

A CUDA/OpenMP Hybrid Multi-GPU Parallel Computing Framework for Large-scale Phase-field Fracture Simulations

Hanming Yang^a, Chenqi Zou^b, Daniel Morikawa^c, Yiyu Tan^d, Toshiyuki Imamura^e, Xiaofei Hu^f, Shunhua Chen^{a,*}

^aSchool of Ocean Engineering and Technology, Sun Yat-sen University & Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai, People's Republic of China

^bSchool of Mechanics and Aerospace Engineering, Dalian University of Technology, Dalian, People's Republic of China

^cCollege of Civil Engineering, Tongji University, Shanghai, People's Republic of China

^dFaculty of Science and Engineering, Iwate University, Iwate, Japan

^eRIKEN Center for Computational Science, Kobe, Japan

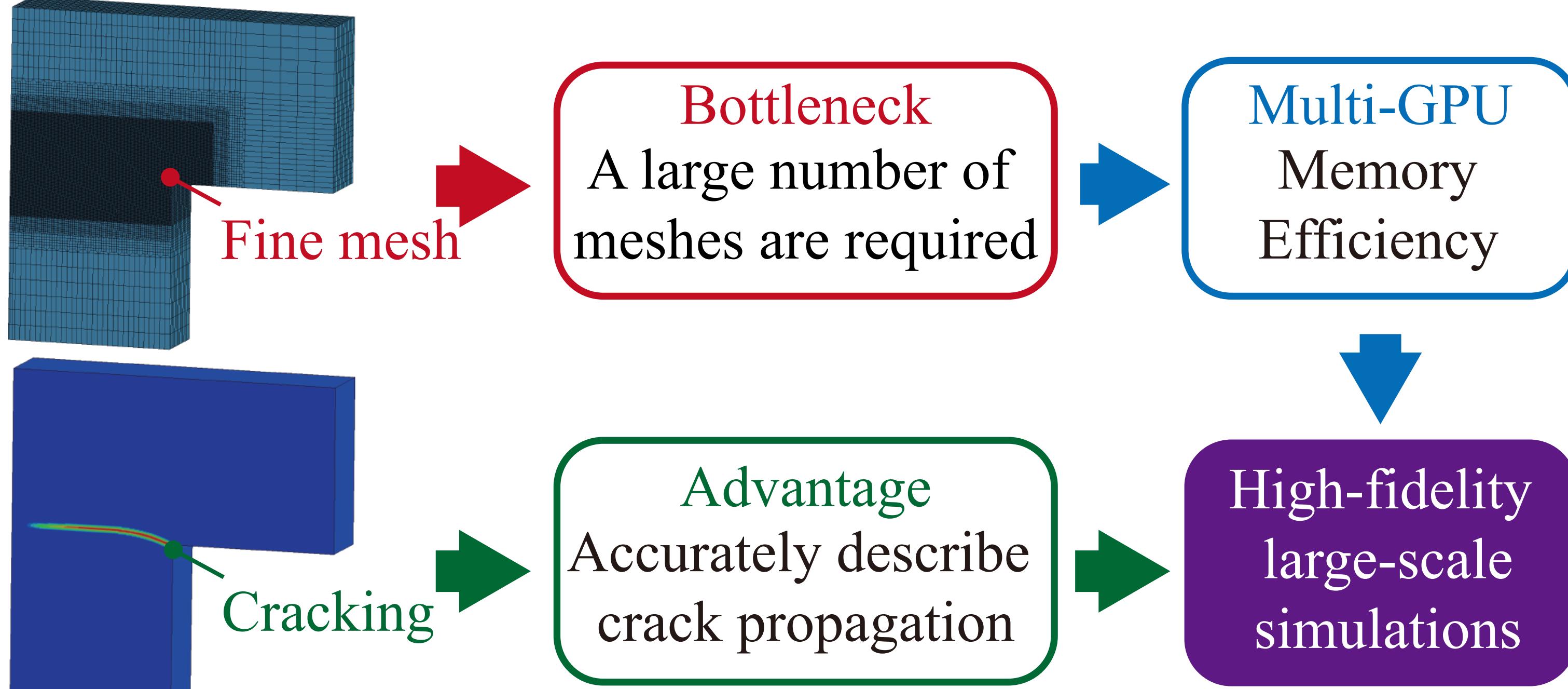
^fState Key Laboratory of Intelligent Construction and Healthy Operation and Maintenance of Deep Underground Engineering, China University of Mining & Technology, Xuzhou, People's Republic of China

Abstract

Phase-field fracture simulations can capture complex crack topologies, but large-scale analyses are still constrained by the intensive computation and memory costs of extremely fine meshes. Prior studies have mainly relied on multi-CPU [1] or single-GPU solvers [2] for large-scale simulations. Here, we develop a dedicated multi-GPU phase-field framework for large-scale fracture simulations. We use a hybrid CUDA/OpenMP model, with GPU-resident phase-field kernels and OpenMP for inherently sequential parts. Simulation results with strong scaling shows a $6.75\times$ speedup on eight GPUs ($\approx 900\times$ vs a single-core CPU baseline). A wind-turbine blade fracture case further demonstrates engineering-scale applicability.

