studied. It was shown that strength immobilization of the joint system with opening of most joints leads to Type I deformation behavior, while slight strength mobilization of the joint system with partially close of some joints after peak strength leads to type II deformation behavior. Full strength mobilization of the joint system with entire close of all joints, accompanied by severe damage developed in the matrix at the first peak (peak strength), leads to Type III deformation behavior. Salient strength mobilization of the joint system with entire close of most joints at the last peak (peak strength), as well as damage in the matrix mainly developed after the first peak, leads to Type IV deformation behavior.

A0288-CHARACTERISTICS OF ROCK FRACTURE DAMAGE INDUCED BY SHEAR

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The surface damage and evolution of gouge materials in rock fractures or faults undergoing shear can change fracture properties in terms of shear strength and dilation, fluid transmissivity and retardation for contaminants. In order to better understand the fracture surface damage characteristics during shear, both lab testing and particle-based discrete element method were used to examine the process of gouge particle plowed off from fracture asperities and subsequently their evolution in a fracture segment undergoing shear. The results show that significant abrasion and damage occurred by wearing the contact asperities and cracking the fracture surfaces. Gouge particles behave in two different ways under low and high normal stresses, respectively. Under low normal stress, gouge particles mainly roll with the moving fracture walls, with little surface damage. Under high normal stress, gouge particles can be crushed into a few major pieces and a large number of minor comminuted particles, accompanied by more severe damage (abrasion and micro-cracking). The size of the sheared-off fragments under different normal stresses was found to follow a Weibull distribution. Based on the volume of asperity degradation, a new joint damage coefficient was proposed. Combining the proposed joint damage coefficient and the Weibull size distribution of the sheared-off fragments can approximately predict the potential effects of sheared-off fragments on solute retardation coefficient in rock fractures.

A0411-NONLINEAR CREEP DAMAGE MODEL CONSIDERING EFFECT OF PORE PRESSURE AND LONG-TERM STABILITY EVALUATION OF BANK SLOPE OF RESERVOIR

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Recently a number of large hydropower engineering with high dam and vast reservoir have been put into operation in China. Most of these engineering have high rock slopes with poor geological condition. Under natural condition, the geology of this region is in pre-existing equilibrium state. But reservoir impoundment would make rock structure deviate from the equilibrium state. Especially, the hydrostatic pressure changes natural seepage and weakens rock mass, which would speed up the time-dependent deformation of rock mass. These greatly challenge the safety of these engineering.

A non-linear creep damage model based on elastic-viscoelastic model, viscoplastic model and damage model is brought up considering the effect of pore pressure, in which overstress is the driving force of inelastic deformation and damage evolution. The damage variable function considers exponential relation between damage variable and viscoplastic strain. This constitutive model has been implemented in ABAQUS. Then it is applied in the deformation mechanism analysis and long-term stability evaluation of bank slope of reservoir.

A0438-EVALUATION CRITERION OF THE DAMAGE AND CRACKING OF ROCK MASS BASED ON UNBALANCED FORCE

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Rock mass is a discontinuous structure whose deformation and failure ordinarily reveal strong nonlinearity. From local cracking to final failure of rock mass, there is still a large margin of bearing capacity, while traditional FEM may not converge when the rock mass is not completely destroyed. Meanwhile, because of the discontinuity of rock mass, it is hard for FEM to reflect the cracking and failure process, especially in the prediction of rock mass deformation, which exists a big gap from reality. It is found that there exists strong correlation between the unbalanced force and the cracking of dam toe and dam heel. By the comparison between nonlinear FEM and geo-mechanical model test, in this paper, based on engineering examples, the relationship between unbalance force and deformation and failure of rock mass is deeply analyzed. Furthermore, the evaluation criterion of the damage and cracking of rock mass based on Unbalanced force is explored.

A0646-BOUNDARY ELEMENT ANALYSIS OF FRACTURE MECHANICS IN GRADIENT MATERIALS

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Over the last decade, the authors have extended the classical boundary element methods (BEM) for analysis of the fracture mechanics in gradient materials. The new BEM is based on the fundamental solution of a layered solid and overcomes the mathematical degeneration that is associated with the solitary use of the displacement boundary integral equation for cracked bodies by developing the multi-region and single-region methods of BEMs. Effective implementation of the methods is detailed, devoting special attention to the description of accurate algorithms for the evaluation of various singular integrals in the boundary element formulations. The layered discretization technique is used to simulate the variations of the material property of graded materials with depth. The proposed numerical methods, together with fracture mechanics theories, are used to calculate the stress intensity factors of three-dimensional cracks in graded materials and to analyze the crack growth. The influence of the material parameters and crack dimensions on the fracture properties has been analyzed and quantified.

MS18: Multiscale Modeling of Damage and Failure in Quasi brittle Materials

A0449-A ELASTOPLASTIC DAMAGE CONSTITUTIVE MODEL FOR CONCRETE BASED ON A S-TYPE DAMAGE VARIABLE

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A 3D elastoplastic damage constitutive model is developed by combining the a novel S-type damage variable with the previous established unified hardening/softening elastoplastic constitutive model. The developed model is capable of reasonably describing the deformation and strength properties of concrete under complex stress condition, and can also reflect the stiffness degradation under reciprocating loads. The performance of the constitutive model is evaluated by comparing prediction and experimental results under reciprocating load. Finily, the model is integrated in ABAQUS via UMAT.

