GRADUATE AERONAUTICAL LABORATORIES
California Institute of Technology

Professor Ares Rosakis

Theodore von Kármán Professor of
Aeronautics and Professor of Mechanical Engineering
Chair, Division of Engineering and Applied Science

Research Topics

- *Experimental and Analytical Studies of Dynamic Crack Initiation in Highly Ductile Solids*
- *Experimental Study of Adiabatic Shear Banding in Crystalline Metals*
- *Investigation of Dynamic Failure Properties of Metallic Glasses*
- *Dynamic Delamination of Coherent and Frictional Bimaterial Interfaces*
- *Dynamic Shear-Dominated Intersonic Crack Growth in Homogeneous Systems with Weak Crack Paths of Various Geometries*
- *Subsonically and Intersonically Moving Dynamic Cracks in Unidirectional Laminated Composites*
- *Studies of Damage Evolution in Heterogeneous Materials, Composites and Sandwich Structures*
- *Concepts of Dynamic Fracture Mechanics Applied to the Analysis of Blast-Induced Failures in Pressurized Structures*
- *Dynamic Deformation and Fracture Behavior of "Pentelicon" Marble (Parthenon Restoration)*
- *High Speed Infrared Imaging of Transient Temperature Fields in Solid Subjected to Dynamic Loading*
- *Laboratory Earthquakes*
- *Validation of Large Scale Fracture and Fragmentation Simulations*
- *The Influence of Fault Bends on Rupture Growth*
- *CGS Interferometry as a Full-Field, Real-Time, and In-Situ Wafer Inspection and Reliability Tool*

GALCIT Current Research Interests

Professor Ares Rosakis

Experimental and Analytical Studies of Dynamic Crack Initiation in Highly Ductile Solids

Faculty: A.J. Rosakis, G. Ravichandran

A drop weight tower and a high speed gas gun are being used to provide a wide spectrum of loading rates for the study of dynamic crack initiation process in highly ductile metals . The effect of rate sensitivity on the value of the dynamic J integral (a parameter characterizing the near tip plastic strains at initiation) is investigated at a number of loading rates by means of high speed photography and the optical methods of reflected caustics, Shadow Moire, and Coherent Gradient Sensoring. The experimental results are compared to three-dimensional, elastic-plastic, numerical simulations of the impact event. Materials tested include HY100, HY130, HSSLA, 4340, 304 stainless Steels and Aluminum alloys. High-speed infrared temperature sensors are also being used to measure temperature generated at the crack tip plastic zone during dynamic loading prior to crack initiation. The temperature signature is used to measure the time history of J up to initiation and to thus establish the dependence of fracture toughness on the loading rate. Analytical models of unstable void growth (cavitation) are used to investigate the fracture initiation process in such highly ductile metals. In such solids cracks typically initiate and propagate in a "tunneling" mode through the specimen thickness. Initiation is then followed by the formulation of extensive shear lips on the specimen surface. The models view crack growth as a consequence of the nucleation growth and coalescence of microvoids in front of the main crack and provide estimates of the levels of fracture toughness as functions of material parameters, inclusion size and distribution, etc.

Experimental Study of Adiabatic Shear Banding in Crystalline Metals

Faculty: A.J. Rosakis, G. Ravichandran

In this work we use a high velocity air-gun to provide the asymmetric "shear" loading in prenotched metal plates. It has often been observed that low impact velocities (up to 100 m/s) result in the generation of dynamic cracks at the tip of the prenotch. If, however, the impact velocities are increased, the mode of failure switches from that of fracture to that of dynamic shear banding. This phenomenon of loading-rate dependent failure mode transition is not well understood. Here we use both optical and high speed infrared diagnostics to measure dynamically both deformation and temperature fields at incipient failure. The experiments are also modeled by extensive thermoviscoplastic finite element computations, which provide a benchmark for comparison with the experimental measurements. Materials to be tested include Ti alloys, C-300 steel as well as a variety of metallic glasses synthesized at Caltech.

Investigation of Dynamic Failure Properties of Metallic Glasses

Faculty: A.J. Rosakis, W. Johnson (MS) D. Rittel (Technion, Israel) **Staff:** D. Conner (MS)

The terminology "Metallic Glasses" or "Amorphous Metals" refers to a class of materials that exhibit a metastable amorphous atomic arrangement. Metallic glasses can be formed by a process of very rapid quenching of a melt that "freezes" the microstructure and does not allow for the establishment of the classically observed crystalline structure. In the past, the requirement of rapid quenching has limited the site of metallic glass specimens and has hampered the potential of these solids for structural applications. However, recent advances in the casting of such solids have made it possible for the first time to produce large enough samples suitable for mechanical testing. The project concentrates on the investigation of the extraordinary quasistatic and dynamic fracture properties of metallic glasses. The initial investigation concentrates on glass systems involving Zr, Al and Ti. The quasi-static and dynamic fracture behavior of these unusual materials as well as their localization behavior is studied by using a variety of experimental methods. Recent efforts concentrate on the investigation of energetic issues related to dynamic crack initiation, dynamic crack growth and dynamic branching in such amorphous solids.

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Dynamic Delamination of Coherent and Frictional Bimaterial Interfaces

Faculty: A.J. Rosakis **Student**: G. Lykotrafitis

The field of dynamic crack initiation and growth in coherent and frictional bimaterial interfaces is virtually unexplored from both the experimental and analytical points of view. In recent years we have launched an extensive investigation of the mechanics of dynamic crack growth in bimaterials and have conducted a series of dynamic experiments in Homalite-steel, Homalite-glass, and Homalite-Al3O bimaterial fracture specimens. High speed optical and thermographic techniques are used in this study. Experiments concentrate on the dependence of the bimaterial toughness on near tip mixity and crack tip velocity. Analytical models of dynamic subsonic crack growth in bimaterials have been used to interpret the experiments and to investigate the parameters appropriate for the formulation of a unified, dynamic fracture criterion. For frictionally healed bimaterials, we have used particle velocimetry to investigate the conditions leading to the formation of self-healing rupture pulses.

Dynamic Shear-Dominated Intersonic Crack Growth in Bimaterials, Homogeneous Systems with Weak Crack Paths of Various Geometries

Faculty: A.J. Rosakis **Student:** G. Lykotrafitis

Dynamic, shear dominated cracks propagating in the interfaces between materials characterized by a high mismatch in wave speeds (e.g. metal/polymer) are studied using optical techniques (CGS and Photoelasticity) and high-speed photography. These cracks accelerate, within microseconds, to the shear wave speed, (c ~ 1000 m/s), of the more compliant of the two solids (solid -1). At this speed they propagate in a stable manner until enough excess energy is supplied to the system. Subsequently, they further accelerate to supersonic speeds, (v > c ~ 2000 m/s), with respect to the polymer side, eventually reaching the Rayleigh wave speed of the metal, c ~ 3100 m/s. Such cracks become almost completely shear dominated and exhibit large scale frictional contact between the crack faces. They also feature the distinct (shear) shock wave structure expected of intersonically or supersonically moving disturbances. Intersonic crack growth along the fibers of unidirectional graphite/epoxy composite plates is also investigated. Here also, shock waves are visible and the crack speed is as high as 6,000 m/s. Finally, intersonic shear cracks propagating along the interface between two identical homogeneous and isotropic solids bonded by means of bonds of various strengths are also studied. This is the first time that intersonic and supersonic crack growth has ever been reported in a laboratory setting. However, in a much larger scale, such processes are known by geophysicists to occur in stratified layers within the earth's crust (shallow crustal earthquakes). The similarities between the laboratory observations and crustal earthquakes are a subject of intense interest and are systematically pursued.

Subsonically and Intersonically Moving Dynamic Cracks in Unidirectional Laminated Composites

Faculty: A.J. Rosakis, M. Ortiz, A. Pandolfi (Polytechnico di Milano) **Student:** G. Lykotrafitis

Here we study the phenomenon of highly dynamic crack growth events in unidirectional thick composite laminates. The crack growth events take place in graphite fiber, epoxy matrix composite plates containing an edge pre-notch in the fiber direction. The dynamic, in-plane loading is provided either by a high impact speed gas gun or a low speed drop weight tower. High speed photography and the optical method of CGS are used in a reflection arrangement to record dynamic crack initiation and growth. The different specimen geometries and loading configurations are designed to promote dynamic failure at different modes and crack tip velocity regimes. For Mode-I types of loading, the results reveal highly dynamic subsonic, crack growth processes, and predict decreasing dynamic toughness with crack tip speed. For Mode-II types of loading, the results however, reveal highly unstable and intersonic, shear-dominated crack growth along the fibers. The intersonic cracks propagate with phenomenal crack tip speeds as high as 10,000 m/s and feature a shock-wave (mach-cone) structure typically expected of disturbances traveling with speeds higher than some of the characteristic wave speeds in a material. These complex dynamic failure phenomena are modeled numerically by using the cohesive element methodology recently developed by M. Ortiz and his research group. Particular emphasis is given to the study of dynamic frictional sliding between the faces of the intersonically moving shear cracks and the resulting localized "hot spots." High speed infrared thermography is used to visualize the process of frictional heat dissipation and to guide numerical and analytical modelling of the phenomenon.

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Studies of Damage Evolution in Heterogeneous Materials, Composites and Sandwich Structures

Faculty: A.J. Rosakis, M. Ortiz, G. Ravichandran **Staff:** J. Knapp, V. Chalivendra

This work concentrates on the experimental study of damage evolution in thick composite or sandwich structures subjected to quasi-static compression and out of plane impact loaded by high speed projectiles. Issues to be investigated include the formation of localized damage zones in individual plies as well as areas of high speed delamination between plies. High speed photography and optical interferometric methods are used to observe the phenomena described above in real time. Experimentally calibrated, 3-D numerical calculations using the recently developed cohesive element terminology (Ortiz and Yu) are compared with the dynamic impact experiments. The final goal of this two-pronged approach is to investigate appropriate criteria governing the dynamic decohesion behavior of layered or sandwich structures, subjected to a variety of out of plane impact histories. This study also involves experimentation on model layered structures (bi-layers, tri-layers) subjected to in-plane out-of-plane impact. Emphasis is given on the study of the sequence and interrelation of the various failure mechanisms of layer dillamination and matrix cracking.