Introduction

Phase-field fracture model



Multi-GPU phase-field framework

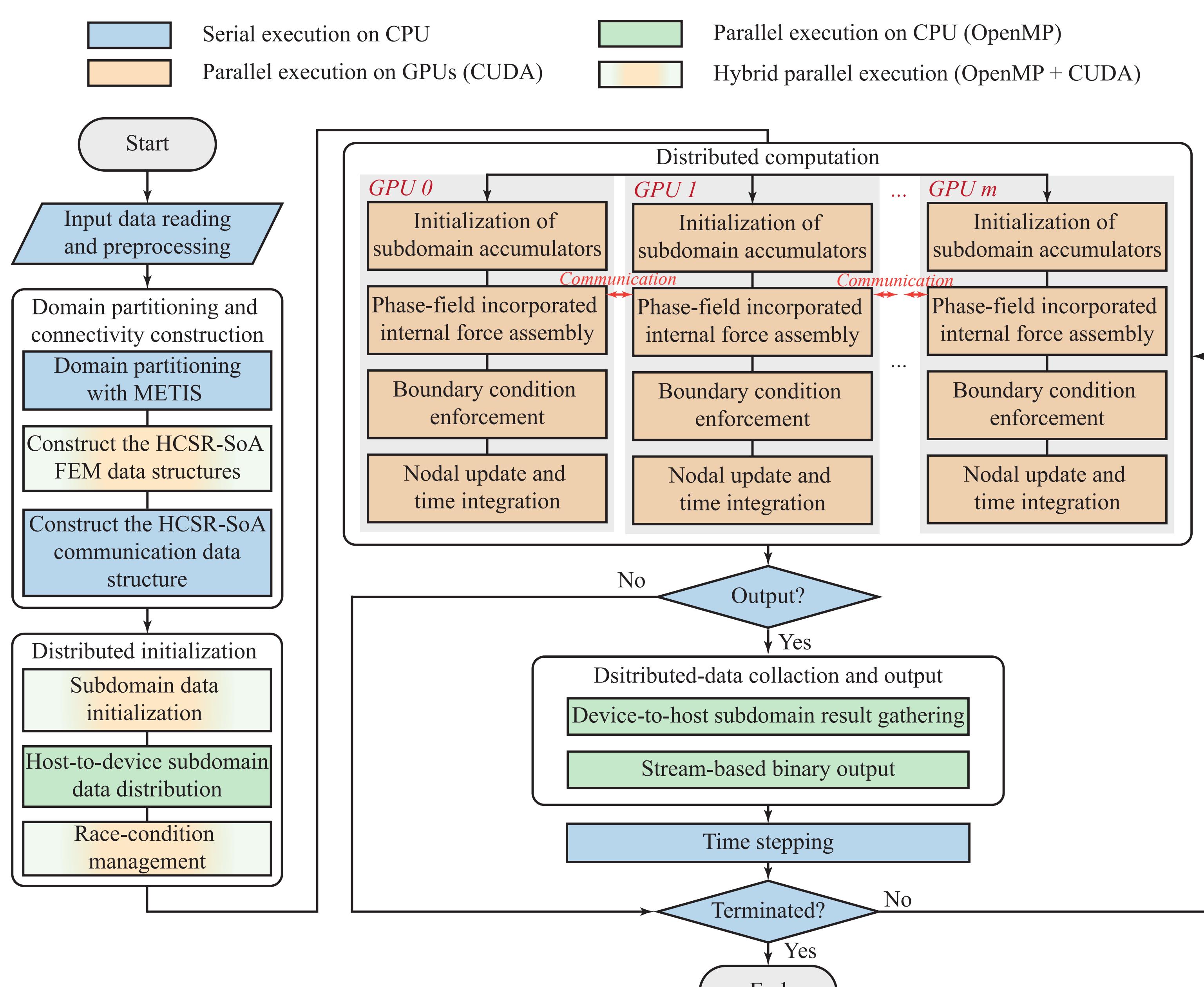


Figure 1: Flowchart of the CUDA/OpenMP hybrid multi-GPU phase-field computational framework.