A0709-A REVIEW ON THE MICROPLANE CONSTITUTIVE MODEL OF QUASI-BRITTLE MATERIALS: THEORY AND APPLICATION

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Microplane model is a powerful tool to simulate the progressive failure of quasi-brittle materials (rock, concrete, composite, sea ice et al.). This work make a detailed review on the framework of microplane model. How to use microplane theory to simulate isotropic as well as anisotropic materials is addressed. The advantages and defects of microplane model are discussed, and the possible solutions to overcome those shortcomings are suggested. The application of microplane model to simulate material failure are presented at last.

A0933-MODELING OF HYDRAULIC FRACTURING IN ANISOTROPIC ROCKS WITH A HYBRID EDFM-XFEM METHOD

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In this paper, we shall investigate anisotropic effects of both elastic properties and permeability on hydraulic fracturing process of porous rocks. To this end, a new hybrid EDFM-XFEM method (embedded discrete fracture model and extended finite element method) is proposed to coupling fluid flow and rock deformation in the process of fracture propagation. Fractures are embedded into a non-conforming grid where the fluid flow in the porous matrix

is solved by the mimetic finite difference method accounting for an anisotropic permeability tensor. On the other hand, the stress-strain problem is solved by the extended finite element method with the same grid as the fluid flow. The couplings between rock deformation; permeability evolution and fracture propagation are taken into account by an iterative scheme. The proposed model is validated against the analytical solutions for Mandel's problem and KDG model. Sensitivity studies are performed in order to capture effects of anisotropy of rock permeability and elastic properties on hydraulic fracturing. It is found that the anisotropy of permeability has a significant influence on the geometrical characteristics of fracture, while the anisotropy of elastic properties mainly affects the propagating direction of fracture. The effect of Biot's coefficient on hydraulic fracturing is also studied.

A0938-MICROMECHANICS OF ROCK DAMAGE AND FRICTION: ANALYTICAL AND NUMERICAL STUDIES

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When subjected to external loads, brittle rocks are susceptible to be damaged and experience the initiation, propagation and coalescence of microcracks. Cracks are the main sources of energy dissipation and the associated complex nonlinear mechanical phenomena on different scale. Also, they provide the site of multiphyscal coupling, particularly for poromechanical coupling. Generally, crack propagation changes the poromechanical properties and in verse pore pressure enhances the damage evolution.

The present work presents a full version of anisotropic damage model with the consideration of induced material anisotropy by microcracking and unilateral effects. The constitutive model is formulated using an upscaling method by linear homogenization process. The system free energy being determined theoretically, the state variables are derived within the framework of irreversible thermodynamics and the governing criteria are formulated on local scale. By such a multiscale method, a series of relations for coupling processes will be established naturally, thus reducing significantly the number of the model’s parameters involved. Some trans-scale relationship between the parameters on different scales will be established.

A0943-MODELING ROCK WITH DAMAGED VIRTUAL MULTIDIMENSIONAL VIRTUAL INTERNAL BOND

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The rock contains many micro cracks and pores on the meso scale. These drawbacks can be considered as internal damage. Due to these damage, the mechanical properties of weakened. Subjected to the external load, these damage evolves, which weakens the rock seriously. In this paper, these damage behaviors will be modeled by the multidimentional internal bond conception. The damage effect is reflected into the virtual internal bond. By this model, the damage and fracture behaviors can be well simulated.

A0947-MICROMECHANICS-BASED MODELS FOR POROUS GEOMATERIALS WITH INCLUSION DEBONDING

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Some micromechanical modelings of the overall elastoplastic behavior and damage evolution in ductile porous geomaterials will be proposed in this work. According the microstructure of the studied materials, the one which is composed of a porous matrix that is embedded by linear elastic mineral inclusions is firstly considered. The solid phase of porous matrix is described by a pressure sensitive plastic model with a non-associated flow rule. With a two-level homogenization procedure, a macroscopic plastic criterion of the heterogeneous material is deduced and takes into account the effects of pores and mineral inclusions. Then it is assumed that the material damage is related to progressive debonding of mineral inclusions. The Weibull's statistical function is used to describe the varying probability of inclusion debonding. The debonded inclusions are considered as completely separated from the matrix and regarded as voids for simplicity. For porous geomaterials with two or more different types of inclusions, the incremental approach initially proposed by Hill will be adopted in the second model to account for these effects (porosity, size of inclusion, debonding of inclusion, plastic compressibility, etc.) on the macroscopic behavior. Comparisons between the numerical results and experimental data show that the proposed models are able to capture the main features of the mechanical behavior of the studied materials.