Concepts of Dynamic Fracture Mechanics Applied to the Analysis of Blast-Induced Failures in Pressurized Structures

Faculty: A.J. Rosakis, G. Ravichandran

Conventional numerical studies of failure mechanisms in full-scale structures loaded by explosive loading often utilize simplistic failure criteria based on the attainment of critical levels of stress corresponding to failure initiation. Such stress levels are often arbitrarily chosen to be fractions of the yield stress and are assumed to be uniform through the structure, irrespective of the rate of loading experienced at different locations. In the present work, we use basic concepts of dynamic fracture mechanics to rationalize and refine this simple approach. An explosively loaded, full scale structure (e.g. an airplane fuselage) is subdivided into smaller elements containing pre-existing fatigue cracks emanating from rivet holes. These elements are then subjected to the transient loads predicted by a global stress analysis of the dynamically loaded structure. The dynamic fracture problem is then solved "locally" (numerically and, when possible, analytically) and the resulting time histories of dynamic stress intensity factor are obtained at different locations. These time variations are compared to the dynamic fracture toughness of the material to determine crack initiation. Experimental data of the dependence of fracture toughness on loading rate are utilized. This comparison determines the times and critical stress levels for crack initiation as functions of loading rate. The approach provides a simple, fracture mechanic based, relation between the failure stress and local stress rate, to be used in structural codes modeling the response of aircraft and other pressurized structures to dynamic loading.

Dynamic Deformation and Fracture Behavior of "Pentelicon" Marble (Parthenon Restoration)

Faculty: A.J. Rosakis. I. Vardoulakis (NTUA, Greece)

The Parthenon, the temple of Goddess Athena, situated on the Acropolis of Athens, is perhaps the most important surviving monument of Classical Antiquity. The European Union has devoted substantial resources for its restoration, a project which in addition to its archaeological challenges also involves a substantial structural mechanics and materials component. The Parthenon is built of high quality marble extracted from known quarry sites on the mountain of Pentelis. This anisotropic and rate sensitive solid is a surprisingly good structural material with interesting non-linear constitutive and fracture properties uncharacteristic of other nominally brittle geomaterials. In 1687, when Francisco Morosini, the Doge of Venice, was besieging the Acropolis, a cannon ball pierced the roof of the then intact structure, and caused the explosion of the gun powder stored in its interior. Archeologists are interested in this explosion because they want to know how far and in what size distributions the resulting fragments have flown. They believe that this will help them in the reconstruction of this three dimensional puzzle. Our project involves the complete constitutive and fracture characterization of both ancient and newly quarried marble pieces subjected to a variety of loading rates. Eventually this information will form the basis for the construction of numerical models simulating the explosion and fragmentation of the monument. Initial activities include the experimental and numerical study of damage created due to individual and multiple cannon ball impacts on column drums in order to estimate their residual strength and load carrying ability. To achieve this the dynamic constitutive behavior of “Pentelicon” marble is studied in detail.

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High Speed Infrared Imaging of Transient Temperature Fields in Solid Subjected to Dynamic Loading
Faculty: A.J. Rosakis, G. Ravichandran

Highly dynamic failure processes often involve the generation of transient temperature fields resulting from either the conversion of plastic work into heat or from dissipation through dynamic frictional contact and sliding. These phenomena, which are often responsible for accelerating the failure process, happen under nearly adiabatic conditions and over very short time scales (microsecond time scales). In the past years we have been developing a unique instrument capable of providing two dimensional temperature images at a framing rate of one million frames per second. This high speed infrared camera prototype is now used to visualize in real time temperature fields at the vicinity of initiating and dynamically growing cracks, propagation shear bands, as well as for the investigation of frictional hot spots at the faces of dynamic shear cracks in heterogeneous solids.

Laboratory Earthquakes
Faculty: A.J. Rosakis, H. Kanamori (Caltech Seismo Lab), N. Lapusta, J. Rice (Harvard), M. Bouchon (U.S. Fourier, France)
Students: K. Xia and X. Liu

The goal of the this work is to create model laboratory experiments mimicking the dynamic shear rupture process. Such experiments are used to observe new physical phenomena and to also create benchmark comparisons with existing analysis and numerics and field observations. The experiments use high-speed photography, photoelasticity, and infrared thermography as diagnostics. The fault systems are simulated using two photoelastic plates (Homalite) held together by friction. The far field tectonic loading is simulated by pre-compression and the triggering of dynamic rupture (spontaneous nucleation) is achieved by an exploding wire technique. The fault forms an acute angle with the compression axis to provide the shear driving force necessary for continued rupturing. We investigate the dependence the characteristics of rupturing, such as rupture speed, rupture mode on experimental conditions such as far-field biaxial compression, tilt angle and interface roughnes. Both homogeneous and bimaterial interfaces are investigated. For bimaterial interfaces, various combination of dissimilar materials, including Homalite/polycarbonate pairs, are chosen to mimic wave speed mismatch conditions that are reported to exist across mature, crustal faults. Here we investigate the issue of directionality of earthquakes in relation to well studied historic sequences of ruptures occurring along the North Anatolian fault in Turkey.
So far we have concentrated on the experimental observation of the phenomenon of, spontaneously nucleated, supershear rupture and on the visualization of the mechanics of the Sub-Rayleigh to supershear rupture transition in such frictionally held interfaces. The results suggest that under certain conditions supershear rupture propagation can be facilitated during large earthquakes (e.g. the 2001 central Kunlunshan earthquake in Tibet or the 2002 Denali earthquake in Alaska). Future plans include the study of inhomogeneous tectonic loads and non-uniform fault structures.

Validation of Large Scale Fracture and Fragmentation Simulations
Faculty: A.J. Rosakis, M. Ortiz **Staff:** V. Chalivendra, J. Knapp, S. Hong

A detailed experimental and numerical program has been designed to validate large scale numerical simulations of dynamic crack propagation, branching, deflection, and penetration at interfaces in brittle homogeneous materials. High-speed photography in conjunction with the dynamic photoelasticity has been used to observe real-time failure mode transition mechanism at the interfaces. Wedge-loaded Homalite-100 plate specimens produce a single, straight, mode-I propagation crack towards an inclined interface. A modified Hopkinson bar setup is used to accurately control initial and boundary conditions of crack face loading. Various interface angles and different bond strengths are modeled using large scale computations which feature both bulk and interfacial cohesive elements laws. The penetration/deflection behavior of incident mode-I cracks, and the crack tip speed history studied in detail.

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The Influence of Fault Bends on Rupture Growth
Faculty: A.J. Rosakis, J. Rice (Harvard), C. Rouseau (URI)

Earthquake ruptures are modeled as dynamically propagating shear cracks with the aim of gaining insight into the physical mechanisms governing their arrest or, otherwise, the often observed variations in rupture speeds. Fault bends, or forks, have been proposed as being a major cause for these variations. Following this line of reasoning, the existence of deviations from fault planarity is embraced as the main focus of this study. In this project asymmetric impact is used to generate shear loading and to propagate dynamic mode-II cracks along the bonded interfaces of two otherwise identical homogeneous constituents. Secondary planes inclined at various angles are also introduced to represent fault bends or kinks. High speed photography and dynamic photoelasticity are used to study the kinking phenomenon in real time.

CGS Interferometry as a Full-Field, Real-Time, and In-Situ Wafer Inspection and Reliability Tool
Faculty: A.J. Rosakis, S. Suresh (MIT), Y. Huang (Univ. of Ill), E. Ustundag (Ohio State Univ.)
Staff: T-S. Park **Student:** M. Brown

As the semiconductor industry retools for the processing of larger diameter (300 mm) wafers with smaller circuit features (0.13 μm or less), the need for accurate full-field, in-situ and real-time inspection and reliability analysis tools becomes imperative.

In this work, we concentrate on the development of a vibration insensitive interferometric method designed especially to meet these new inspection and stress management challenges. Coherent Gradient Sensing (CGS) interferometry is used to study wafer planarity issues that arise throughout the entire wafer processing cycle. In particular, CGS is used to measure the non-uniform curvature tensor evolution of entire wafer surfaces in real-time during the cycle, as an in-situ process diagnostic. Issues addressed in this work include a) the use of CGS during film deposition as a means of continuously monitoring film uniformity and coverage within a deposition reactor, b) its use in conjunction with elaborate stress analysis tools for the measurement of stresses on thin films and lines during wafer processing or thermal cycling and, c) its ability of mapping highly non-uniform, non-linear deformations and curvature bifurcations that become important as wafer sizes scale up. X-ray microdiffraction measurements, performed at Lawrence Berkeley, are used for validating the curvature and stress fields independently obtained from CGS interferometry.

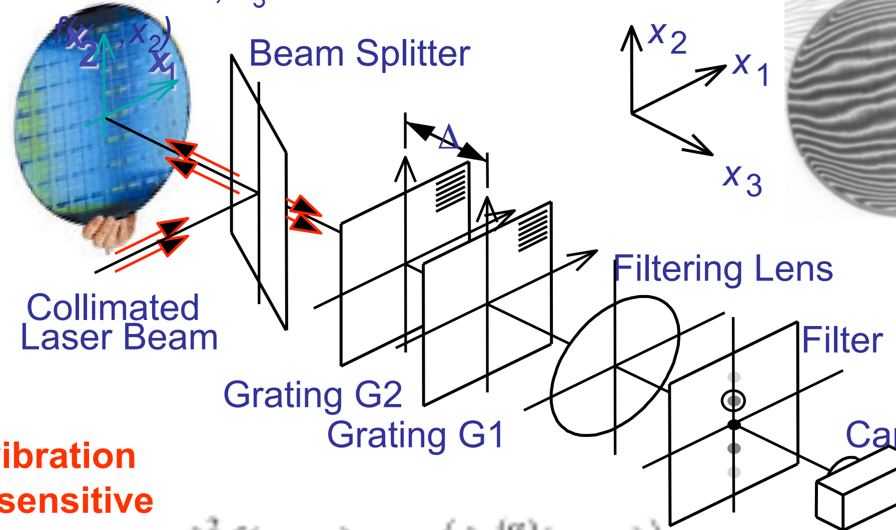
Throughout the project, emphasis is given to the suitability of the method as an in-situ process diagnostic. Other applications of the technique, include deformation measurements in the die and packaging levels and the study of large deformation and gravity effects and wafer support design in large, thin wafers.

