

TIME TABLE

TIME	Monday September 6	Tuesday September 7	Wednesday September 8	Thursday September 9	Friday September 10
09.00 - 09.45	Registration	Schrefler	Schrefler	Schrefler	Tao Ni
09.45 - 10.30	Shao	Khoei	Khoei	Khoei	Tao Ni
11.00 - 11.45	Shao	Khoei	Khoei	Khoei	Tao Ni
11.45 - 12.30	Ampuero	Shao	Ampuero	Galvanetto	Tao Ni
14.00 - 14.45	Ampuero	Shao	Ampuero	Galvanetto	
14.45 - 15.30	Svetlizky	Svetlizky	Galvanetto	Ampuero	
16.00 - 16.45	Svetlizky	Svetlizky	Galvanetto	Ampuero	
16.45 - 17.30	-	Poster Session	Galvanetto	Poster Session	
18.00	Welcome aperitif				

ADMISSION AND ACCOMMODATION

The course is offered in a hybrid format, allowing participants the flexibility to attend either in person or remotely via the Microsoft Teams platform. Admission to on-site attendance is granted on a first-come, first-served basis to comply with the capacity of the lecture room.

Registration fees:

- **Early Bird On-Site Participation: € 650.00 + VAT***

Deadline: July 6, 2027

- **Late On-Site Participation: € 800.00 + VAT***

Deadline: August 25, 2027

- **Live Streaming Online Participation: € 250.00 + VAT***

Deadline: August 25, 2027

On-site participation includes a complimentary bag, five fixed menu buffet lunches, hot beverages, downloadable lecture notes.

Online participation includes downloadable lecture notes.

Application forms should be submitted online through the website: <http://www.cism.it>. A confirmation message will be sent to participants whose applications are accepted.

Upon request, and subject to availability, a limited number of on-site participants can be accommodated at the CISM Guest House for € 35 per person per night.

To request accommodation, please contact: foresteria@cism.it

* where applicable; bank charges are not included - Italian VAT is 22%.

CANCELLATION POLICY

Applicants may cancel their registration and receive a full refund by notifying the CISM Secretariat in writing (via email) no later than:

- July 6, 2027, for early bird on-site participation;
- August 6, 2027, for late on-site participation;
- August 25, 2027, for online participation.

No refunds after the deadlines. Cancellation requests received before these deadlines and incorrect payments will be subject to a € 50.00 handling fee.

CISM GRANTS

A limited number of participants from universities and research centers who do not receive support from their institutions can request a waiver of the registration fee and/or free lodging.

Requests must be submitted via the CISM website by **July 6, 2027**. Applicants should select the relevant option in the online application form and provide a curriculum vitae and a letter of recommendation from their department head or supervisor confirming that their institution is unable to provide financial support. Preference will be given to applicants from countries that sponsor CISM.

For further information please contact:

CISM (Seat of the course)
Palazzo del Torso - Piazza Garibaldi 18 - 33100 Udine (Italy)
tel. +39 0432 248511 (6 lines)
e-mail: info@cism.it | www.cism.it

Centre International des Sciences Mécaniques
International Centre for Mechanical Sciences
Ted Bohdan Belytschko Session



FORERUNNING, SUB- AND SUPERSHEAR RUPTURE IN DRY AND FLUID-SATURATED MEDIA

CISM Advanced School
coordinated by

Bernhard A. Schrefler
University of Padua, Italy

Jianfu Shao
Université de Lille, France

Udine September 6 - 10 2027

FORERUNNING, SUB- AND SUPERSHEAR RUPTURE IN DRY AND FLUID-SATURATED MEDIA

This six day advanced course presents recent theoretical and numerical advances in dynamic fracture mechanics, focusing on sub , inter , and supershear rupture in dry and fluid saturated media. Emphasis is placed on mode I tensile fracture, mode II shear rupture, forerunning (mother–daughter crack mechanisms), and the role of poroelastic coupling in accelerating rupture beyond classical wave speed limits. The course integrates theory, experiments, numerical modeling, and geophysical relevance.

Classical fracture mechanics predicts an upper limit for crack speed: Rayleigh for tensile fractures and shear wave speed for shear ruptures. Yet experiments, earthquake observations, and modern simulations show that fractures can exceed these limits, sometimes surpassing even

the compressional wave speed. Supershear ruptures are crucial in earthquake physics because rupture speed controls seismic radiation, ground motion amplification, and Mach cone formation. About 15–20% of large earthquakes ($M_w > 7$) involve supershear rupture, but the mechanisms governing the transition remain incompletely understood, especially in fluid saturated faults.

Mode I fracture is examined first, using FEM, XFEM, phase field, peridynamics, and hybrid FEM/PD models. Tensile cracks can propagate faster than shear and even compressional waves. Numerical results reveal a progressive transition with increasing loading or injection rate: smooth propagation, stepwise advancement, and forerunning, where cracks nucleate ahead of the main tip. Importantly, forerunning

also occurs under subsonic conditions, such as in beams on elastic foundations under sinusoidal loading, showing it is not inherently tied to supersonic motion. In saturated media, increasing injection rates promote transitions from smooth to stepwise to forerunning, highlighting strong coupling between pore pressure diffusion, stress waves, and fracture dynamics. Relevant cases are solved with XFEM, phase field, and a new 2 D hybrid FEM/PD model.