A0951-DISCRETE ELEMENT NUMERICAL SIMULATION OF LOADING RATE ON TESTED STRENGTHS OF ROCK

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Discrete element method is capable of simulating large deformation, failure and dynamic processes of rock. In this research, it is applied in the investigation of loading rate on the tested strengths of rock, from static, to quasi-static, to quasi-dynamic, to dynamic state. Based on the discrete element software MatDEM, a discrete element model was built for the tests of uniaxial compressive strength and uniaxial tensile strength, and a series of numerical tests were run. The numerical simulation results show that the failure processes, failure patterns and tested strengths are significant influenced by the loading rate. Stress-strain curves and energy conversion curves provide important clues for the mechanism of effect of different loading rates. Because static and quasi-static numerical simulations are very time-consuming, we suggest greater system viscosity could be used in some cases to increase the speed of numerical simulations.

A1043-EXPERIMENTAL INVESTIGATION ON COHESIVE ZONE MODEL FOR THE DIFFERENT RANK COALS BY DISK-SHAPED COMPACT TENSION TESTS

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Cohesive zone mode (CZM) is introduced into the research on the crack propagation behavior in coal materials. The constitutive relations of CZM for the different rank coals, including weakly caking coal, gas coal, fat coal, meager-lean coal and anthracite, are defined by fitting experimental parameters which are obtained from the disk-shaped compact tension (DC(T)) tests. The different rank coals have the diverse shapes of softening curves of load and crack tip opening displacement (CTOD), and there are five cohesion-separation laws, including linear law, bilinear law, exponential law, power law and Karihaloo polynomial law, for describing these softening curves, Among them, Karihaloo polynomial law has the best degree of regression fitting for all the coals and it can capture the essence of CZM, moreover, the power law, the power law with different parameters, the exponent law, the bilinear law and linear law, can also represent the constitutive relationships of CZM well for the weakly caking coal, the gas coal, the fat coal, the meager-lean coal and the anthracite respectively. As the coal rank rises, the critical crack separation displacement (wc) and the fracture energy reduce, and this illustrates that the characteristics of coals become from more ductile to more brittle with the rising degree of coalification. Meanwhile the he roughness coefficients (Rs) of the fracture surface and the fracture aperture were measured by means of a 3-D topographic scanner. For the lower rank coals, the crack propagation paths are more tortuous and the values of the Rs are larger, meanwhile the fracture aperture increases with the coal rank reducing. And it is observed that more nonlinear behaviors occurs in the FPZ of lower rank coals and more fracture energy is consumed during crack growth in these coals.

MS19: Damage and Fracture in deformation-based manufacturing and materials processing

A0027-OPTIMIZATION DESIGN ON EXPLOSIVELY-FORMED PROJECTILE OF MULTI-FUNCTIONAL WARHEAD

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The explosive forming process of EFP (Explosively-Formed Projectile) in a novel multi-functional warhead is analyzed by using explicit dynamic simulation software. In order to increase the directional damage ability, the novel multi-functional warhead put steel fragments at the front end. Compared to traditional EFP structure the novel structure results in the difficult formation of EFP, thus reducing the penetrating performance. Based on numerical simulation, this paper analyzes formation mechanism of liner material, material change in the formation process and liner design parameters. The formation problem of EFP is solved by optimizing taper angle, liner thickness and rate of liner thickness change. The optimization design effect is achieved.

A0217-A NEW FATIGUE DAMAGE MODEL FOR LIFE CALCUTION OF METAL SPECIMEN

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In this paper, a new model based on the continuum damage mechanics is proposed to study the fatigue damage behavior of metal specimens manufactured by the additive manufacturing (AM) process. First, the damage-coupled elastic-plastic constitutive equations are presented. Then the new fatigue damage evolution equations are proposed to evaluate the fatigue life of specimen. At last, the numerical calculation of the proposed model is implemented and the fatigue lives of metal specimen are calculated, which are compared with the experimental.

A0299-DETERMINATION OF A COMBINED JOHNSON-COOK AND GTN DAMAGE MODEL FOR PREDICTING THE FRACTURE OF ALUMINUM ALLOY EXTRUDED PROFILES UNDER DIFFERENT STRESS STATE

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6061 aluminum alloys extruded profiles has been widely used in the components of automotive vehicles. Predicting its fracture under different loading conditions is an important issue. In view of the Johnson-Cook damage model and the GTN damage model can only well predict aluminum alloy fracture under certain small range of stress triaxiality. To predict aluminum alloy fracture under a large range of stress triaxiality, a damage model combined with Johnson-Cook and GTN was established and the constitute parameters were determined through testing and simulation coupling method. Fracture prediction using this model by FE simulation under wide range of stress triaxiality was compared with the experiment and fairly good results were obtained.

A0453-THE EFFECT OF PRE-STRAIN ON THE FRACTURE LOCUS

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For complex non-proportional loading conditions, fracture is generally predicted prematurely. The possible reason could be the shift of fracture loci due to the existing of pre-strain, just analogue to the shifted forming limit curve. For this purpose, a series of non-proportional loading tests were designed to investigate the influence of pre-strain on the final fracture loci, with the help of parallel simulations. Finally a strategy to adapt the initial fracture loci based on the pre-strain was established.

A0455-EXPERIMENTAL INVESTIGATION ON NUCLEATION STRAIN UNDER DIFFERENT STRESS STATE AND PRE-STRAIN CONDITIONS

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Nucleation strain is a critical threshold in GTN model to evoke quick evolution of void fraction. For different stress state and pre-strain situations, constant value of nucleation strain could lead to large error of fracture prediction. For this purpose, a series of tests with 6061 aluminum alloy under different stress state and pre-strain conditions were performed. With the help of SEM and image processing technique, nucleation strains under various stress state were obtained, and meanwhile the influence of pre-strain on the nucleation strain was investigated.

