Identifying the unique ground motion signatures of supershear earthquakes:
The one-two punch effect on high-rise buildings

University of California, Los Angeles
The Civil & Environmental Engineering Department
Distinguished Lecture Series, February 7, 2012
ARES J. ROSAKIS
Graduate Aerospace Laboratories (GALCIT), Chair, Division of Engineering and Applied Science, California Institute of Technology

2002 $M_w$ 7.9 Denali, Alaska

1906 $M_w$ 7.8 San Francisco, CA Was it supershear?

Producing surrogate earthquakes in GALCIT’s seismological wind tunnel
What Is a crustal Earthquake?

Earthquakes are spontaneous frictional (shear) ruptures occurring along weak planes in the crust:

“Spontaneous” implies quasi-static tectonic loading and sudden triggering of dynamic slip.

“Rupture” means propagation of slip along a frictional (incoherent) interface. The rupture speed is the speed of dynamic unzipping and governs the nature of near-fault ground shaking.


Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip.
A GLIMPSE AT A POTENTIALLY BIG PROBLEM

“Rupture” means propagation of slip along a frictional (incoherent) interface

Brad Aagaard (CE Ph.D., 2000)
Robert Graves (GPS PhD, 1990) - Equivalent to fast unzipping - SCEC ShakeOut Simulation workgroup

Pressure Wave \( (c_p \sim 5 \text{km/s}) \), Shear Wave \( (c_s \sim 3.5 \text{km/s}) \) Rayleigh Wave \( (c_R \sim 3 \text{km/s}) \)

- The ground-shaking intensity and radiated energy are related to rupture speed

How big could the Rupture Speed \( (v) \) be?
Evidence of Supershear ($c_S < v < c_P$) Rupture speeds
A shear wave Mach Cone only

- Within resolution of the inversion process the majority of field evidence suggests rupture speeds, $v$, between $0.8 \ C_R$ to $\ C_R$ of crustal rock (~2.9Km/s) Venkataraman and Kanamori, JGR (2004)

- Evidence of supershear ($C_S < v < C_P$) rupture bursts along fault segments.

<table>
<thead>
<tr>
<th>References</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Song and Beroza, <em>BSSA</em> (2006)</td>
<td>1906 San Francisco, CA ; $M_w$ 7.8</td>
</tr>
<tr>
<td>• R. Archuleta, <em>JGR</em> (1984)</td>
<td>1979 Imperial Valley, CA ; $M_w$ 6.5</td>
</tr>
<tr>
<td>• Bouchon, Bouin, Karabule, Toksöz, Dietrich and Rosakis, <em>GRL</em>, (2001)</td>
<td>1999 Izmit, Turkey ; $M_w$ 7.4</td>
</tr>
<tr>
<td>• Robinson, Brough and Das, <em>JGR</em> (2006)</td>
<td></td>
</tr>
<tr>
<td>• Walker and Shearer, <em>JGR</em> (2009)</td>
<td></td>
</tr>
<tr>
<td>• Ellsworth et al., (2004);</td>
<td>2001 Kunlunshan, China ; $M_w$ 7.8 (Transition)</td>
</tr>
<tr>
<td>• Walker and Shearer, <em>JGR</em> (2009)</td>
<td></td>
</tr>
</tbody>
</table>

$\theta = \sin^{-1}(c_S / v)$

Personal favorites: [Ellsworth et al., 2004; Walker and Shearer, 2009]
A Rare NEAR-FAULT Record of a just transitioned, SUPERSHEAR event

Mw 7.9, 2002 Denali, Alaska Earthquake. Transition at 72Km (18Km W. of pump 10 station located at 3Km north), Ellsworth et al. (2004). Right lateral slip, West to East.

From Real to Laboratory Earthquakes
(Mimicking Spontaneous Rupture Events in Frictional interfaces)

Mw 7.9, 2002 Denali, Alaska Earthquake. Transition at 72Km (18Km W. of pump 10 station). Elsworth et al. (2003), Walker and Shearer (2009).

- Rock → Photoelastic Polymer
- Fault → Inclined Contact Interface
- Tectonic stress → Far Field Load
- Hypocenter → Triggering Site
Experimental setup that mimics pre-stressed faults

Non-dimensional shear prestress = $\tau_0 / \sigma_0 = f_0 = \tan \alpha$

Exploding wire

(H. Kanamori, Seismo-Lab, Caltech)

James R. Rice
SEAS/E&PS
Harvard

Kaiwen Xia
CE, Univ. of Toronto

(K. Xia, AJ. Rosakis and H. Kanamori, Science 2004)
Fiber optic heterodyne laser interferometers enable continuous particle velocity records at a fixed location with high temporal resolution. All three components measured.