WAFER LEVEL METROLOGY – CGS INTERFEROMETER

Ares Rosakis

Developed at Caltech, the instrument measures full field, wafer curvature by reflecting a 300mm collimated laser beam off the wafer surface, passing it through gratings to generate a self referencing interference pattern. The images on the right are a contour map of the **wafer's slope**. Spacing between fringes generates **curvature.**

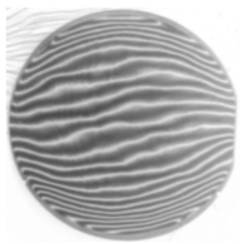
CGS Instrument Schematic*



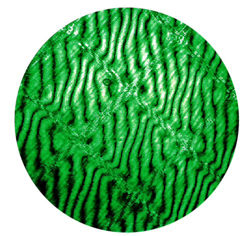
vibration insensitive

$$\kappa_{\alpha\beta}(x_1,x_2) \approx \frac{\partial^2 f(x_1,x_2)}{\partial x_\alpha \partial x_\beta} \approx \frac{p}{2\Delta}\left(\frac{\partial n^{(\alpha)}(x_1,x_2)}{\partial x_\beta}\right), \quad n^{(\alpha)} = 0, \pm 1, \pm 2, \ldots$$

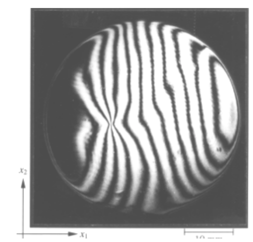
Polished Wafer



Patterned Wafer



Wafer with a problem



The Cleanroom

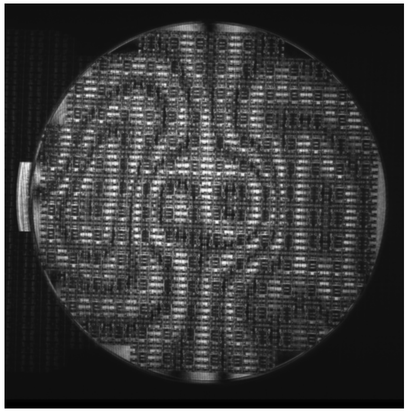
*** U.S. Patent Number: 6,031,611 (Rosakis *et al.*, 2000)**

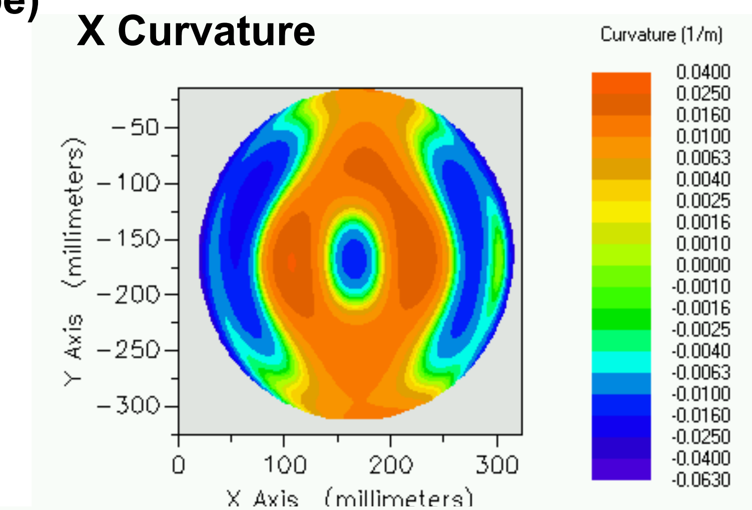
300MM PATTERNED WAFER (CURVATURE MAPS)

Ares Rosakis

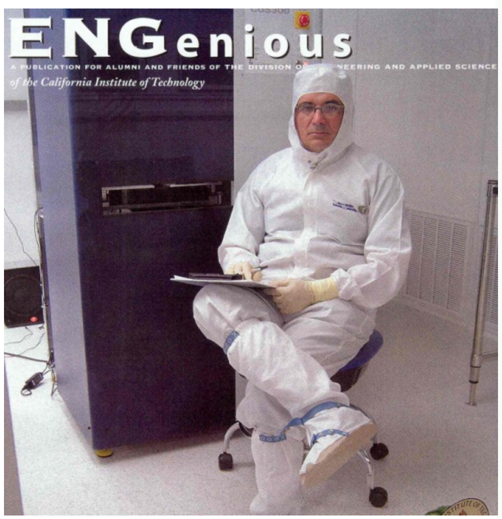
Curvature components are used to estimate film stress maps over the wafer surface

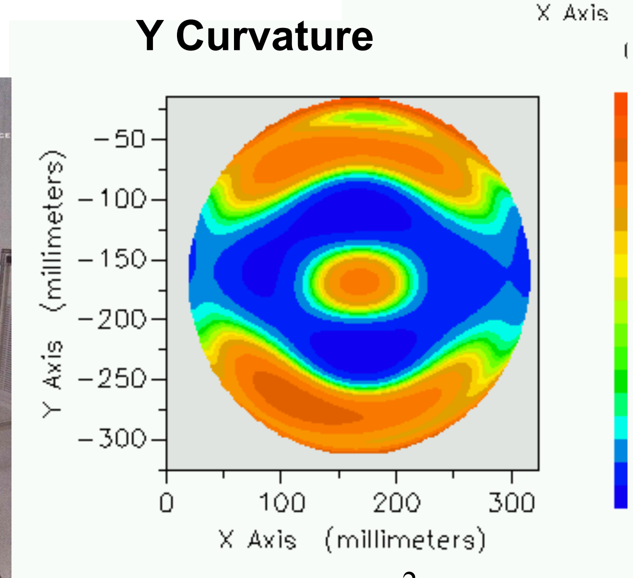
X Interferogram (slope)

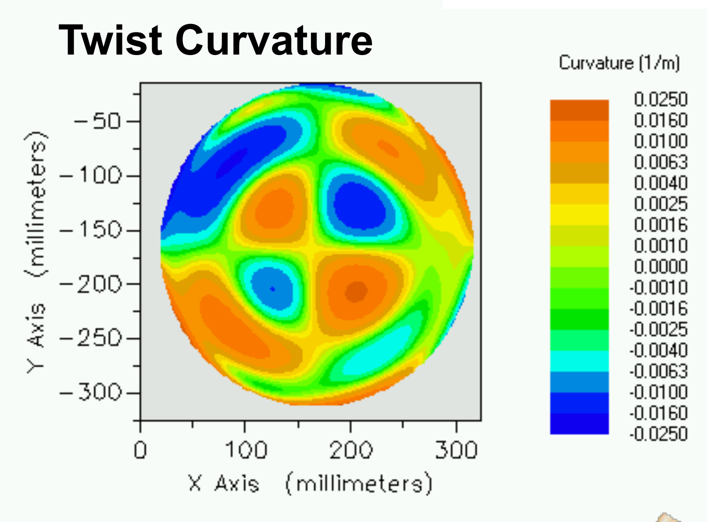




$$K_{11} = \frac{\partial^2 f}{\partial x_1^2}$$



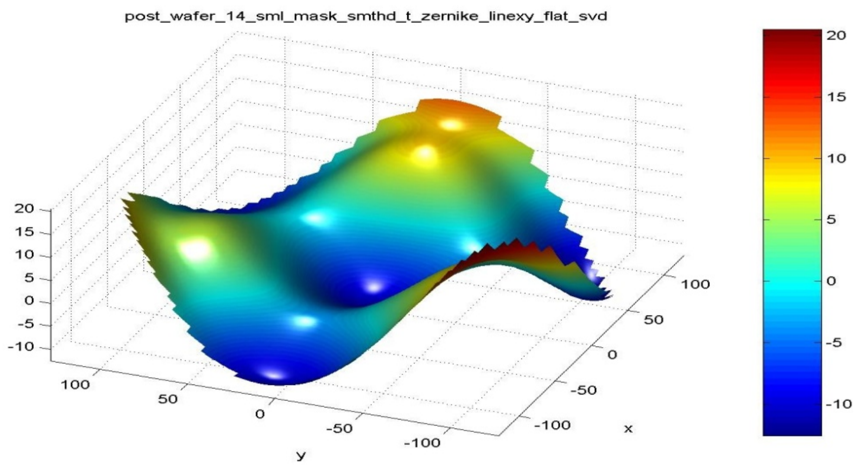


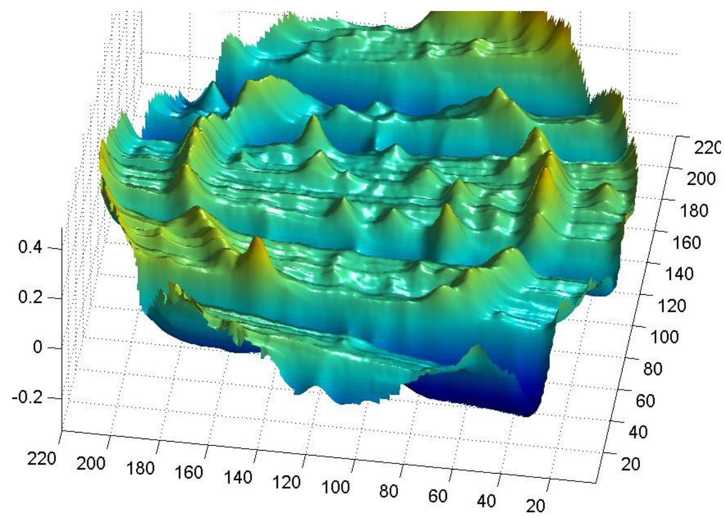


$$K_{22} = \frac{\partial^2 f}{\partial x_2^2}$$

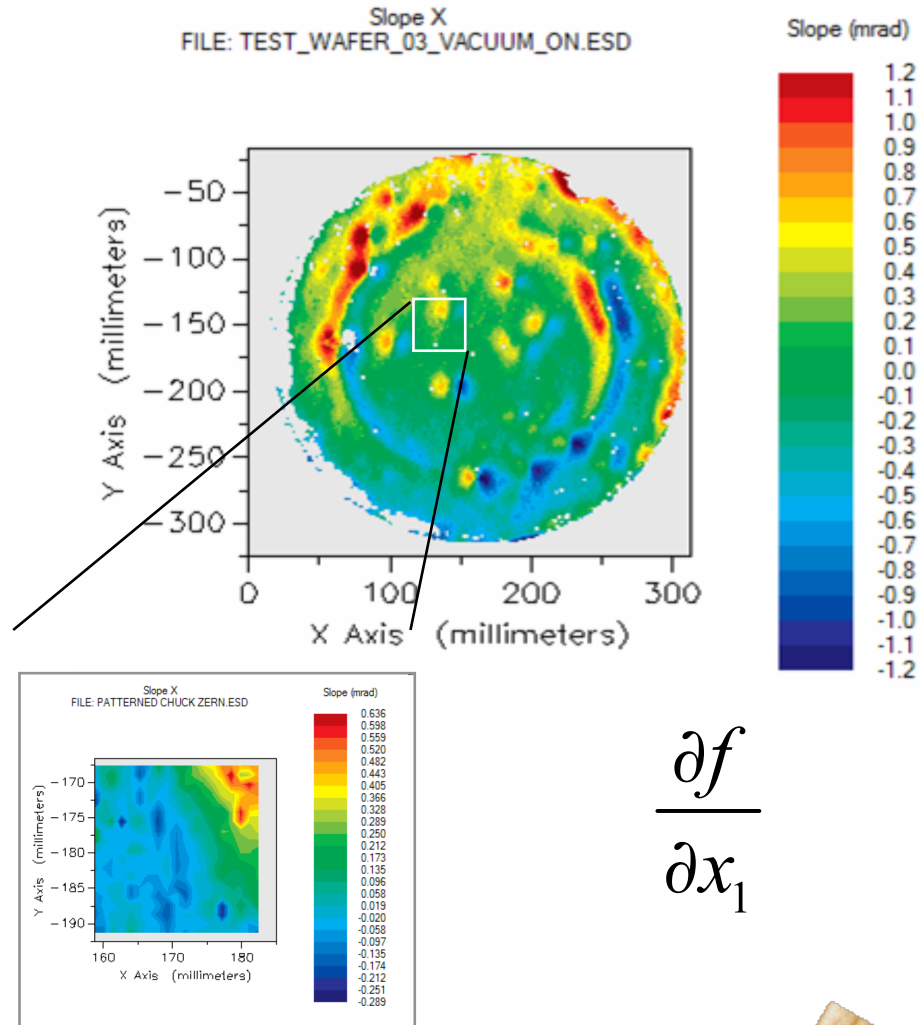
$$K_{12} = \frac{\partial^2 f}{\partial x_1 \partial_2}$$