A0480-INFLUENCES OF STRESS TRIAXIALITY, LODE PARAMETER AND GRAIN SIZE ON DUCTILE FRACTURE IN MICRO-SCALE PLASTIC DEFORMATION

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A series of micro-scale copper specimens including tensile, compressive and shear specimens are designed and annealed to obtain different grain sizes in this research. Digital image correlation is employed to calculate the mechanical properties of these specimens in micro-scale plastic deformation. The finite element (FE) simulation of each test using the combined surface layer and grain boundary strengthening constitutive model proposed in prior study is performed. Based on the good correlation of FE simulations and physical experiments, the interaction among fracture strain, stress triaxiality, lode parameter and grain size in micro-scale plastic deformation is constructed. Furthermore, fractographs of specimens are observed to explore the fracture mechanism, mode and behavior in micro-scale deformation. Finally, different ductile fracture criteria are evaluated in a wide range of stress triaxiality to determine the suitable one in different stress states. The research thus facilitates the understanding of ductile fracture in micro-scale deformation.

A0517-DAMAGE EVOLUTION AND FRACTURE PREDICTION IN CYCLE BENDING

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Multi-stage forming such as the drawing and reverse redrawing processes can significantly improve the forming limit and formability of sheet metal. However, due to strain path changing, accurately fracture prediction for multi-stage forming is a non-trivial and challenging issue that still needs to be addressed in greater depth. In this study, a physical modeling, the cycle bending, is designed to explore damage evolution and fracture behavior in multi-stage forming with loading path changing. Microstructure such microvoid after each bending cycle and fracture morphology are analyzed. Then, based on the experiments and damage and fracture mechanism, various fracture criteria are utilized for predicting the onset of ductile fracture in the cycle bending and a feasible fracture criterion related to the strain path is attempted to be proposed. Applicability of the ductile fracture criteria in multi-stage forming is evaluated and discussed.

A0662-FORMING LIMIT PREDICTIONS OF MAGNESIUM ALLOY SHEET BASED ON TWO FRACTURE CRITERIA

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As a structural lightweight material, magnesium alloy, is attracting more and more attentions in vehicle manufacturing due to its high strength-weight ratio. Wrought magnesium alloy is preferable for structural applications compared with cast magnesium alloy. However, the poor formability of magnesium alloys at room temperature obstacles their applications. A lot of efforts are devoted to develop new magnesium alloys with a formability comparable to aluminum alloy at room temperature. In addition, since magnesium alloys fail as ductile fracture with slight necking, ductile fracture criteria instead of various necking models are more suitable to predict failure in magnesium alloys.

The present research was aimed to evaluate the formability of a newly developed magnesium alloy sheet with addition of rare earth element. The uniaxial tension tests and Nakazima tests were conducted to investigate the constitutive behavior and the ductile fracture of the magnesium alloy at room temperature. Based on two ductile fracture criteria, the Modified Mohr-Coulomb (MMC) and the DF2012, three-dimensional fracture surfaces were built. A new method to construct the Fracture Forming Limit Diagrams (FFLD) was proposed by combining the fracture locus of plane stress with the Hill'48 function. The comparative analysis between the FFLD and the experiment-based FLD is carried out. The comparison reveals that the established FFLD is preferable for the forming limit predications of magnesium alloy sheets.

A0704-EFFECT OF LOADING HISTORY ON MECHANICAL PROPERTIES OF HDPE

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This paper presents results from a study that quantifies the influence of loading history on mechanical properties of high density polyethylene (HDPE). The experimental investigation is through the application of a novel two-stage test approach to D-split tensile test of notched pipe ring specimens (NPR). The first-stage test is to introduce damage by subjecting the specimens to different pre-strain levels under various loading modes, including monotonic tensile, creep and fatigue loading conditions. Two months later, the second-stage test is conducted to characterize mechanical properties for specimens that have had damage generated from the first-stage test. The period of two months between the two tests is to minimize the effect of viscous recovery on the measured mechanical properties from the second-stage test. The experimental results show that elastic modulus and yield stress decrease with the increase of pre-strain applied in the first-stage test. The results further indicate the variation of elastic modulus is mainly a function of pre-strain introduced in the first-stage test, but also depending on the loading mode used to generate the deformation. Furthermore, the relationship between damage parameter measured from the degradation of elastic modulus and residual plastic strain generated under the three loading modes can be

described using one damage evolution equation, suggesting plastic strain can serve as a good damage indicator for HDPE materials under creep or fatigue loading conditions.