Photo-elastic interferometer with high speed cameras: Interference fringes correspond to iso-contours of $\sigma_1 - \sigma_2 = 2\tau_{max}(x_1, x_2)$, camera operated at 1 Million frames per second.
8 µs
Transition: From Sub-Rayleigh to Supershear
(Xia, Rosakis and Kanamori, Science 2004)

Shear Mach front

$L \propto P^{-3/2}$

R. Burridge, G. Cohn, L.B Freund “The stability of a rapid mode II shear crack with finite cohesive traction”, JGR (1979) VOL. 85 NO. B5, 2210 – 2222
Evolution of Rupture Speed for Supershear Ruptures

1. $\left[ \sqrt{2}c_s, c_p \right]$ is the stable supershear rupture speed regime
2. Higher interface pre-stress results in higher super-shear speeds

THEORY: R. Burridge, G. Cohn, L.B Freund, JGR (1979); Gao, Huang, Gumbsch, Rosakis, JMPS (1999); Samudrala, Huang and Rosakis JGR 2002; Rosakis, Advances in Physics (2002).
How does a Mach front sound?

- In this example from Aeronautics, Mach Fronts correspond to sudden (audible) Jumps in Pressure while in earthquakes they are Jumps in Shear stress.

- We want to study the effect of Shear “Mach Fronts” generated by super-shear ruptures.
Laser Interferometers to Record Ground Shaking in both **Super-shear** and **Sub-Rayleigh** Ruptures

*Simultaneous Pair of Fault Normal & Fault Parallel Velocity Measurements*

*Mello, Bhat, Rosakis and Kanamori*, Tectonophysics, Special Volume on Supershear 2010
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture (station, north of Fault in compressive side)

\[ P = 5.4 \text{ MPa} \; \alpha = 29^\circ \]

\[ P = 24.1 \text{ MPa} \; \alpha = 29^\circ \]
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear rupture

\[ P = 5.4 \text{ MPa} ; \alpha = 29^\circ \]

\[ P = 24.1 \text{ MPa} ; \alpha = 29^\circ \]
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear rupture

P = 5.4 MPa ; $\alpha = 29^\circ$

P = 24.1 MPa ; $\alpha = 29^\circ$
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

$P = 5.4 \text{ MPa} \; ; \; \alpha = 29^\circ$

$P = 24.1 \text{ MPa} \; ; \; \alpha = 29^\circ$
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

\[
P = 5.4 \text{ MPa} ; \alpha = 29^\circ
\]

\[
P = 24.1 \text{ MPa} ; \alpha = 29^\circ
\]
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

\[ P = 5.4 \text{ MPa} ; \alpha = 29^\circ \]

\[ P = 24.1 \text{ MPa} ; \alpha = 29^\circ \]
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

\[ P = 5.4 \text{ MPa} ; \alpha = 29^\circ \]

\[ P = 24.1 \text{ MPa} ; \alpha = 29^\circ \]
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

$P = 5.4 \text{ MPa} ; \alpha = 29^\circ$

$P = 24.1 \text{ MPa} ; \alpha = 29^\circ$
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

$P = 5.4 \text{ MPa} ; \alpha = 29^\circ$

$P = 24.1 \text{ MPa} ; \alpha = 29^\circ$
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

\[ t = 41 \mu s \]

\[ P = 5.4 \text{ MPa} ; \alpha = 29^\circ \]

\[ P = 24.1 \text{ MPa} ; \alpha = 29^\circ \]
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

$t = 50\mu s$

P = 5.4 \text{ MPa} ; \alpha = 29^\circ$

P = 24.1 \text{ MPa} ; \alpha = 29^\circ
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

P = 5.4 MPa ; \( \alpha = 29^\circ \)

P = 24.1 MPa ; \( \alpha = 29^\circ \)
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

$t = 60 \mu s$

SR

SS

$P = 5.4 \text{ MPa} ; \alpha = 29^\circ$

$P = 24.1 \text{ MPa} ; \alpha = 29^\circ$

Parallel
Normal

Time ($\mu s$)

