Super-shear determination

Bringing an innovative approach to the field of earthquake research, **Professor Ares Rosakis** has been making important discoveries in the laboratory about earthquake rupture speeds, ground motion signatures, and hazard mitigation

What is the background to this latest research and what are its main objectives?

My engineering expertise lies within the study of dynamic failure of materials; in particular I am a dynamic fracture mechanician who works in the area of solid mechanics. The purpose of the work is to study the creation of cracks, ruptures, and delaminations of all types, in particular their dynamic spreading through different materials. In the initial part of my work I have been concentrating on cracks that grow dynamically in monolithic materials of interest to the field of engineering, such as metals, ceramics and polymers. I have been using a number of optical techniques, high-speed photography, and laser velocimetry to follow these cracks that propagate in very high speeds in monolithic solids.

How does this project lead on from your previous work?

The transition to researching earthquakes happened through the study of modern multi-phase engineering materials when I first recieved funding from the Office of Naval Research here in the US, to look experimentally and theoretically at the process of the impact-induced dynamic cohesion of bi-materials and composite materials, which are solids that feature more than one phase. These materials contain very interesting coherent interfaces, which have intrinsic toughness and strength.

We discovered that there was a very different failure behaviour exhibited by these multi-phase solids compared to their monolithic analogues, which I had been studying during the initial part of my career. The difference was that in composite materials cracks resulting in the catastrophic breaking up of the solid tended to be trapped and propagate mainly along interfaces. They also did so extremely fast. This new discovery was of great surprise to both myself and my former student Professor John Lambros of the University of Illinois as well as my former postdoc Hareesh Tippur of Auburn University. The results showed very fast shear-dominated, interfacial cracks, that we called 'intersonic', because they were propagating at speeds between the shear and the pressure wave speeds of the surrounding solid.

What are your most significant findings to date and how does that bare similarities to the shear failure of composite materials?

After discovering the existence of intersonic cracks or shear ruptures in coherent engineering interfaces subjected to impact, naturally the next question was whether such ultra-fast cracks or ruptures can also exist in frictional or incoherent interfaces which are present when two solids come in contact under compression and shear loading. The most obvious setting of global interest here is that of crustal plates pushing against each other along Earth's large interfaces which we call 'crustal faults'. The question thus became: Can crustal faults spontaneously rupture at intersonic or super-shear speeds, and if so, can we find unequivocal field evidence of the existence of such super-shear earthquake rupture events? Furthermore, how would super-shear earthquakes feel, and would we be able to design buildings strong enough to withstand their shaking?

I would say that my most significant finding to date is the laboratory discovery of sustained super-shear, crack-like and pulse-like ruptures in such frictional interfaces or faults. This discovery became possible when Professor Kanamori and I introduced our concept of 'Laboratory Earthquakes' and designed a seismologically relevant experimental configuration capable of repeatedly generating miniature earthquakes in a controlled and highly instrumented setting. It was in this setting where my co-workers and I conclusively demonstrated the existence of such super-shear earthquake ruptures and we explored the speed transition mechanism from sub-shear to super-shear. We also visualised the sudden creation of Mach-cone, shear stress, discontinuities (shear shockwaves) at the rupture fronts equivalent to the pressure Mach-fronts (pressure shockwaves) created by supersonic aircraft as they break the sound barrier in air creating the familiar sonic boom.

Your project aims to resolve many arguments regarding the dynamics of earthquakes. What are the main areas of controversy that you are looking to address?

It has taken a lot of discussion, articles, and various scientific publications, to persuade the community that ruptures in the Earth's crust can indeed be super-shear, and that it is natural to expect that all major (M_w>6) earthquakes will likely feature a sub-shear to super-shear speed transition event following long enough rupture growth along a fault. After many years and conferences devoted to this topic, we can say that at least every other month we have publications coming out reporting that earthquakes have featured super-shear rupture components.

Why is this so important?

The significance of this phenomenon to society cannot be underestimated. The possibility of these rupture speeds becoming super-shear is paramount to seismology because it affects the signature of wave radiation during an earthquake, and hence directly affects seismic hazards. For example, if a building sits next to a fault and the fault ruptures in a super-shear fashion, rather than the classical, sub-shear fashion, it will experience very different ground shaking at its foundations, mainly because of the existence of the Mach-fronts or shear shockwaves which will hit it even before much of the primary ground shaking commences. Thus, the damage accumulated and the ability of a building to survive in a near fault location would highly depend on the rupture speed and the distance of the building from the point of the fault where the speed changed from sub to super-shear. We could imagine a zipper unzipping an interface in your sweater: the zipper speed is very important to how the material to the right and left moves. The same goes for an earthquake rupture: the ground shaking is affected by the speed of the rupture in a very major way both in ground velocity amplitude and frequency, as well as in total duration.