300MM WAFER TOPOGRAPHY FOR LITHOGRAPHY APPLICATIONS





Topography of a chucked wafer



$$\frac{\partial f}{\partial x_1}$$

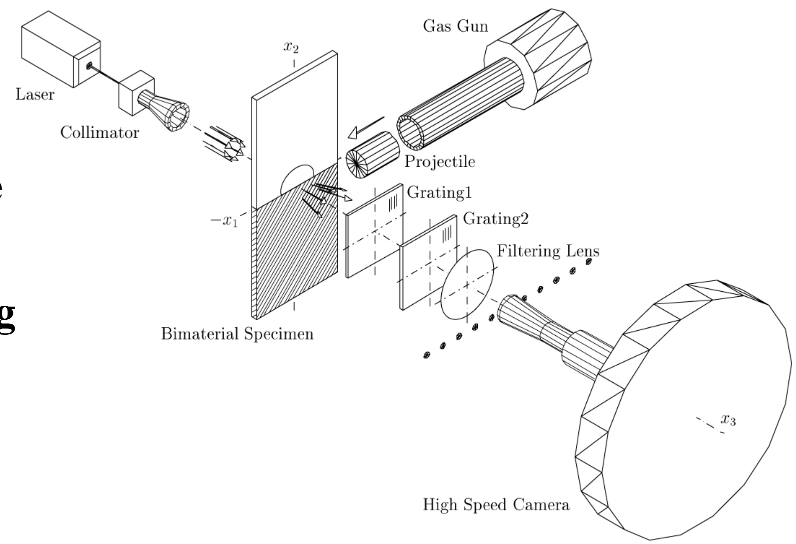
Slope map (resolution ~ 1μrad)

EXPERIMENTAL SET-UP FOR DYNAMIC SHEAR FRACTURE (High speed optical and IR diagnostics)

Ares Rosakis and G. Ravichandran

•Simulation of earthquake rupture in the laboratory

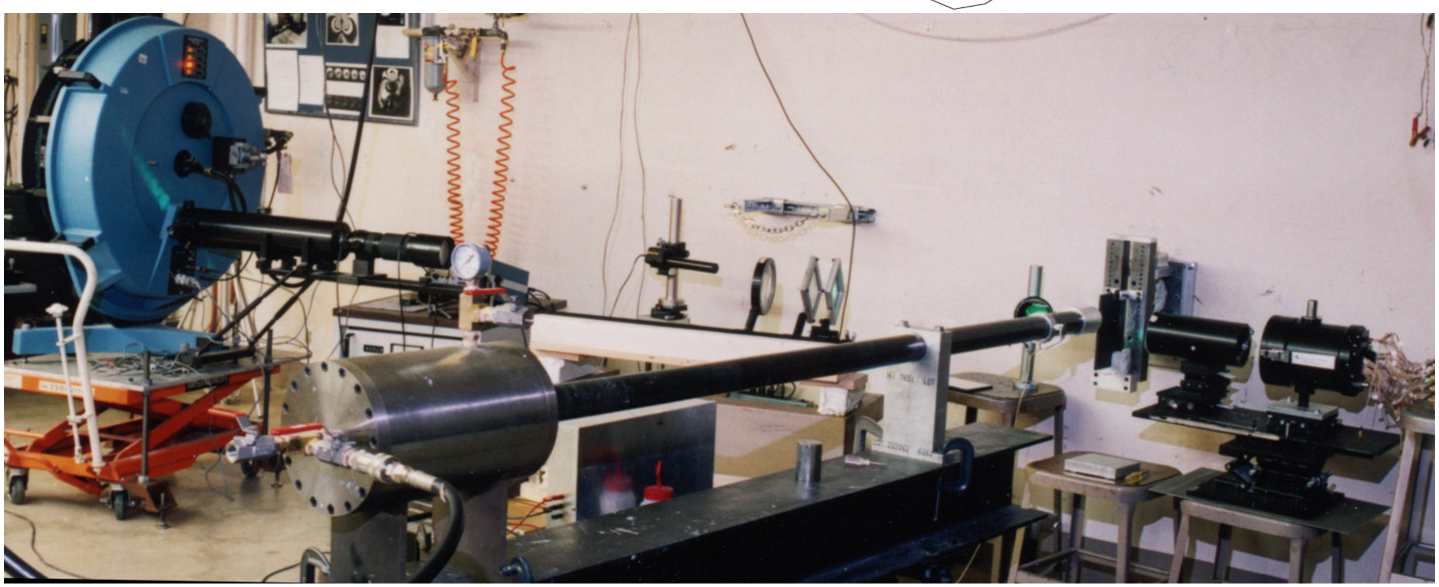
•Effect of explosive loading on bonded structures.



•Dynamic fracture of bonded structures

•Dynamic delamination of bimaterials and layered composites

•Rupture of frictionally held interfaces (Joints)



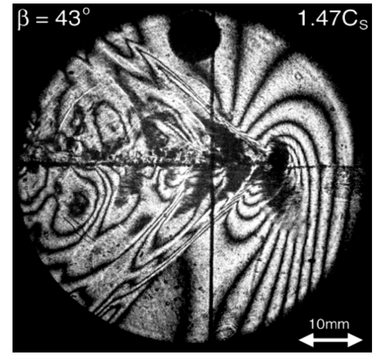
High Speed Optical and IR Diagnostics

Ares Rosakis

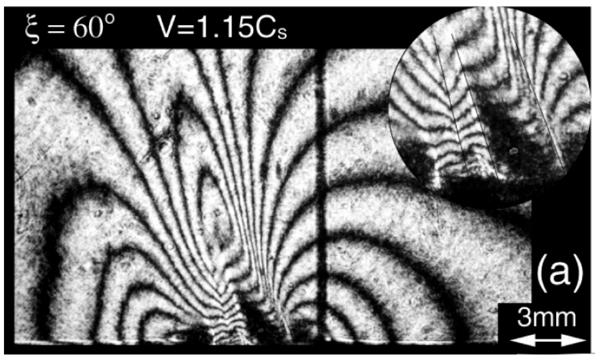
Intersonic Shear Crack Growth in Bonded Structures

Objectives:

- Study shear-dominated dynamic crack growth, first along a single weak interface in model specimens, then parallel to fiber direction in actual composites. Experimentally visualize stress fields using photoelasticity and high speed photography.



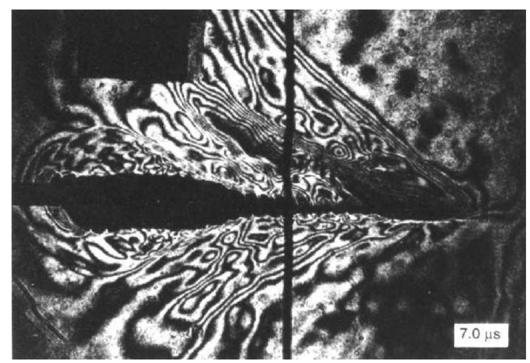
Homalite/homalite



Homalite/steel

Significant Finding:

- Observations of shear-dominated crack growth at speeds between the shear wave and longitudinal wave speeds. (Note the Mach cone-like structures in the interferograms).



Composite

Payoffs:

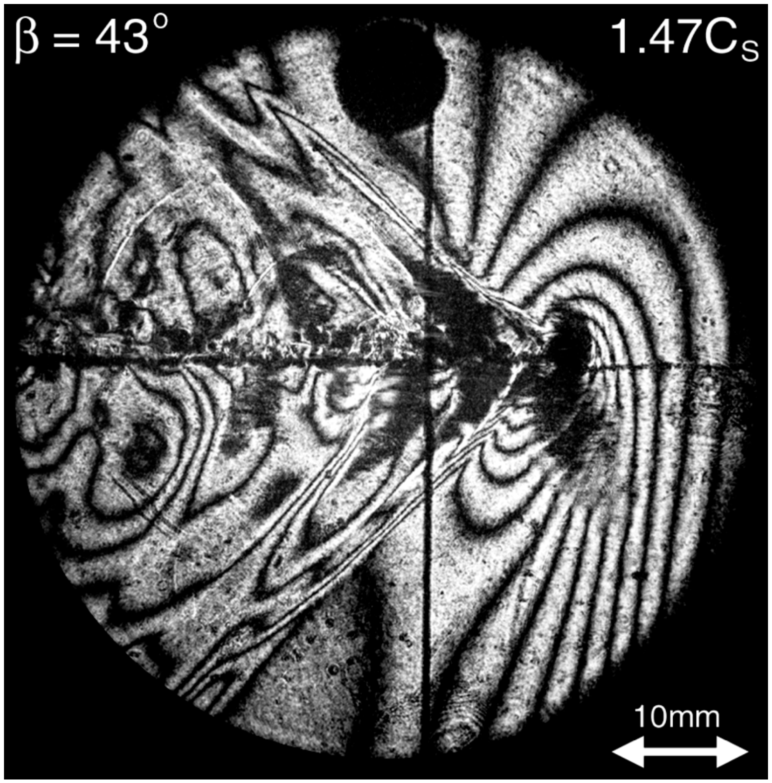
- Revelation of new failure mechanisms in composites that had neither been observed experimentally nor predicted theoretically.
- Awareness of new class of failure criteria for the safe design of composite structures

DEMONSRATING THAT INTERSONIC CRACKS EXIST

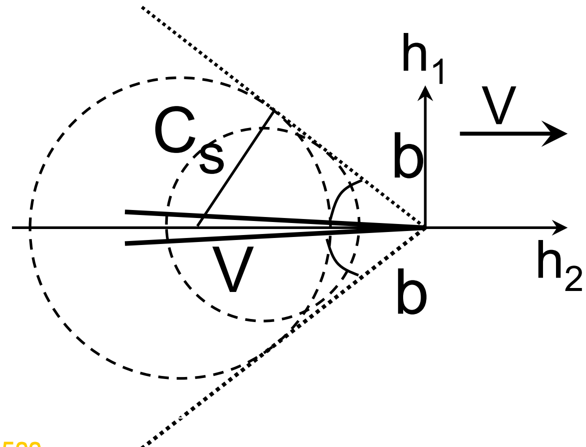
Intersonic Mode-II Crack Propagation and Shockwave Formation