Velocity (m/s)

Time ($\mu s$)
FP and FN Ground Velocity histories for a Sub-Rayleigh and a Supershear Rupture

\[ \frac{\dot{u}_{2\text{max}} - \dot{u}_{2\text{min}}}{\dot{u}_{1\text{max}} - \dot{u}_{1\text{min}}} > 1 \]

\[ \frac{\dot{u}_{1\text{max}} - \dot{u}_{1\text{min}}}{\dot{u}_{2\text{max}} - \dot{u}_{2\text{min}}} > 1 \]

P = 5.4 MPa; \(\alpha = 29^\circ\)

P = 24.1 MPa; \(\alpha = 29^\circ\)
Comparison between Lab and Natural Earthquake
(The trailing Rayleigh and the one-two Punch)

2002 $M_w$ 7.9 Denali, Alaska

Classification of Earthquakes: Ground motion signatures of steady-state, Sub-Rayleigh and Supershear Ruptures

1906 $M_w$ 7.8 San Francisco, CA
1979 $M_w$ 6.5 Imperial Valley, CA
1999 $M_w$ 7.4 Izmit, Turkey
1999 $M_w$ 7.2 Duzce, Turkey
2001 $M_w$ 7.8 Kunlunshan, Tibet
2002 $M_w$ 7.9 Denali, Alaska

Using 2D Numerics to identify Basic Signatures: Delivering the one-two punch

2D Plane-Stress Finite Element simulations using a commercial code, ABAQUS.
Simulation conducted on model material (Homalite-100)
Slip-Weakening frictional constitutive description: $D_c = 10$ microns, $f_s = 0.8$, $f_d = 0.2$
Velocity Signatures of Sub-Rayleigh and Supershear Ruptures

SUB-RAYLEIGH RUPTURE

2D PLANE-STRESS RUPTURE SIMULATED USING ABAQUS WITH LINEAR SLIP-WEAKENING FRICTION LAW

SUPERSHEAR RUPTURE

DILATATIONAL PRECURSOR

SHEAR MACH FRONT

TRAILING RAYLEIGH SIGNATURE

√_{\text{fault-normal}} < √_{\text{fault-parallel}}

√_{\text{fault-parallel}} < √_{\text{fault-normal}}

√_{\text{fault-normal}} > √_{\text{fault-parallel}}
The One-Two Punch: Effect of Supershear Earthquakes on Buildings

We have studied the special, ground shaking, signatures of transitioning super-shear earthquakes.

What are the implications for building safety and Seismic hazard?

Mello, Bhat, Rosakis and Kanamori,
Tectonophysics, Special Volume on Supershear 2010.

Song and Beroza, BSSA (2006), 1906 San Francisco, CA; M 7.8
**Temporally Scaling Laboratory Earthquake to Match Pump Station 10**

Unique ground motion feature common to both sub-Rayleigh and Supershear Earthquakes: 

*Trailing Rayleigh Signature*

- Temporal Scaling achieved by stretching the laboratory record \(t_R^{\text{exp}}\) to match the Trailing Rayleigh Signature in PS10 record \(t_R^{PS10}\). Common to sub-Rayleigh and Super-shear.

- Velocity Magnitude Scaling achieved by matching the amplitudes of the trailing Rayleigh signature between PS 10 and experiment. Note that by using non-dimensional arguments from steady-state rupture dynamics also results in Denali PS10-like velocity magnitudes.
Spatially Scaling Laboratory Earthquake to Match PS10 Record

Spatial Scaling achieved by solving for a station location in the laboratory specimen that would give the same time difference between the arrival of the Main Pulse and the Trailing Rayleigh Signature both in the temporally scaled laboratory record and the PS10 record.

**PROBLEM STATEMENT**

*Given a specific transition length, $L_T$, in the real earthquake, find $(x^{exp}, y^{exp}, L_T^{exp})$ in the laboratory earthquake such that*

$$
\Delta t^{exp} = \Delta t^{PS10, scaled}
$$
Calculating $\Delta t$ for a Supershear Rupture

Arrival time of the main Supershear pulse at Station

$$t_{SS} = \int_0^{L_T} \frac{dx}{v_r(x)} + \int_x^{x} \frac{dx}{v_r(x)} + \frac{y \cos \theta}{c_s} , \quad \sin \theta = \frac{c_s}{v_r}$$