Performance Evaluation

□ 4×10^7 nodal DOFs, with 8 RTX 3090 GPUs (24GB each).

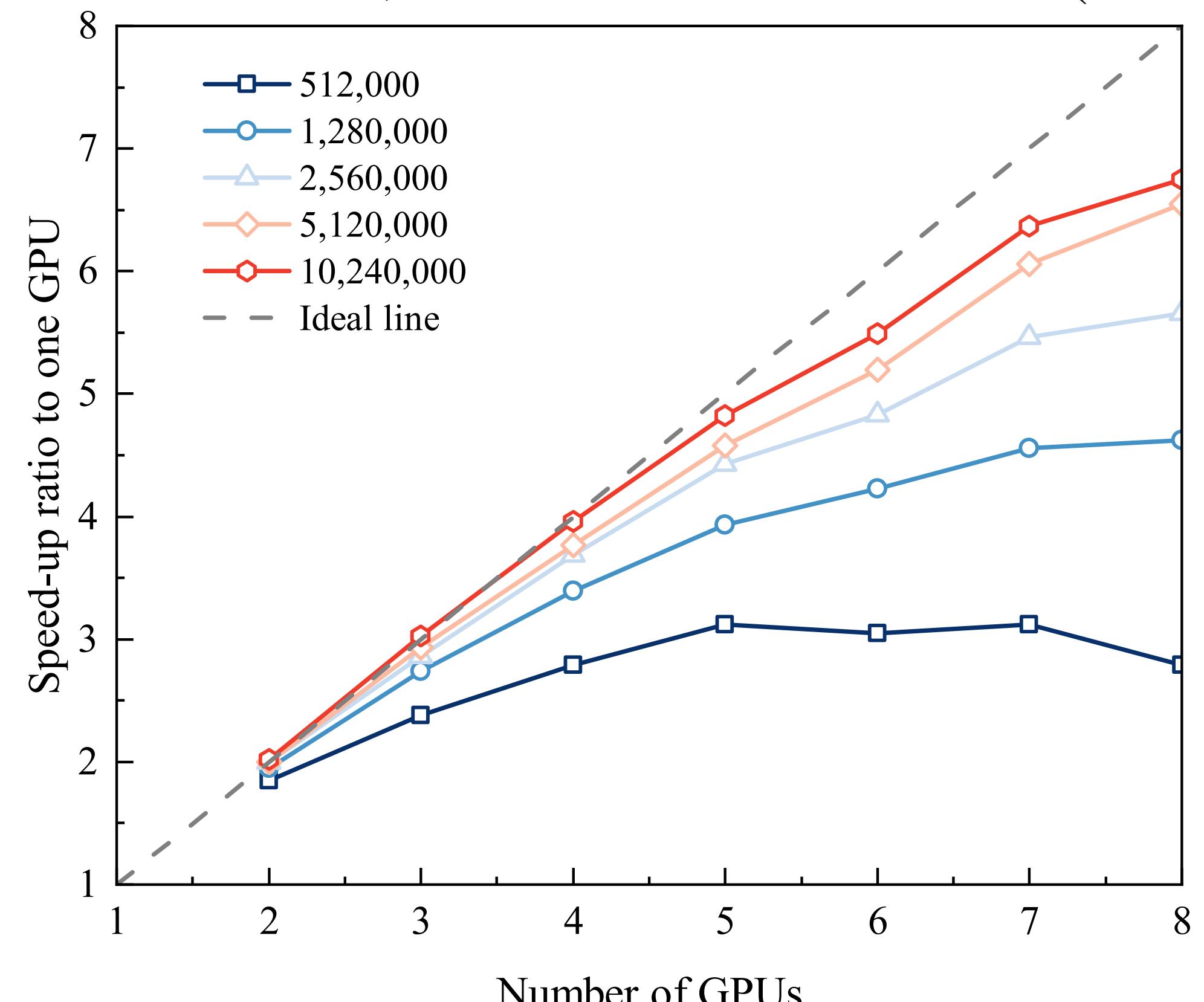


Figure 2: Performance of the framework with strong scaling.

★ Achieves a $6.75\times$ speed-up over a single GPU, which is approximately 900 times relative to the single-core CPU baseline.

□ 3×10^8 nodal DOFs, with 8 A100 GPUs (40 GB each).