Ground breaking **work**

An exciting interdisciplinary project between Engineering and Seismology researchers at the **California Institute of Technology** has been creating laboratory earthquakes to understand their behaviour

Fault planes such as the San Andreas Fault stretch for thousands of kilometres, and whilst a certain amount is known about their behaviour, catastrophic earthquakes still occur within them that send quakes in unexpected directions, causing unprecedented damage and fatality. Professor Ares Rosakis has been using his engineering background as a dynamic fracture mechanics specialist to assess how such faults fail by sliding. He uses experimental methods in the laboratory to study the dynamic ruptures hosted by such fault planes and to analyse the resulting waves which are radiated, causing our familiar earthquake experience. Along with his collaborators at the California Institute of Technology (Caltech), Rosakis discovered arresting results about the speeds at which ruptures can propagate, and demonstrated that they can do so at unexpectedly high 'intersonic' or 'super-shear' speeds – those exceeding the speed of shear-waves in crustal rock.

A MATERIAL APPROACH

Rosakis' project was initially developed in dialogue with seismologists at Caltech, in particular the former Seismo Lab Director Hiroo Kanamori, who is, as Rosakis puts it: "Interested in Earth's big cracks, the ruptures which propagate dynamically along the fault planes". One fault plane of particular interest to their work is the San Andreas Fault, a big interface that exists in the Earth's crust and is almost a vertically dipping strike slip fault that exists throughout California, running all the way up the Western coast of the USA. Rosakis explains its significance: "This interface, from the point of view of a solid mechanician (my background), is a frictional interface, not a coherent interface like in those which exist in the composite materials of interest to engineering. It does not have intrinsic toughness and strength, but it has frictional strength." This comes from the compressive stresses of tectonic plates coming together and squeezing against each other at the interface. The resulting strength resists the shear force of rubbing applied parallel to the interface.

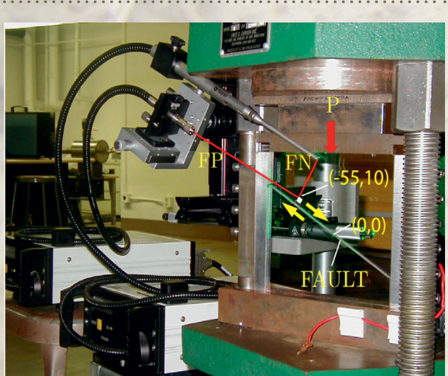

FIGURE 1. This specimen features an inclined interface and pairs of particle velocimeters arranged in two configurations capable of recording fault parallel (FP) and fault normal (FN) motions.

LABORATORY PROCESS

For his project, Rosakis worked with Kanamori and their former graduate student Kaiwen Xia, now a Professor at the University of Toronto, to design the concept of laboratory earthquakes by creating a scaled-down analogue of what is happening on the Earth's crust. This model mimics the Earth's crust and faults, as well as its compression and shear, with contacting pieces of polymer simulating the crustal rocks and with the interfaces between them mimicking the fault planes. Furthermore, Rosakis and his team have modelled the tectonic loading of the plates to create fast ruptures that propagate spontaneously along the interfaces. Unlike the study of real earthquakes, Rosakis' 'lab earthquake events' are able to be placed in a highly instrumented environment, as he describes: "The difference here is that these experiments allow for simultaneous observation through a series of very complex diagnostics – we use high-speed cameras capable of many millions of frames per second". This gives Rosakis and Kanamori a full view of the mini-earthquake ruptures as they propagate along the simulated faults, and the ability to study the resulting simulated ground shaking in the surrounding material.

DIAGNOSTIC TECHNOLOGIES

Rosakis, Kanamori, and mechanical engineering Professor Nadia Lapusta have used a variety of technologies to measure fault slip and ground motion – not only high-speed photography, but also highly sensitive lasers measuring shaking due to the spreading of seismic waves (developed by their former students, Dr Xiao Lu, currently at Intel and George Lykotrafitis, now a Professor at the University of Connecticut). "We have a set of high-speed digital cameras, but just visualising things from black and white photographs is not enough," explains Rosakis. "We need to illuminate the specimens in transmission with laser light and then using optical techniques like dynamic photo elasticity, a polarising technique to highlight things such as stresses in the crustal material that are not visible to the naked eye".