Ares Rosakis

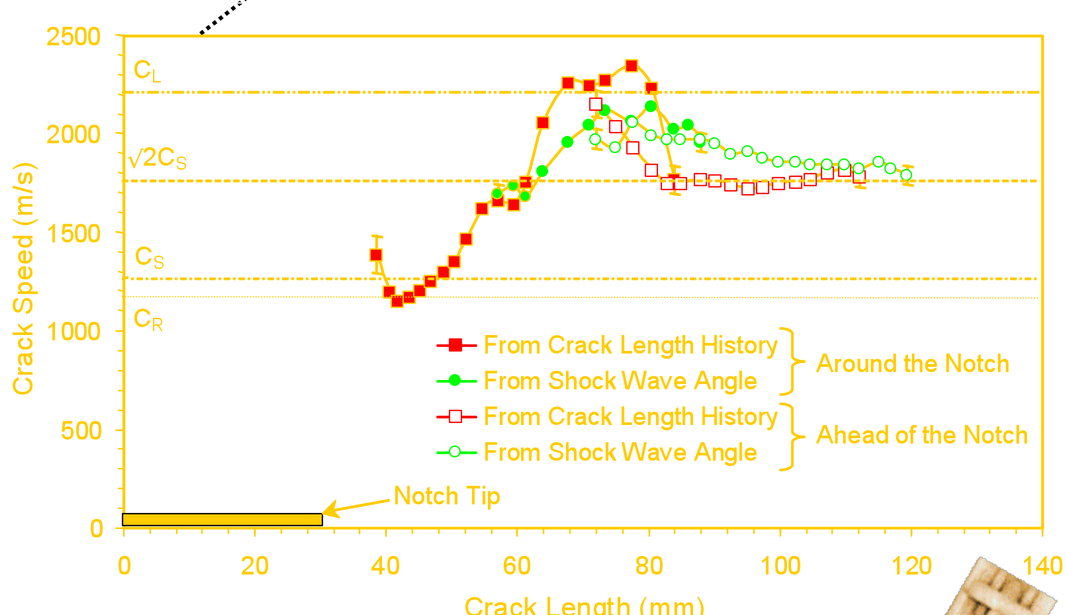
Rosakis, Samudrala & Coker (Science, May 1999)



- Homogeneous interface (homalite/homalite)
- Intersonic shear rupture
- Stable rupture speed at $\sqrt{2}c_s$

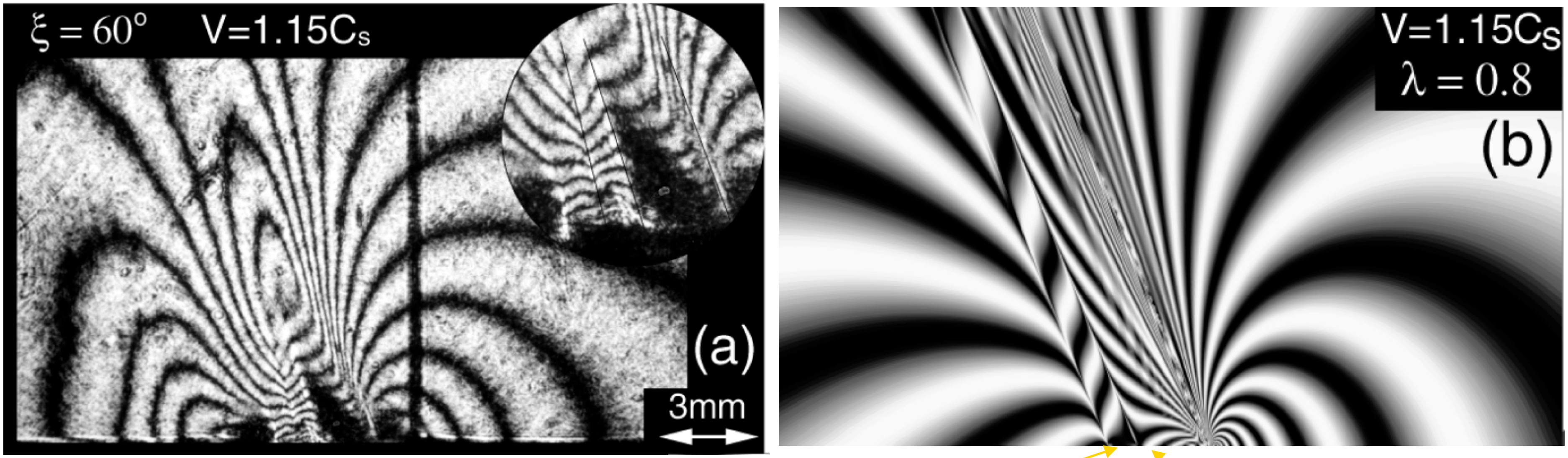


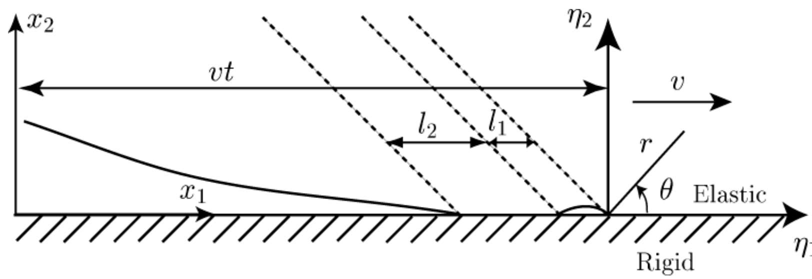
$$V = \frac{C_S}{\sin\beta}$$



INTERSONIC CRACK WITH DETACHED CONTACT ZONE ALONG A POLYMER / METAL INTERFACE

Ares Rosakis

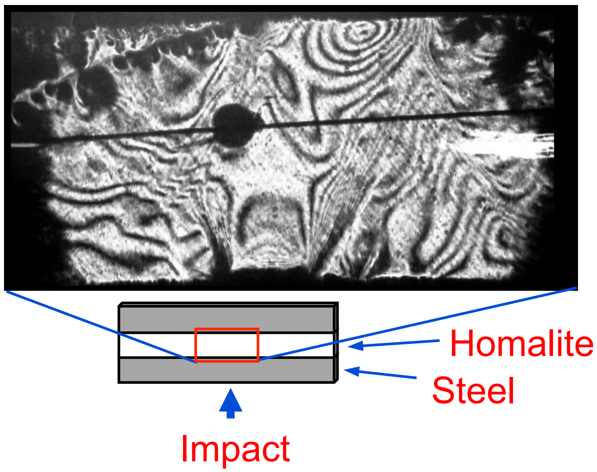




- Multiple contact visible by three shear shock waves
- Comparison between experiment and analysis (model by Huang and Rosakis)
- Intersonic shear rupture model includes contact and friction

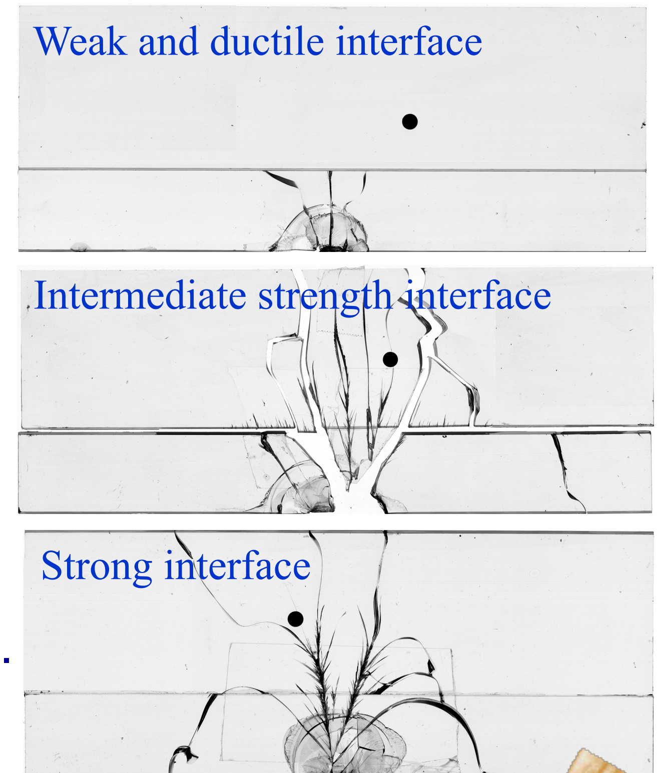
Interface/Damage Interaction In Layered and Sandwich Structures Subjected to Impact

Ares Rosakis



Objectives:

- Study the effect of interface strength and sandwich structure geometry on damage due to transverse impact. Photoelasticity and high speed photography is used to determine the *sequence* of events.



Significant Finding:

- Weaker interfaces reduce the amount of damage propagated to subsequent layers.
- Mismatch in material wave speeds cause intersonic shear cracks followed by intra-layer damage.

Payoffs:

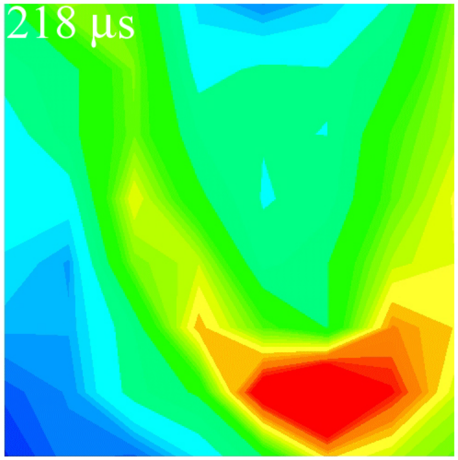
- Benchmark results for computational model validation.
- Improved design of sandwich structures, hybrid joints, armor plate, etc.