The second part addresses mode II rupture, relevant to earthquakes and dams under seismic loading. The hybrid FEM/PD model (extended to mode II and III) and phase field examples reproduce sub Rayleigh and supershear rupture, Mach cones, and both direct transitions and Burridge–Andrews mother–daughter mechanisms. A key result is that in saturated media, poroelastic

effects near the rupture front strongly favor direct supershear transitions, unlike dry media where both direct and indirect mechanisms occur depending on loading and heterogeneity.

Across both modes, supersonic rupture emerges as a robust outcome of wave–fracture interaction and fluid–solid coupling. Forerunning provides a unifying mechanism for tensile and shear supershear rupture, while the stepwise regime reveals a previously unexplored transitional behavior.

The mechanisms explored here are directly relevant to rupture along fluid rich faults, slab tearing, volcanic tremors, dams under seismic loading, and hydro demolition. Understanding how fluids promote rapid rupture acceleration is essential for seismic hazard assessment and interpretation of high frequency ground motions.

INVITED LECTURERS

Jean-Pau Ampuero - IRD & Université Côte d'Azur, France
6 lectures on: Dynamic earthquake rupture, from slow to supershear earthquakes. Phenomenology of earthquake rupture speeds from seismological observations. Theoretical and simulation results on admissible rupture speeds. Unusual earthquake speeds and proposed models.

Ugo Galvanetto - University of Padua, Italy
6 lectures on: Peridynamics for shear and mixed rupture in saturated media, hydromechanical coupling, PD theory, bond and state based models, numerical implementation, failure criteria, hybrid 2 D FEM/PD modeling, and realistic applications.

Amir Khoei - Sharif University of Technology, Tehran, Iran
6 lectures on: XFEM for hydraulic fracture in heterogeneous reservoirs, covering enrichment functions, variational forms, THM equations, XFEM discretization, fracture propagation, and case study applications.

Bernhard A. Schrefler - University of Padua, Italy
3 lectures on: Dynamic fracturing with FEM, lattice models (mode I and II), forerunning, and hydrodemolition.

Jianfu Shao - Université de Lille, France
4 lectures on: Phase field modelling on shear and mixed rupture in saturated media, covering THM coupling, variational and thermodynamic foundations, crack initiation and propagation, hydromechanical effects, and applications to fault activation and sliding.

Ilya Svetlizky - Technion, Israel Institute of Technology, Haifa, Israel
4 lectures on: Sub-Rayleigh rupture fronts, strain fields and equation of motion - experiments and theory, supershear rupture fronts, and strain fields and equation of motion - experiments, theory, and FEM simulations.

Ni Tao - Chengdu University of Technology, China
4 lectures on: Hydromechanical effects in Mode II shear rupture in dams, covering saturated media fracture, coupled dam–foundation–reservoir response, fluid driven weakening, and multiphysics FEM–peridynamic simulation of rupture initiation and acceleration.

LECTURES

All lectures will be given in English.
Lecture notes can be downloaded from the CISM web site.
Instructions will be sent to accepted participants.

PRELIMINARY SUGGESTED READINGS

Zaccariotto, M., Mudric, T., Tomasi, D., Shojaei, A., Galvanetto, U. (2018). Coupling of FEM meshes with peridynamic grids. *Comput. Methods Appl. Mech. Eng.*, 330, 471–497.
Ni, T., Pesavento, F., Zaccariotto, M., Galvanetto, U., Zhu, Q.-Z., Schrefler, B. A. (2020). Hybrid FEM and peridynamic simulation of hydraulic fracture propagation in saturated porous media. *Comput. Methods Appl. Mech. Eng.*, 366, 113101.

Francfort, G. A., Marigo, J.-J. (1998). Revisiting brittle fracture as an energy minimization problem. *J. Mech. Phys. Solids*, 46, 1319–1342.
Silling, S. A. (2000). Reformulation of elasticity theory for discontinuities and long-range forces. *J. Mech. Phys. Solids*, 48, 175–209.
Buehler, M. J., Gao, H. (2005). A mother–daughter mechanism for mode I dominated cracks: Supersonic crack motion along interfaces of dissimilar materials. *Strength Fract. Complex.*, 3, 105–115.

Shu, Y., Shen, Z., Ni, T., Faccenda, M., Galvanetto, U., Di Toro, G., Schrefler, B. A. (2026). FEM–peridynamic modelling of supershear earthquake ruptures in dry and fluid-saturated media. *J. Geophys. Res. Solid Earth*, 131, e2025JB032981.
Khoei, A. R., Mortazavi, S. M. S., Simoni, L., Schrefler, B. A. (2023). Irregular and stepwise behaviour of hydraulic fracturing: Insights from linear cohesive crack modelling with maximum stress criterion. *Comput. Geotech.*, 161, 105570.

Miehe, C., Welschinger, F., Hofacker, M. (2010). Thermodynamically consistent phase-field models of fracture: Variational principles and multi-field FE implementations. *Int. J. Numer. Methods Eng.*, 83, 1273–1311.
Bourdin, B., Francfort, G. A., Marigo, J.-J. (2000). Numerical experiments in revisited brittle fracture. *J. Mech. Phys. Solids*, 48, 797–826.

Khoei, A. R. (2015). *Extended Finite Element Method: Theory and Applications*. Wiley.