MS20:Failures and Damages in Composite Materials and Structures

A0208- COUPLED FLOW, STRESS AND DAMAGE MODELLING OF INTERACTIONS BETWEEN HYDRAULIC FRACTURES AND NATURAL FRACTURES

Haiyan Zhu [a,b] , Heng Wang [a]

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The keys and difficulties of stimulating the sandstone and mudstone thin interbedded (SMTI) reservoir are to avoid hydraulic fracture propagating through the interface between shale and sand as well as control the fracture height. In this paper, the evolution of multiple hydraulic fractures and natural fractures is simulated using zero-thickness Pore Pressure Cohesive Elements (PPCE). A coupled flow-stress-damage (FSD) nonlinear finite element model which consists of pay zone, interlayers, perforation holes, natural fractures is established. The viscoelastic continuum damage induced by hydraulic fracturing is governed by the traction-separation law. Mohr-Coulomb law is used to determine the elastic and plastic behaviors of the formation. The model is applied to the Zhuang 23 tight gas reservior in Shengli oilfield and Xu 5 shale gas reservoir in Sichuan province.

A0376- NUMERICAL MODELING FRACKING IN POROUS MEDIA BY PHASE FIELD APPROACH

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Presently, numerical and mathematical studies of reservoirs such as hydraulic fracturing, and CO_2 sequestration are attracting a lot of attention, in petroleum and environmental engineering. Therefore, many models and numerical approaches are investigated so far. In the most classical model, modeling the fractured system is crucial due to the need pre-knowledge for initiation of fracture, fracture path, branching and singularities at fracture tips. Recently, these difficulties are overcome by phase field approach.

The phase-field approach to model fracture systems introduces a continuous field variable which differentiates between the fully broken and intact material phases. Several Phase field models have been developed in the physics and mechanics communities, however, the theoretical and technical backgrounds for developing the constitutive models and formulations are completely different. In the physics communities, phase field models originate from the phase field evolution equations presented by Landau and Ginzburg. In contrast, the phase field models developed in the mechanic's communities are based on Griffith's theory.

In this research, we follow Francfort and Marigo's variational approach to modeling pressurized fracture. We assume the fracture is filled with fluid and the pressure is given. Furthermore, we place ourselves to the quasi-static setting. In the end, we provide several numerical experiments demonstrating the capabilities of our proposed model.

A1074- THE TIP REGION OF A NEAR-SURFACE HYDRAULIC FRACTURE

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This talk investigates the tip region of a hydraulic fracture propagating near a free surface via the related problem of the steady fluid-driven peeling of a thin elastic layer from a rigid substrate. The solution of this problem requires accounting for the existence of a fluid lag, as the pressure singularity that would otherwise exist at the crack tip is incompatible with the underlying linear beam theory governing the deflection of the thin layer. These considerations lead to the formulation of a nonlinear traveling wave problem with a free boundary, which is solved numerically. The scaled solution depends only on one number K, which has the meaning of a dimensionless toughness. The asymptotic viscosity- and toughness-dominated regimes, respectively, corresponding to small and large K, represent the end members of a family of solutions. It is shown that the far-field curvature can be interpreted as an apparent toughness, which is a universal function of K. In the viscosity regime, the apparent toughness does not depend on K, while in the toughness regime, it is equal to K. By noting that the apparent toughness represents an intermediate asymptote for the layer curvature under certain conditions, the obtention of time-dependent solutions for propagating near-surface hydraulic fractures can be greatly simplified. Indeed, any such solutions can be constructed by a matched asymptotics approach, with the outer solution corresponding to a uniformly pressurized fracture and the inner solution to the tip solution derived in this talk.

A1084- NUMERICAL STUDY OF REPEATED FAULT REACTIVATION AND INDUCED SEISMICITY DURING MULTI-STAGE HYDRAULIC FRACTURING

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Over the past few years, the shale gas revolution first taken place in the United States has spread world widely. Multi-stage hydraulic fracturing is the key technique for the successful stimulation of hydrocarbons from low permeability shale formations. However, concerns have been raised in public because of the impacts of hydraulic fracturing on the environment, while induced seismicity due to fluid injection is one of the major concerns. Both the hydraulic fracturing and the reinjection of co-produced waste water have been proven to cause induced seismicity. The injected fluid may permeate into the pre-existing faults and results in the

release of tectonic stress by elevating the pore pressure and decreasing the effective clamping stress, which leads to sudden fault slippage.

Compared to waste water reinjection, the hydraulic fracturing operation lasts for a much shorter period and typically with significantly smaller injected fluid volume. As a result, the expected seismicity activity level is low compared with other anthropogenic triggers. However, a recent study of induced seismicity in Alberta evidenced a magnitude-3.9 micro-earthquake to hydraulic fracturing. Meanwhile, hydraulic fracturing induced seismicity could also lead to casing deformation caused by shear displacement of reactivated fault. Casing deformation not only defers the fracturing operation but also results in fluid flow into completed clusters and surrounding natural fractures, probably triggering more seismic events. Therefore, induced seismicity directly caused by hydraulic fracturing is a vital issue while identifying the mechanism of fault reactivation triggered by hydraulic fracturing is of great importance to mitigate the seismic hazards.

In this work, we present a case study of repeated fault reactivation and induced seismicity during multi-stage hydraulic fracturing. The attributes of recorded field microseismicity data delineates a fault at the toe of the horizontal well. The 3D geomechanical simulation for the first two hydraulic fracturing stages generates similar features of microseismicity with the field data. This study demonstrates that better understanding of induced seismicity can be achieved by combing field observation with geomechanical modeling, which can be used to mitigate the risks linked to induced seismicity and provide solutions for safer production of unconventional resources.