Arrival time of the Trailing Rayleigh Signature at the Station

$$t_R = \int_0^{L_T} \frac{dx}{v_r(x)} + \int_x^{x} \frac{dx}{c_R} = \int_0^{L_T} \frac{dx}{v_r(x)} + \frac{x - L_T}{c_R}$$

Difference in arrival time of the Trailing Rayleigh Signature and Supershear pulse

$$\Delta t = t_R - t_{SS} = \frac{x - L_T}{c_R} - \int_{L_T}^{x} \frac{dx}{v_r(x)} - \frac{y \cos \theta}{c_s}$$
**Stations \((x,y)\) With the Same \(\Delta t\)**

Difference in arrival time of the trailing Rayleigh Signature and Supershear pulse

\[
\Delta t = t_R - t_{SS} = \frac{x - L_T}{c_R} - \int_{L_T}^{x} \frac{dx}{v_r(x)} - \frac{y}{c_s} \sqrt{1 - \left(\frac{c_s^2}{v_r^2}\right)}
\]

Solving for \((x,y)\) one obtains a locus of stations with same \(\Delta t\) for a fixed transition length

\[
y = x \tan \beta - L^* \quad \text{Locus of Stations with fixed } \Delta t
\]

Where the rupture speed is constant and:

\[
\beta = \tan^{-1} \left[ \frac{c_s \sec \theta}{c_R} - \tan \theta \right] \quad ; \quad L^* = (L_T + c_s \Delta t) \tan \beta \quad ; \quad \sin \theta = \frac{c_s}{v_r}
\]
Constrain the locus of stations with same $\Delta t = \Delta t^{PS10,\text{scaled}}$, with geometric scaling:

$$\frac{y^{PS10}}{(x-L_T)^{PS10}} = \frac{1}{6} = \frac{y^{exp}}{(x-L_T)^{exp}} = S_L \quad \text{(say)}$$

Solving now for station coordinates with geometric scaling constraint gives

$$x^{exp} = \frac{L^* - L_T^{exp} S_L}{\tan \beta - S_L} \; ; \; y^{exp} = S_L (x^{exp} - L_T^{exp})$$

$$\beta = \tan^{-1} \left[ c_s \sec \theta / c_R - \tan \theta \right] \; ; \; L^* = (L_T + c_s \Delta t) \tan \beta \; ; \; \sin \theta = c_s / v_R$$
Implications of Supershear Ruptures on Buildings

Building Studied: Existing, steel moment-frame building of the 20-story class

- 3D Finite Element simulations using FRAME3D
- Developed at Caltech by Prof. Swaminathan Krishnan

Swaminathan Krishnan
CE/GPS Caltech

Sub-Rayleigh Earthquake Rupture

Supershear Earthquake Rupture

Existing Building (Woodland Hills), isometric view (designed according to UBC82 provisions)

$T_1 = 4.43s; T_2 = 4.22s; T_3 = 2.47s$
Asymmetric placement of Moment Frames
(Center of resistance and Center of Mass don’t coincide)

Building Studied: Existing steel moment-frame building of the 20-story class

- 3D Finite Element simulations using FRAME3D
- Developed at Caltech by Prof. Swaminathan Krishnan

Existing Building (Woodland Hills), isometric view
(designed according to UBC82 provisions)

\[ T_1 = 4.43s; \ T_2 = 4.22s; \ T_3 = 2.47s \]
Identical Buildings at two near-fault locations subjected to excitation from *Supershear* or *Sub-Rayleigh* ruptures
Implications of Supershear Ruptures on Buildings

Building Studied: Redesigned steel moment-frame building of the 20-story class

- 3D Finite Element simulations using FRAME3D
- Developed at Caltech by Prof. Swaminathan Krishnan

Redesigned Building
(designed according to UBC97 provisions)
$T_1 = 3.72s; T_2 = 3.51s; T_3 = 2.24s$

Sub-Rayleigh Earthquake Rupture

Supershear Earthquake Rupture
Symmetric placement of Moment Frames (Center of resistance and Center of Mass coincide)

Building Studied: Redesigned, Steel moment-frame building of the 20-story class

- 3D Finite Element simulations using FRAME3D
- Developed at Caltech by Prof. Swaminathan Krishnan

Redesigned Building
(designed according to UBC97 provisions)
$T_1 = 3.72s; T_2 = 3.51s; T_3 = 2.24s$

Sub-Rayleigh Earthquake Rupture

Supershear Earthquake Rupture
Identical Buildings at two near-fault locations subjected to excitation from **Supershear** or **Sub-Rayleigh** ruptures
After Scaling, the dominant features of 2002 Denali PS10 record captured by laboratory record
Summary and Conclusions

• We have experimentally shown that:
  – In the stable supershear rupture velocity regime, the FAULT PARALLEL ground motion velocity component DOMINATES over the fault normal component.
  – In the SUB-RAYLEIGH velocity regime, the FAULT NORMAL ground motion component dominates.