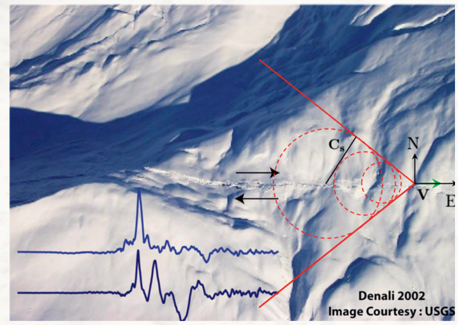

FIGURE 2. Surface evidence of the fault trace hosting the Supershear 2002 M_w 7.9 Denali, Alaska earthquake rupture, as it shows through the snow pack.

DYNAMIC RUPTURES

The project has shown that research like Rosakis' past work on the dynamic failure of composite and bi-material systems can feed into seismological work, as he reflects: "It is a very good example of how the mechanics of materials/solids can be conceptually extended and applied across multiple scales from the engineering world (metres), up to the geophysical world (thousands of kilometres)". Through the laboratory earthquake experiments, Rosakis, Kanamori and Lapusta, in close collaboration with Professor James Rice of Harvard University, have also produced interesting evidence on the existence of various modes of ruptures in systems featuring different combinations of crustal solids; there had been conflict in the scientific community about how plates rub and rapidly slide together near ruptures, but the team has experimentally discovered the existence of dynamic pulse-like ruptures in frictional interfaces, a theory forwarded by Rice.

SHOWING THE 'SUPER-SHEAR' FACTOR

Unlike air, which carries sound or pressure waves, solid materials such as the Earth's crust, feature two characteristic types of waves in their bulk. These are the shear waves and the faster pressure waves. Until relatively recently, it was believed that defects, dynamic cracks and ruptures growing in solids can only do so at speeds much lower than the speeds of growth of both the shear and the pressure waves, and are thus doomed to remain strictly 'sub-shear'. Consistent with this belief, it was also expected that earthquake ruptures are also restricted to propagate at sub-shear speeds and that 'super-shear' was not possible. However, Rosakis and Kanamori set out to show in the lab that super-shear rupture speeds were attainable, and moreover – by examining evidence from real earthquakes – that they were often very relevant to large earthquakes: "Under very controlled scientific conditions and detailed, real-time scrutiny we discovered that super-shear rupture speeds were possible in nature, and that super-

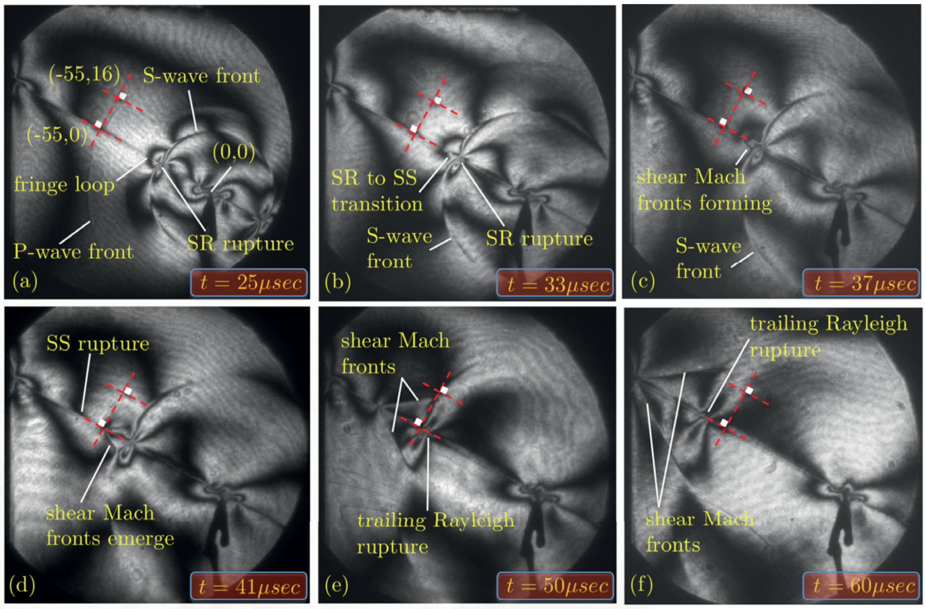

FIGURE 3. Experimental demonstration of sub-Rayleigh to Supershear transition and the formation of Mach-fronts.