A1087-EFFECT OF A CAPILLARY BRIDGE ON THE CRACK OPENING OF A PENNY CRACK

Fuqian Yang [a] , Ya-Pu Zhao [b]

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In this work, we analyze the effect of a capillary bridge or a liquid droplet on the crack opening of a penny crack under the action of a far-field tensile stress. Using the Hankel transformation, we reduce the crack problem to the solution of dual integral equations, and obtain closed-form solutions for both the crack opening and the stress intensity factors, which are functions of the size of the capillary bridge or droplet, surface tension, and contact angle. The capillary bridge can lead to the crack closure. We obtain the analytical solution of the minimum far-field tensile stresses needed for complete crack opening, i.e. no crack closure.

A1091-DIMENSIONLESS ANALYSIS OF MULTI-FRACTURES INTERFERENCE IN VOLUME FRACTURING

Haiyan Zhu[a,b], Yapu Zhao[b,*], Wenhao Shen[b], Huiying Tang[a]

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The staged volume fracturing is one of the key techniques for the commercial exploitation of shale gas reservoir. According to microseismic data, most of the wells are well stimulated. However, there are still some zones which are not broken thoroughly between adjacent two clusters. When decreasing the cluster space in the adjacent well, this bad phenomenon can be avoided. The cluster space is the key factor for the multi-stage hydraulic fracturing. How to choose it? Two things must be concerned, one is the fracture geometry, and the other is the induced stress field between each two adjacent fractures.

A two-dimensional (2D) multi-fractures propagation model was developed. The mixed boundary element method (BEM) was used to describe the propagation of the 2D multi-fractures. The fluid flow in a fracture was modeled by the lubrication equation. The fluid flow in the wellbore was considered as the one-dimensional flow. Newton-Raphson and Picard iterative methods were used to discrete the multi-fractures propagation behavior. And then, the variables in the governing equations, initial and boundary condition equations are normalized. Using the characteristic quantities as the system of units, the stimulated reservoir area (SRA) is related with the dimensionless parameters. Based on the geomechanical and volume fracturing parameters of the shale reservoir in Sichuan Basin, the fracture geometry and stress interference between each two adjacent fractures are simulated. The effects of the fracture geometrical, fracture number, fracture energy, the minimum and the maximum horizontal stress on the fracture geometries and stress induced area are systematically investigated. Finally, the dimensionless model of multi-fractures interference are proposed and applied in the shale gas volume fracturing.

A1094-NON-PLANAR FRACTURES INITIATION AND PROPAGATION OF DURING THE HYDRAULIC FRACTURING IN GAS SHALE

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In this paper, the initiation and propagation of non-planar fractures during the hydraulic fracturing experiments of gas shale based on CT scanning technologythe. Hydraulic fractures tend to initiate and propagate along the heterogeneous interface, natural fracture, and weak horizontal bedding surface, which result in that the position of fracture initiation does not always align with the direction of the horizontal maximum principal stress. The internal defects and natural fractures in the rock samples are the direct reasons for the hydraulic fracture branching and twisting. Compared with linear gel, slick-water fracturing fluid can generate more complex fractures, the smaller fracture initiation pressure and the smaller propagation pressure.

A1097-EXPERIMENTS AND REGULAR RESEARCH ON THE EFFECT OF NATURAL FRACTURE SIZE ON HYDRAULIC FRACTURE PROPAGATION IN 3D

Liming Wan, Mian Chen, Bing Hou

China University of Petroleum, Beijing

The three-dimensional hydraulic fracture (HF) geometry of intersection with the natural fracture (NF) is significant in shale. In this paper, an orthogonal fracture intersection geometry model in 3D was proposed, where the size of natural fracture was mainly studied. To verify the accuracy of the model, laboratory experiments were conducted separately in hydrostone and shale outcrop using the true tri-axial system. The influence of NF size and bedding planes were investigated. The results show that when HF intersection with different sizes of NF, the fracture propagation can be classified with five ways: arresting, bypassing, diversion, vertical extension, vertical extension and then diversion. When NF size is bigger than that of HF, it is more likely for HF to bypass, when smaller, more likely to diverse or extend vertically. Well-developed bedding planes increase the probability of diversion to form complex fracture network only when the size of NF is big. High fluctuation intensity of pump curve indicates more complex fracture network. When HF extends vertically, the curve shows an even fluctuation, and when changes direction, the extension pressure will be much higher than fracturing pressure. The 3D model and experimental results can predict fracture pattern when intersection and detect the fracture network.