• We have explored transitions to super-shear and have identified the unique “one-two punch” effect on ground shaking signatures.

• We also have demonstrated the potentially catastrophic effect of such supershear ruptures on buildings.
ACKNOWLEDGEMENTS

Past and Current Students and Post-Doctoral Scholars

Professor R. Narasimhan       (1986)    IIS, Bangalore, India
Professor X. Deng                (1990)    U. of S. Carolina
Dr.  L. Lu                      (1991)    EDS/Unigraphics
Professor J. Mason              (1993)    U. of Notre Dame
Professor J. Lambros         (1994)    UIUC
Dr. C. Liu                      (1994)    LANL
Professor H.A. Bruck           (1995)    U. Maryland
Dr. Professor K. Fey            (1996)    A.E. Mann Foundation
Dr. J. Hodowany                (1997)    Rosetta Inpharmetics
Professor D. Conner            (1998)    Caltech
Dr. K. Haberman                (2000)    LANL
Professor L.R. Xu              (2001)    Vanderbilt Univ.
Dr.  B. Chow                   (2001)    Rustic Canyon Ventures
Dr. O. Samudrala               (2001)    GE Global Res. Ctr.
Professor K. Xia               (2005)    U. Toronto
Professor G. Lykotrafitis      (2006)    U. of Connecticut
Dr.  M. Brown                  (2006)    NGST
Dr. X. Lu                     (2006)    Intel Corporation
M. Mello                      (2011)    Caltech
J. Mihaly                     (2011)    Caltech
V. Gabuchian                   (2011)    Caltech

Dr.  D. Anderson           GE. Global Res. Ctr.
Dr. H. Bhat                   IPG. France
Dr. F. Benitez               Univ. of Seville, Spain
Prof. V. Chalivendra        U.Mass., Dartmouth
Professor S. Hong            Michigan State Univ.
Dr.  H. Lee                   nLight Photonics
Dr. Y.J. Lee                  Dow Corning
Dr. D. Owen                   Ultratech. Inc.
Dr. T.-S. Park                Novellus
Professor C. Rousseau       U. Rhode Island
Dr. Vito Rubino              Caltech
Dr. O. Samudrala             G.E. Global Res. Ctr.
Professor R. Singh          Stony Brook State Univ.
Professor H. Tippur           Auburn University
Professor M. Zhou            Georgia Tech
Professor V. Eliasson        USC

Office of Naval Research (Y.D.S. Rajapakse, Program Monitor)
National Science Foundation (Geophysics)
ACKNOWLEDGEMENTS

Mentors and Collaborators

Dr. M. Adams
Jet Propulsion Laboratory

Professor F.G. Benitez
University of Seville, Spain

Professor J. Duffy
Brown University

Professor B. Freund
Brown, UIUC

Professor H. Gao
Brown University

Professor H. Georgiadis
National Technical Univ. of Athens, Greece

Professor Y. Huang
Northwestern University

Professor H. Kanamori
Caltech

Professor S. Krishnan
Caltech

Professor N. Lapusta
Caltech

Professor A. Molinari
Metz, France, Caltech

Professor A. Needleman
Brown, U. North Texas

Professor M. Oda
Kagoshima University, Kagoshima, Japan

Professor D. Oglesby
UCR

Professor M. Ortiz
Caltech

Professor K. Papoulia
University of Waterloo, Canada

Professor G. Ravichandran
Caltech

Professor Ravi-Chandar
U. Texas - Austin

Professor J. Rice
Harvard Univ.

Professor D. Rittel
Technion

Professor C. Sammis
USC

Professor D. Semen ski
University of Zagreb, Croatia

Professor A. Shukla
U. Rhode Island

Professor S. Suresh
MIT, NSF

Professor S. Suzuki
Toyohashi University of Technology, Japan

Professor I. Vardoulakis
National Technical Univ. of Athens, Greece