Dynamic Failure Mode Selection in Steels
High Speed IR Imaging

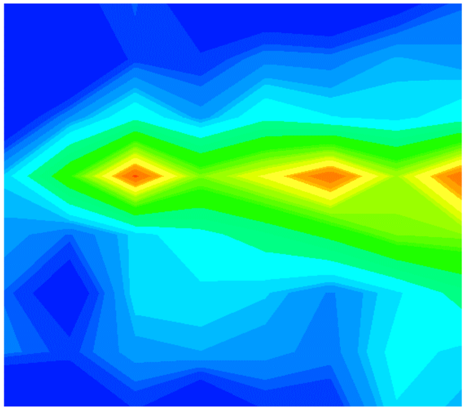
Ares Rosakis

Objectives:

- Study the near-tip plastic zone structure of different materials/loading configurations using high speed microthermography (1mm by 1mm field of view, 1 million frames per second)



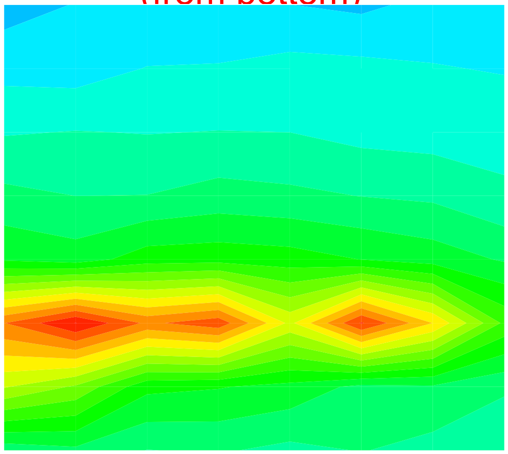
Steel, mode I crack (from bottom)



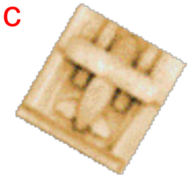
Bimaterial, intersonic shear crack (from left)

Significant Finding:

- Hot spots/vortical microstructures behind shear cracks and within shear bands
- Significant temperature rise at the crack tip (In steel ~50 °C for mode I, ~600 °C for shear bands)



Steel, dynamic shear band (from left)



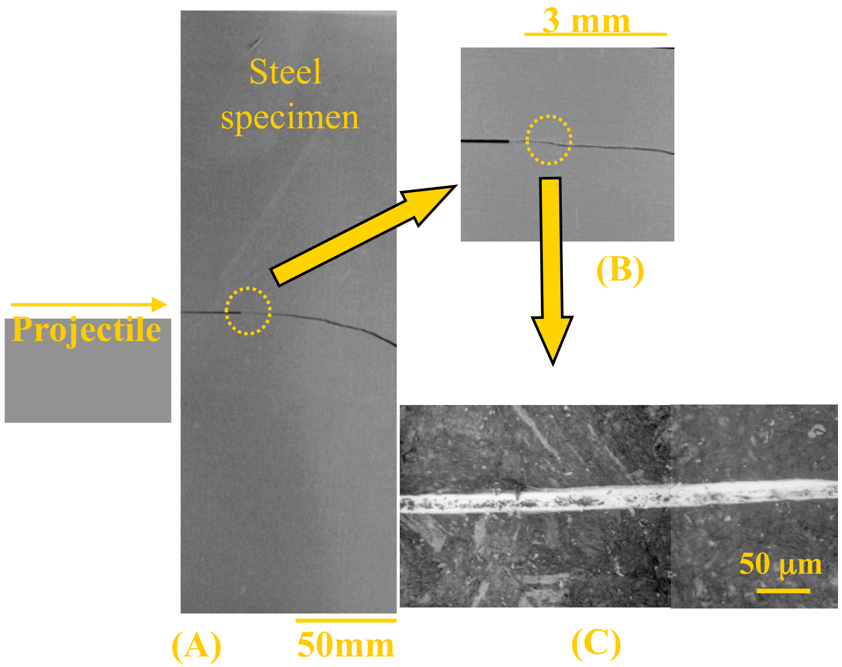
Payoffs:

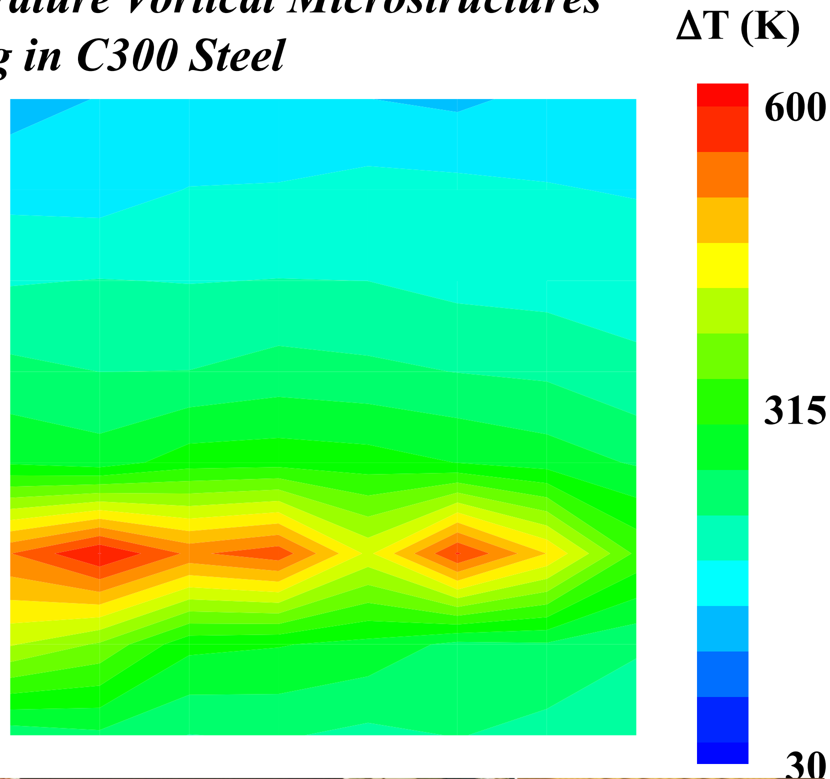
- Structure within dynamic shear bands and dynamic crack tips observed for the first time.
- Guidance and validation for computational models

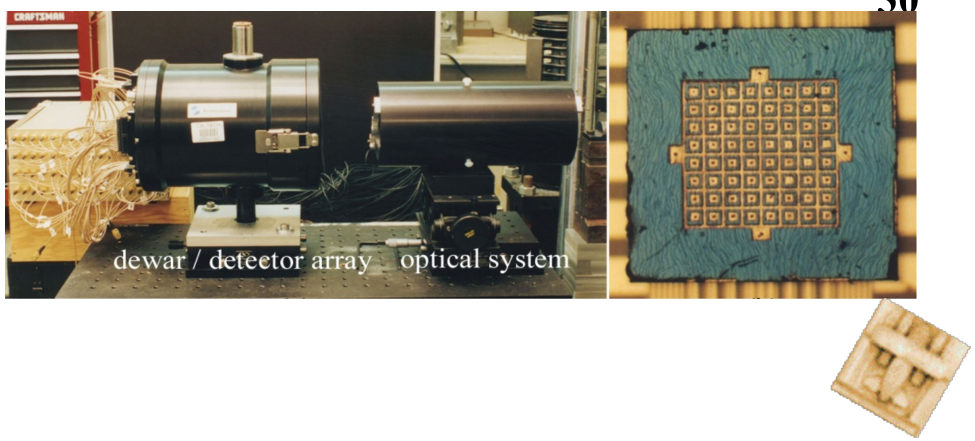
Ares Rosakis

VORTICES AND INSTABILITIES IN SOLIDS

Observations of Transient High Temperature Vortical Microstructures During Shear Banding in C300 Steel







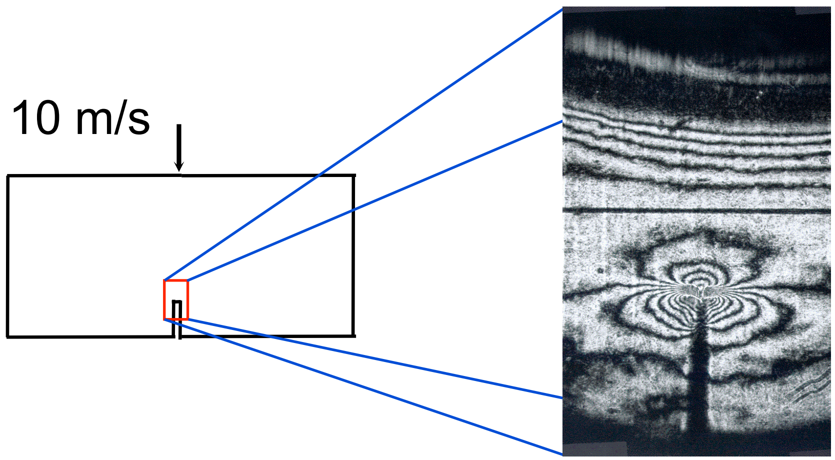
- Shear band speeds: 1 km/s
- Framing rate: 1 million frames per second
- Guduru, Rosakis & Ravichandran (Physical review E, 2001)
- Coker & Rosakis (Philosophical Magazine A, 2001)

Ares Rosakis

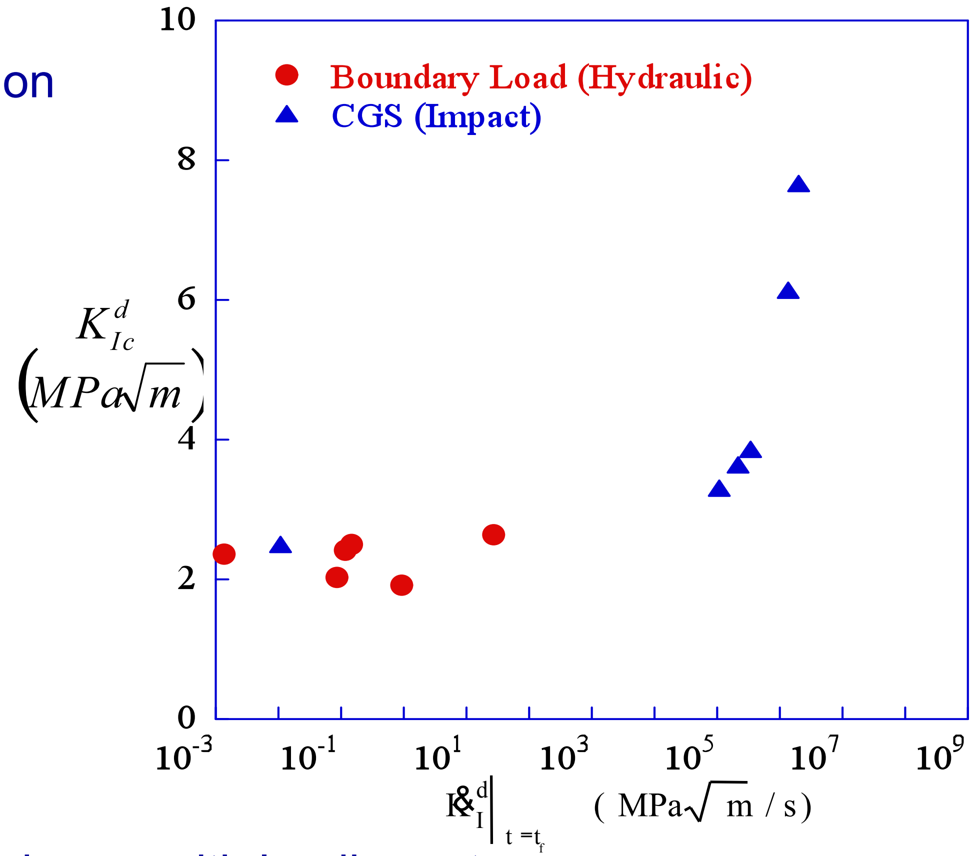
Crack Initiation Criteria in Composites

Objectives:

- Establish Mode I dynamic crack initiation criteria for unidirectional composites.