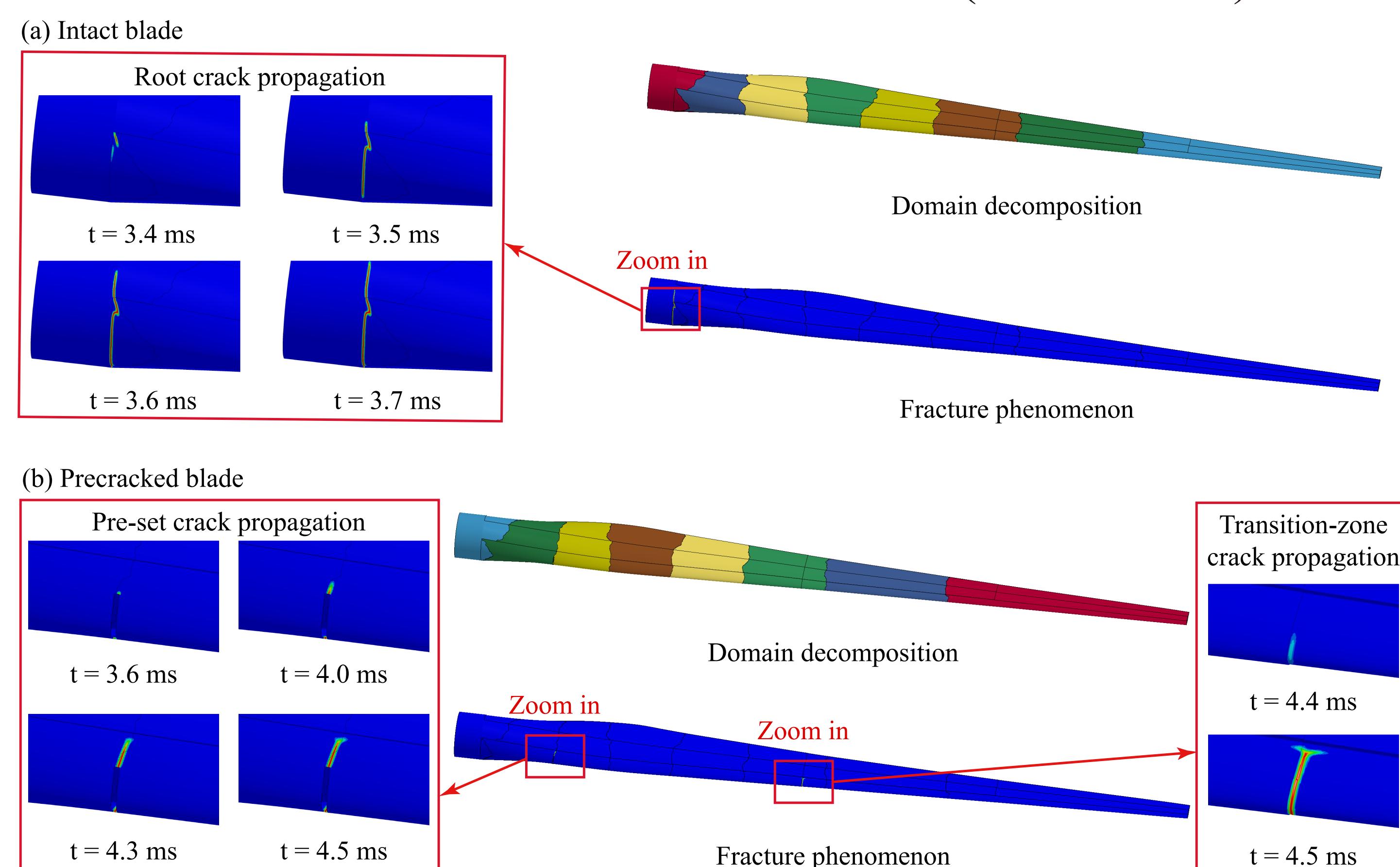


Figure 3: Large-scale wind-turbine blade fracture simulation.

★ Fracture simulations completed in 12 hours.

Conclusion

We present a CUDA/OpenMP hybrid multi-GPU parallel framework for large-scale phase-field fracture simulations. The framework achieves a $6.75\times$ speed-up over a single GPU in the case of number of elements being 10.24 million. For the first time, it enables an engineering-scale fracture simulation of a wind turbine blade with 3×10^8 DOFs.

References

- [1] Z. Chafia, J. Yvonnet, J. Bleyer, S. Vincent, S. El Ouafa, Massively parallel phase field fracture simulations on supercomputers: Towards multi-billion degree-of-freedom computations, *Advanced Modeling and Simulation in Engineering Sciences*, 2024, 11(1): 25.
- [2] V. Ziae Rad, Y. Shen, Massive parallelization of the phase field formulation for crack propagation with time adaptivity, *Computer Methods in Applied Mechanics and Engineering* 312 (2016) 224–253.