A1101-The Adsorption and Displacement of Shale Gas: A Molecular Dynamics Study

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The recovery dynamics of confined shale gas with water (H2O), carbon dioxide (CO2) and nitrogen (N2) were studied by molecular dynamics simulations. We obtained a simple yet effective method to calculate the stress caused by adsorption/desorption. By comparing the adsorption energies and configurations of methane (CH4), H2O, CO2 and N2 on graphene surface, it indicated that CO2 is the best candidate in displacing CH4. The energy barriers of displacing one adsorbed CH4 molecule by CO2, H2O and N2 were found to depend on the displacement angle. The energy barriers of displacing one molecule in an adsorbed CH4 layer under different conditions were also obtained. Furthermore, displacement efficiencies of CH4 by supercritical fluids were compared. The displacement efficiency is in the order of CO2 >

$N2 > H2O$. By analyzing the changes in configuration entropy of different molecules in free and adsorption states, the spontaneous process of supercritical fluid displacement of CH4 is clarified. Additionally, we explored the thermodynamic properties of shale gas in different sizes of nanopores. The mechanisms of the effect of the pore size on the adsorption capacity of shale gas are clarified. Our study may help to understand the shale gas recovery from the atomic level and provide new idea in shale gas exploitation technology.

A1104-Prediction of the mechanical properties of shale based on stochastic modeling and deep learning

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Exploitation of shale gas has initiated a new epoch of natural gas industry. To understand the mechanical properties of shale is vital to optimize the drilling and hydraulic fracturing processes. In the mesoscale, a shale sample is considered as a complex heterogeneous composite that consists of multiple types of mineral components. The mechanical properties of each mineral component vary significantly, and mineral components are distributed in an utterly random manner within shale samples. Therefore, it appears too complicated to establish an explicit relationship between the macroscale mechanical properties of a shale sample and its microstructure. On the other hand, machine learning methods are broadly employed to excavate inherent rules and correlations based on a large amount of data. Especially, deep neural networks are established to deal with situations where input-output mappings are extensively complex. In this paper, a large quantity of shale samples are generated based on mesoscale SEM images using a stochastic modelling algorithm. Finite element method is utilized to evaluate the mechanical properties of the stochastic shale samples. A deep neural network is established to reveal the inherent relation between shale microstructure and mechanical properties. The network is trained based on the images of stochastic shale samples and their mechanical properties. The trained network is further employed to predict the mechanical properties of real shale samples.

A1107-Elasto-plastic damage modeling of hydraulic fracture propagation via xfem

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In this study, we present an elasto-plastic damage model for hydraulic fracture propagation. The Lamaitre’s model is adopted to describe the damage evolution of rock. The classic criterion for crack propagation is replaced by a damage-based criterion, and critical value of damage variable is used to specify the threshold of crack growth. The stress-strain damage

problem is solved by the extended finite element method (xfem). Furthermore, the fluid flow in the fractured porous media is determined by the embedded discrete fracture model (edfm). The implicit return-mapping scheme is chosen for integration of elasto-plastic constitutive relation. The fixed stress split method is adopted to solve the coupled processes of fluid flow and rock deformation. Several numerical simulations are presented to analyze the effect of rock elasto-plastic damage on hydraulic fracturing process. It is indicated that when the bulk plastic damage of rock is considered, hydraulic fracture exhibits shorter length, wider width and higher pressure compared to the model which doesn't consider rock elasto-plastic damage. Besides, the coupling of fluid flow and rock deformation also has a significant influence on the fracture propagation kinetics.

A1111-EXPERIMENTAL AND NUMERICAL SIMULATION OF WATER VAPOR ADSORPTION AND DIFFUSION IN LONGMAXI FORMATION SHALE

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Despite the success of deep horizontal drilling and hydraulic fracturing in yielding large production increases from unconventional shale gas reservoirs, uncertainties associated with basic transport processes require understanding in order to improve efficiency and minimize environmental impacts. The hydraulic fracturing process introduces large volumes of water into shale gas reservoirs, most of which remains unrecoverable and interferes with gas production. Understanding water retention in reservoirs is crucial for predicting gas productivity and for optimizing extraction conditions. In this study, water vapor adsorption isotherms were measured on granular fractions of the lower Silurian Longmaxi shale in south China sieved after crushing. The water adsorption isotherms were obtained at 30 and 50 ℃, for relative humidities from 11.1 to 97.0%. Four different isotherm models were tested for fitting the experimental data and to help understand water adsorption in shale rocks. Water adsorption in these shale rocks conformed to the type Ⅱ isotherm, and were nearly identical for the two experimental temperatures. In order to better understand the isotherms, a computational model based on the Maxwell-Stefan diffusion equations was constructed to analyze water adsorption and gas diffusion in shale rocks. Based on the experimental results, the Guggenheim-Anderson-de Boer (GAB) isotherm for gas adsorption was included in the model.

A1114-Numerical Calculations for the Full-Stress Hydraulic Fracturing model with and without a Fluid-Lag Zone

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Hydraulic fracturing has been widely used in geology and unconventional gas industry. In the past seventy years, mathematical models become more and more complicated from two-dimensional uniform pressure without the leakage of fluid to distributed pressure, penny-shaped cracks, pseudo-three-dimensional cracks and cracks with the leakage of the fracturing fluid. However, historical issues, such as the stress singularities and the fluid-lag zone, still exist in the classic theoretical models. Together with the dominant-regime transitions and the lack of shear stress in the boundary conditions, these issues have seriously restricted the development of high-precision numerical calculations and theoretical analyses. In this talk, numerical calculations for the full-stress model will be presented to discuss these issues. For a model without a fluid-lag zone, based on the Chebyshev polynomial, a high-precision numerical calculation method is established with the asymptotic solution at the crack tip. The dominant-regime transitions and near-crack-tip asymptotics can be obtained with this method directly. For a model with a fluid-lag zone, a mass-conserving numerical scheme is used to tracing the two moving boundaries, i.e., the crack tip and the fluid tip. The size of the fluid-lag zone is estimated based on the numerical calculations. The results presented in this study are useful for the simulation and design of hydraulic fracturing.

