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Pulselike and Cracklike Ruptures in Earthquake Experiments

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Lab experiments that mimic the way the ground moves during destructive earthquakes require some sophisticated equipment, and they yield valuable insights. Caltech scientists studying how sliding motion spreads along a fault interface conducted a series of experiments involving ultrafast digital cameras and high-speed laser velocimeters to replicate a range of realistic fault conditions.

The team documented for the first time a systematic variation in earthquake rupture patterns called pulselike and cracklike ruptures. The experiments also revealed that both types of ruptures can transition to a state known as supershear speed, which generates its own characteristic ground shaking. The results appeared in the November 27 issue of the journal Proceedings of the National Academy of Sciences.

The scientists include Xiao Lu, graduate student in aeronautics; Nadia Lapusta, assistant professor of mechanical engineering and geophysics; and Ares Rosakis, the von Kármán Professor of Aeronautics and Mechanical Engineering and director of the Graduate Aeronautical Laboratories.

Simple theoretical models of earthquake ruptures show they slide like a crack--the entire length of the fault slides for just about as long as the earthquake lasts. But slip models used by seismologists to match records of ground motions from past earthquakes have suggested a different mode of rupture, one that moves like a pulse. A pulse of slip would travel down the length of a fault like a ripple passing over the surface of a pond, with all motion contained in the ripple, and the fault surface "healing" in its wake.

The forces that build up on either side of a fault, known as tectonic loading, can vary greatly and lead to different types of fault slip behavior. "Numerical calculations of earthquake ruptures that use friction laws guided by laboratory experiments produce both crack- and pulselike modes, depending on how loaded the fault is," says Lapusta. "We set out to test the predictions of these calculations in our experimental study." Pulse modes are predicted by calculations where faults are less loaded, but to make a fault slip under these conditions, models have to assume that fault friction decreases as the fault slip gets faster. This behavior, called rate-weakening friction, has been of long-standing interest to Lapusta and to Thomas Heaton, professor of engineering seismology, whose influential work on slip pulses demonstrated their short duration, and who proposed rate-weakening friction as a likely explanation.

The experiments began with a 9.5-millimeter-thick photoelastic plate sliced at an angle through its length, simulating a fault in Earth's crust. Pressure on the two sides of the fault was applied incrementally at an angle to build up the different components of loading. To trigger an earthquake rupture, a nickel wire the diameter of a human hair was embedded in the plate interface and then electrically discharged, creating a small explosion followed by a spontaneously spreading rupture.

Lasers measured the relative movements on each side of the fault after the shock, and a high-speed camera captured the movements in 5-microsecond intervals. The mini-explosions were repeated for various orientations of tectonic loading.

The experimental setup mimics conditions under which very large earthquakes rupture Earth's crust along major strike-slip faults like California's San Andreas fault or the Kunlun fault in northern Tibet. The initial experimental design was devised by Rosakis; Smits Professor of Geophysics, Emeritus Hiroo Kanamori; and their joint graduate student Kaiwen Xia, who is now a professor at the University of Toronto.

The new experimental results support the models that suggest faults can have pulselike ruptures. "This is the first time we observed this spontaneous pulselike rupture in an experiment that mimics crustal earthquakes. We proved its existence," says Lu.

The experiments also documented under what conditions pulselike ruptures arise. When the plate interface was oriented at a 70-degree angle to the direction of compression, the rupture propagated as a narrow pulse. At smaller angles, the pulses got wider, until they transitioned into cracklike sliding modes. These experimental observations demonstrate the role that tectonic loading plays in how earthquakes rupture, and imply that real faults are governed by rate-weakening friction.

Another experimental result is related to earthquake rupture speeds. Calculations since the 1970s have predicted phenomena known as supershear bursts, which would cause destructive, high-frequency ground motions. Rosakis, Kanamori, and Xia have demonstrated such bursts in their experiments in recent years. Supershear bursts were shown to have caused damage during the 1979 Imperial Valley, 1992 Landers, and 1999 Izmit, Turkey, earthquakes.

In the experiment by Lu, Lapusta, and Rosakis, supershear propagation is seen to arise during both pulselike and cracklike earthquake ruptures. "That's new--nobody has seen before that either of those modes could transition to supershear," says Rosakis. Shock waves generated by supershear propagation generate more ground shaking, he adds, and notes that with more details about exactly how earthquakes rupture, scientists can devise more sophisticated ways for buildings to survive the specific types of shaking that arise.

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