shear ruptures had a few interesting similarities to supersonic aircraft in relation to their ability of producing 'shock-like' ground shaking conditions equivalent to the familiar sonic boom," Rosakis reflects. Whilst the project's experiments in the lab have been highly successful in terms of providing a wealth of useful information that simply would not be available from field measurements of real earthquake events, the challenge now is for Rosakis' team to show that the findings can directly translate, as he explains: "For the approach to be successful, we ultimately have to demonstrate with science and mechanics that what we see in the lab is truly representative of what is happening on the earth's crust (what is known as scaling). Our first attempts are very encouraging".

Indeed, his recent work with past postdoc student Dr Harsha Bhat, currently a researcher in the Institute de Physique du Globe de Paris, and past student Mike Mello, currently a Professor at Georgia Tech, shows that scaling is a success in predicting near fault shaking behaviour, such as recorded by a station on the trans-Alaska pipeline during the 2002, M_w7.9 mega quake in Denali, Alaska.

COLLABORATIVE EFFORTS

Collaboration is key to Rosakis' project, not only in his close working with Kanamori, but in his productive relationships with other colleagues at Caltech and other institutions in the US and Europe. Professor Swaminathan Krishnan from the Department of Civil Engineering at Caltech, for instance, has been able to create numerical full-scale models of existing buildings with existing geometry, taking into account particular locations of shear walls, structural strength, amongst other factors. These have then been subjected to the 'scaled-up' ground shaking measured in Rosakis' model experiments, for various rupture speeds and have been used to examine the buildings' damage accumulation and propensity to fall down or to withstand certain earthquakes. The whole 'Laboratory Earthquake' project, embraces the interdisciplinary philosophy of Caltech, involving Rosakis' colleagues from mechanical engineering like Professor Nadia Lapusta (Rice's former student from Harvard) – an expert in numerical techniques, and large-scale computing of complex geological processes, as well as pure geophysicists such as Kanamori and civil engineers like Krishnan. "In this project we all behave both as engineers as well as scientists," states Rosakis. "The details of our training becomes blurred".

AN EXCITING FUTURE

In addition to its value as a scientific tool, Rosakis' concept of 'Laboratory Earthquakes' has great potential practical impact in the area of earthquake preparedness: "This kind of experiment can feature complex and realistic fault geometries and to host repeated earthquakes," he elucidates. "Through the discovery of a phenomenon like the super-shear earthquakes, as well as through understanding enhanced ground shaking and the special signatures that exist in these particularly 'weird earthquakes', the team have started looking at new designs that buildings should feature – not only city buildings, but dams, nuclear reactors and bridges too". The project has huge potential for the future – further research could explore not just super-shear but other types of earthquakes on different types of faults, such as the thrust fault which hosted the last catastrophic earthquake and tsunami in Japan. Because of its great success and significance across earthquake physics, Rosakis' project receives constant international calls from other researchers and scientists interested in comparing their new theories to 'real' experiments: "We are expanding day by day and have constant chances for collaboration with a large number of important institutions," he enthuses. "We are excited to see how this expansion and these collaborations unfold".

INTELLIGENCE

LABORATORY EARTHQUAKES: CHARACTERISATION OF GROUND MOTION AND STRESS STATES IN COMPLEX RUPTURE SCENARIOS USING HIGH RESOLUTION OPTICAL DIAGNOSTICS

OBJECTIVES

This research focused on the advancement of a unique experimental capability for generating earthquake-like ruptures under controlled laboratory conditions. The experiment features a model specimen with an interface that simulates a natural fault in the Earth's crust. Work under the support of this grant targeted the development and integration of new optical diagnostics for the precise measurement of the resulting particle (ground) motion and associated stress fields in these experiments.

KEY COLLABORATORS

Professor Hiroo Kanamori, Seismo Lab, Caltech

Professor Nadia Lapusta, Mechanical Engineering, Caltech

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ARES J ROSAKIS researches quasi-static and dynamic failure of metals, composites, and interfaces with emphasis on the use of high speed visible and infrared diagnostics and laser interferometry. He brings together concepts from engineering fracture mechanics and geophysics to understand earthquake source mechanics and the physics of dynamic rupture.