CGS
Interferogram



Significant Finding:

- Dramatic increase in fracture toughness with loading rate.

Payoffs:

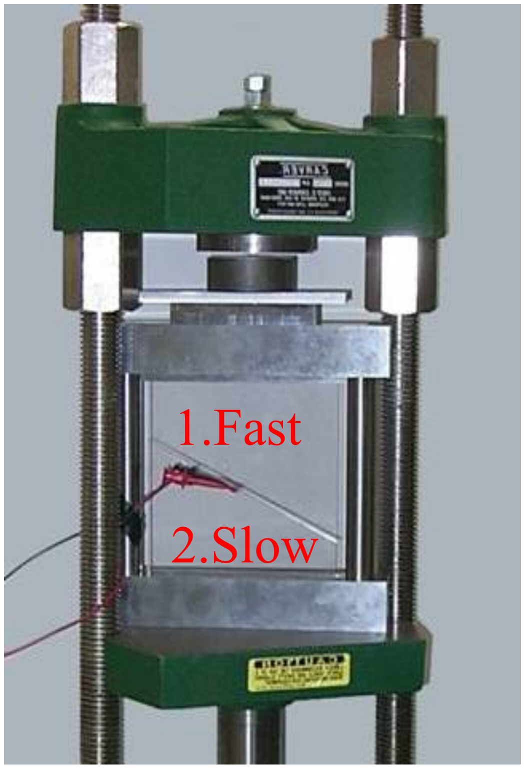
- Quantify potential improvements in composite design and fabrication.
- Improve analyses of failure due to dynamic loading.

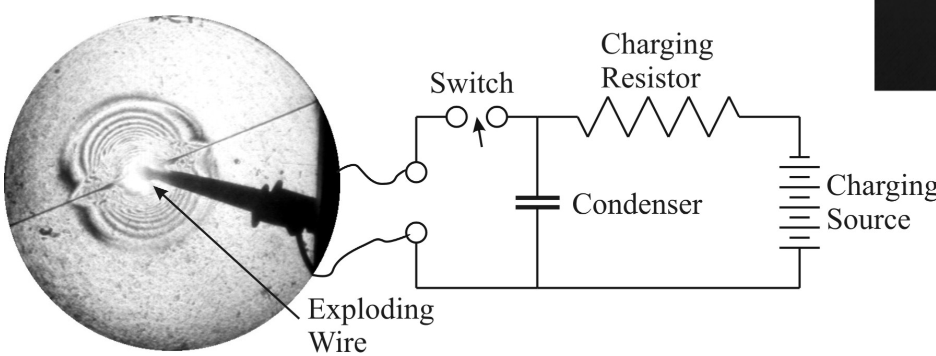
LABORATORY EARTHQUAKES

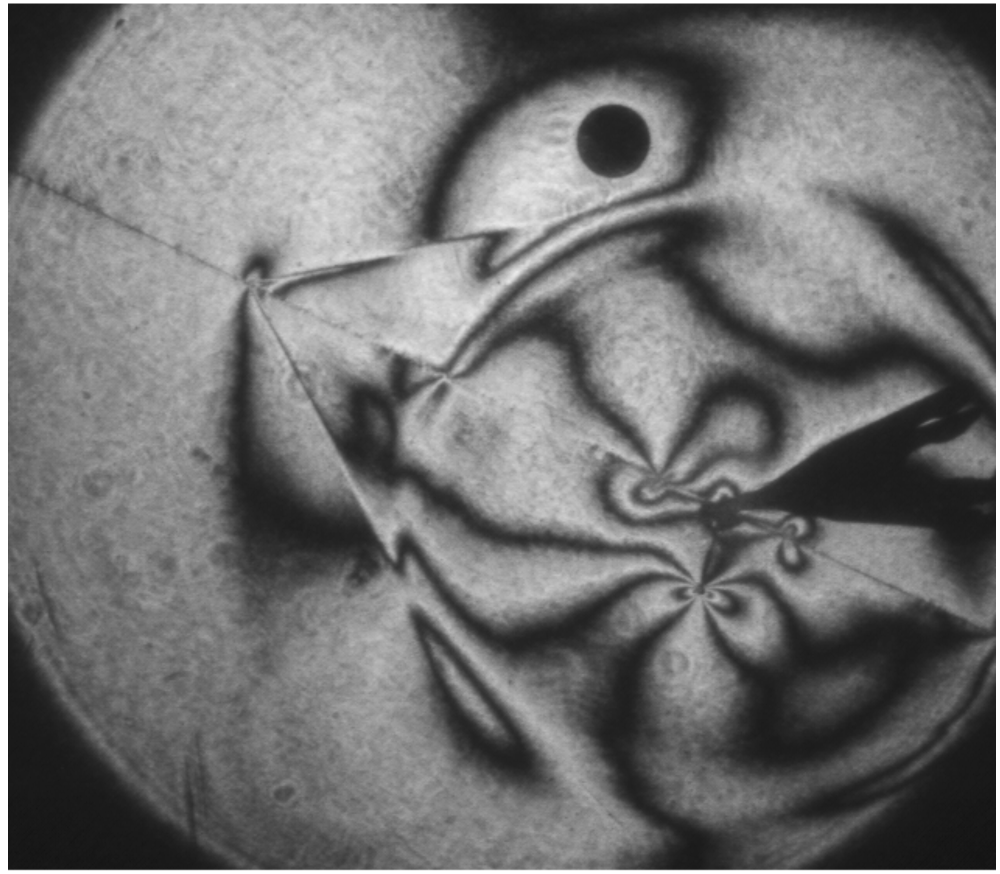
(Compressive Far-Field Loading and Local Release of Pressure: Spontaneous Rupture)

Ares Rosakis

(Xia, Rosakis and Kanamori, Science, March 2004)







An inter-sonically moving fault rupture

Frictionally held (incoherent) interfaces are used to simulate earthquake ruptures in a controlled laboratory setting. This is collaborative work with H. Kanamori of the Caltech Seismo Lab

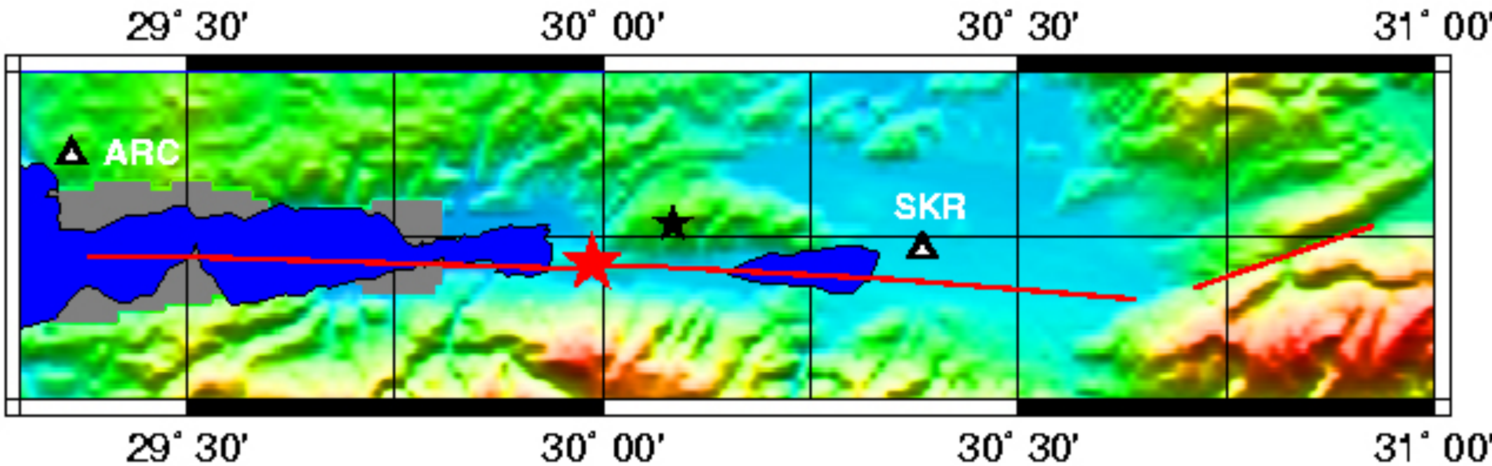
FIELD EVIDENCE OF INTERSONIC RUPTURE DURING IZMIT & DUZCE EARTHQUAKES IN TURKEY (1999) NORTH ANATOLIAN FAULT

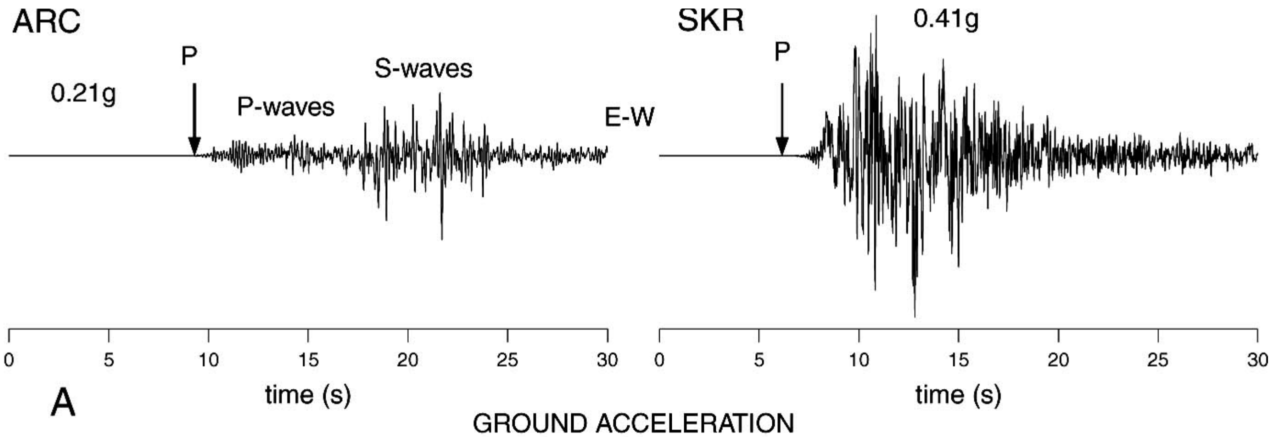
Ares Rosakis

Collaborative work with Universite Joseph Fourier (France)

M. Bouchon, M. Bouin, H. Karabulet, M. Toksöz, M. Dietrich and A. Rosakis,
Geophysical Research Letters, 2001

Fault Speed (West: Rayleigh, East $\sqrt{2}\ C_S$ = 4.9 km/s)