A1117-THE EFFECTS OF DRILL PIPE VIBRATION ON CHINA SHALE BREAKING MECHANISM WITH MICRO-PDC BIT: A LABORATORY EXPERIMENT STUDY

Xiaohua Xiao[a] , Teng Wang[b] , Haiyan Zhu[c] , Zhaowei Wang[d]

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This work sought to find the effect of drill pipe vibration on shale breaking mechanism when the polycrystalline diamond compact (PDC) bit drilled the shale that is rich in stratification. A laboratory-scale drilling device based on a drilling machine is developed, referring on the conventional drill bit and rock interaction method. A class of drilling experiments with six inclination angles (β = 0°, 15°, 30°, 45°, 60°, and 90°), two rotation rates (63 r/min and 80 r/min) and three drilling feeds (0.04 mm/r, 0.06 mm/r and 0.1 mm/r), total thirty-six groups, are carried out. The changes in the weight on bit (WOB) and the torque which were selected as the drilling parameters during the shale drilling process were analyzed. The influences of rotation rates and inclination angles on the drilling parameters were investigated. Starting with the shale heterogeneity and elastic deformation of drill pipe, the shale fragmentation at

different inclination angles was also studied. Furthermore, the variation characteristics of the WOB and the torque at different inclination angles were analyzed in depth from two aspects of amplitude and frequency, demonstrating that the dynamic behavior of downhole tools is affected by the different angles between the drilling direction and shale stratification.

A1121-Stress field evolutions with different fracturing treatments for sand-shale interbedded reservoir

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The keys and difficulties of stimulating the sandstone and mudstone thin interbedded (SMTI) reservoir are to avoid hydraulic fracture propagating through the interface between shale and sand as well as control the fracture height. In this paper, the evolution of multiple hydraulic fractures and natural fractures is simulated using zero-thickness Pore Pressure Cohesive Elements (PPCE). A coupled flow-stress-damage (FSD) nonlinear finite element model which consists of pay zone, interlayers, perforation holes, natural fractures is established. The viscoelastic continuum damage induced by hydraulic fracturing is governed by the traction-separation law. Mohr-Coulomb law is used to determine the elastic and plastic behaviors of the formation. The model is applied to the Z12 tight gas reservoir in Shengli oilfield and X5 shale gas reservoir in Sichuan province.

Programme-At-A-Glance

July 4,2018 Registration and Reception	
14:00--21:30	Registration
15:30--17:00	ICDM director meeting
19:00--21:00	Ice Breaker /Cocktail (The 3rd floor of Kingswell Hotel)
July 5, 2018 Technical Sessions	
8:00--18:00	Registration
8:20--8:40	Welcoming Remarks
8:40--8:50	Group Photo
8:50--10:10	Plenary Lectures（Sino-French Center C201）
	Professor Jiann-Wen Woody Ju INNOVATIVE THERMO-ELASTOVISCOPLASTIC DAMAGE -HEALING MODEL FOR BITUMINOUS COMPOSITES.
9:30--10:10	Professor Wanlin Guo Three-dimensional fatigue fracture mechanics: Bridge the gap from laboratory to engineering structures.
10:10--10:30	Coffee Break
10:30--12:15	Technical Sessions
12:15--13:30	Lunch(The 3rd floor of Kingswell Hotel)
14:00--14:40	Plenary Lectures（Sino-French Center C201）
	Professor Khemais Saanouni, Fully coupled constitutive equations in the framework of generalized continua for metal forming simulation.
14:50--15:50	Technical Sessions
15:50--16:10	Coffee Break
16:10--17:55	Technical Sessions
18:15--20:00	Dinner (The 15th floor of Shanghai Jinjiang Metropolo Hotel)
20:00--22:00	Ceremony and Concert (The 15th floor of Shanghai Jinjiang Metropolo Hotel)
July 6, 2018 Technical Sessions	
8:30--9:50	Plenary Lectures（Sino-French Center C201）
8:30--9:10	Professor George Z. Voyiadjis Fundamental issues in continuum damage and healing mechanics.
9:10--9:50	Professor Gilles Pijaudier-Cabot, CONTINUUM DAMAGE IN QUASI-BRITTLE MATERIALS: A REVIEW OF RECENT RESULTS OBTAINED WITH THE HELP OF LATTICE MODELS.
9:50--10:10	Coffee Break
10:10--11:55	Technical Sessions
12:00--13:30	Lunch(The 3rd floor of Kingswell Hotel)
14:00--14:40	Plenary Lectures（Sino-French Center C201）
	Professor Jian-Ying Wu A unified phase-field/gradient-damage theory for the modeling of failure in solids.
15:00--16:00	Technical Sessions
16:00--16:20	Coffee Break
16:20--18:20	Technical Sessions