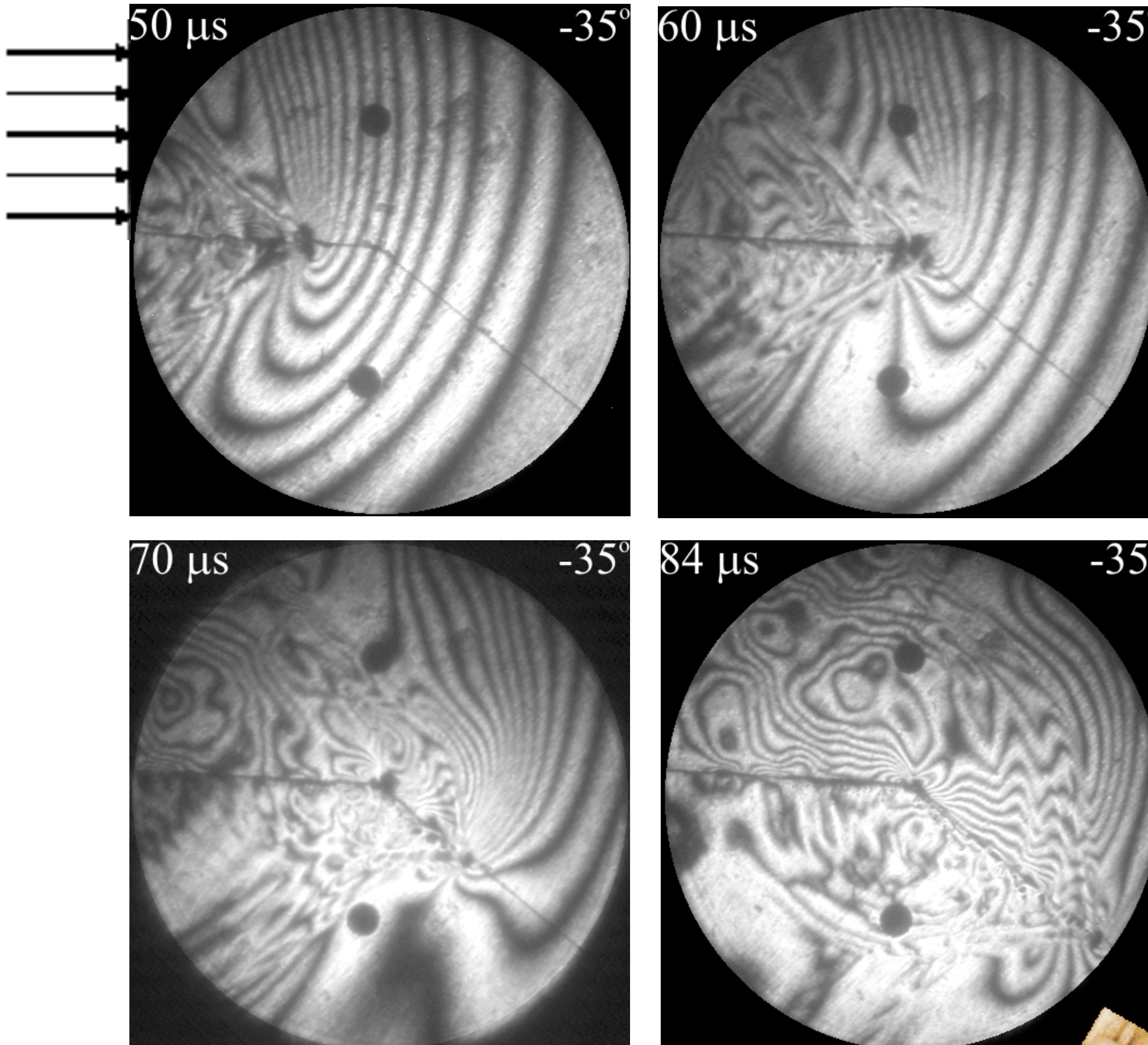


HOW DO EARTHQUAKE RUPTURES TURN A CORNER?

Ares Rosakis

Dynamic Shear Ruptures Encountering Interfacial Bends and Branches

Earthquake faults are often "kinked" and "jogged". This study looks at the effect of geometry on the growth or arrest of earthquake structures. For engineering composite structures the issue is related to the catastrophic failure evolution along complex interfaces.



Rousseau and Rosakis JGR 2004

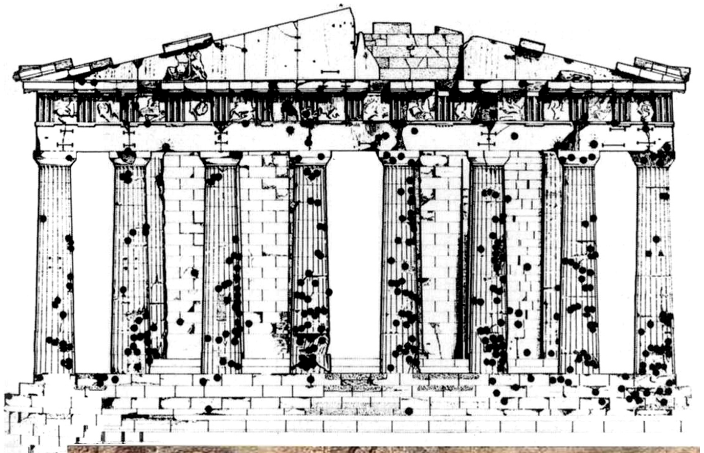
$V_{in} = 1.39c_S$ $V_{out} = 1.40c_S$

$c_S = 1310$ m/s

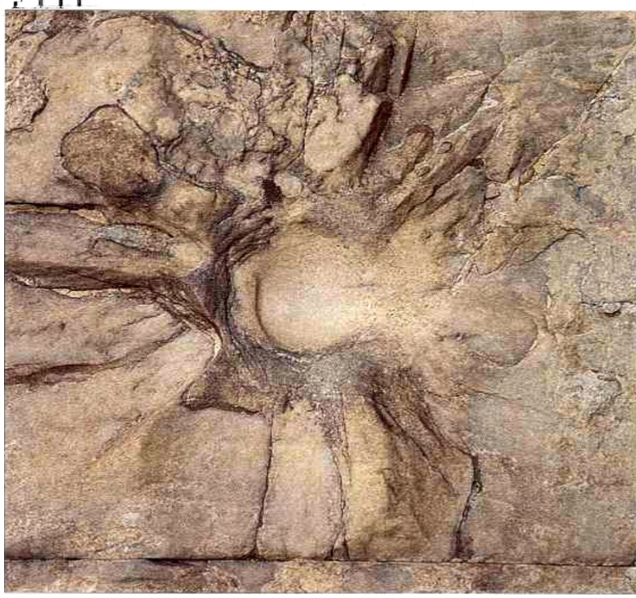
FRANCISCO MOROSINI, DOGE OF VENICE BESIEGES THE ACROPOLIS (SEPT. 26, 1687)

Ares Rosakis

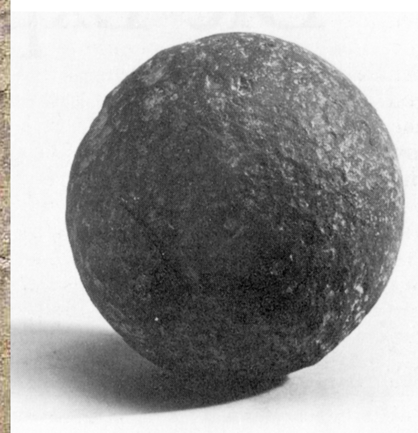
A coalition of Venice, Austria and Papal forces attacks the Ottoman Empire



Locations of cannonball damage on the facade



Cannonball imprint on a marble column

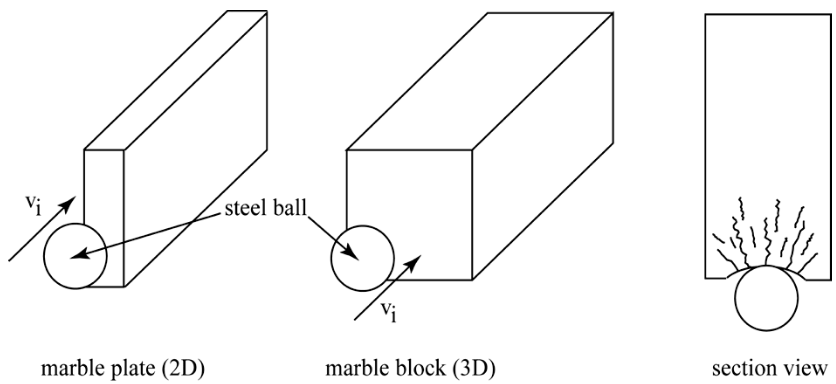


One of Morosini's cannonballs

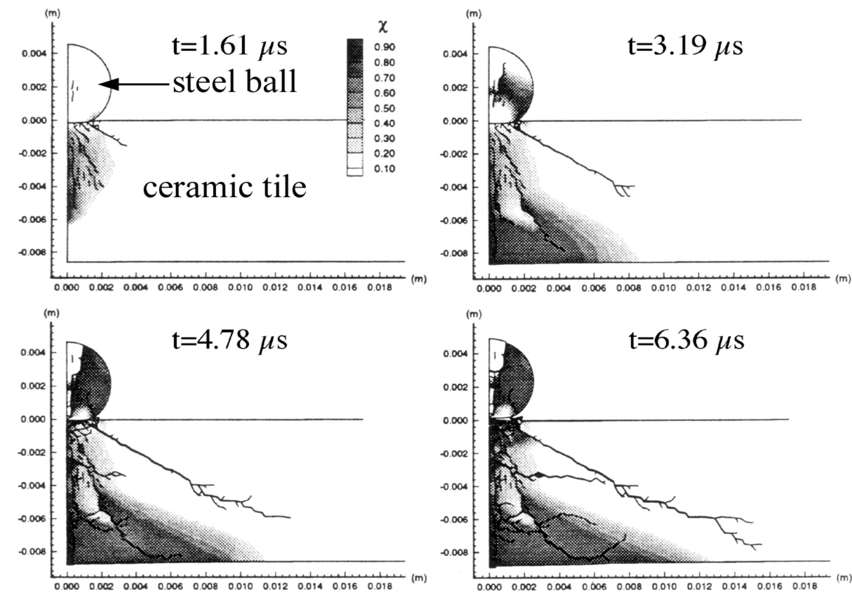
Collaborative work with Professor I. Vardoulakis, The Technical University of Athens

A PROGRAM TO SIMULATE COLUMN DRUM IMPACT DAMAGE:
Experiments and validated numerics

Ares Rosakis



Proposed configurations for verification experiments and simulations: (a) in-plane impact of a marble plate, (b) impact of a marble block and (c) section view of damage.



Results from the numerical simulation of the impact of a steel ball on a ceramic tile using the cohesive-law model of failure (from Camacho & Ortiz).