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RESEARCH INTERESTS – *Breaking the Code Hidden in the Data of Complex Engineered Systems*

Physics-Based Learning and Characterization of Complex Engineered Systems

- **Micro-scale: Learning physics** from experimental evidence of materials and systems, e.g. energy storage systems (batteries) and biophysical systems (viruses)
- **Macro-scale: System performance and failure prognostics** of complex engineered systems (such as batteries and offshore infrastructures) with data-driven approaches
- **Multiple-scales: Advanced computational models** for high-dimensional systems involving multiple phases, physics, and scales, particularly **physics-informed machine learning algorithms**

Socio-Technological Landscape in Multiphysics and Multiscale Systems

- **Next-generation batteries** with high energy- and power-density, long lifespan, and low risk
- **Battery-Vehicle Integration** and **Lightweight Design** of electric vehicles and electric aircraft
- **Reducing Environmental Impact** (e.g. recycling and second-life applications of Li-ion batteries)

AREAS OF EXPERTISE

Continuum Mechanics

- Solid Mechanics
- Structural Mechanics
- Computational Inelasticity

Material Characterization

- In-situ Micro Testing
- Nano X-ray CT
- Battery Manufacturing and Testing

Electrochemistry

- Porous Electrode Theory
- Thermodynamics
- Mass Transport

Data Science

- Machine Learning
- Inverse Methods
- PDE-Constrained Optimization

EDUCATION

- | | | |
|--------------|--|-----------|
| Ph.D. | Massachusetts Institute of Technology , Mechanical Engineering
Thesis: Mechanical Failure of Lithium-ion Batteries | May 2019 |
| M.S. | Tsinghua University , Mechanical Engineering (Graduation with Top Honor)
Thesis: Modeling the Strain-rate Dependent Yielding and Failure of High Strength Steels | July 2015 |
| B.S. | Tsinghua University , School of Vehicles and Mobility (Graduation with Honor) | July 2012 |

AWARDED GRANTS

- | | | |
|-----|---|--|
| [1] | “Physics-guided Machine Learning Model of Interfaces of Solid-State Energy Storage Systems”
National Aeronautics and Space Administration (NASA)
▪ Leading author of the proposal | Proposed period: 2020-2022
Awarded: \$450k |
| [2] | “New CAE Tools for Batteries”
MIT Industrial Battery Consortium , Phase IV | Funding period: 2020-2022
Awarded: \$1.25M |

Sponsors: Apple, AVL, Hyundai, Murata, Tesla, Toyota, Volkswagen/Porsche

- Technical leader of the research team and co-author of the proposal
- [3] **“Characterization of Next-Generation Batteries to Stabilize Charge-discharge Cycles”**
MIT-Indonesia Seed Fund Funding period: January - December 2020
 ▪ Leading author of the proposal **Awarded: \$20k**
- [4] **“Mechanical Integrity of Electric Vehicle Battery Packs”** Funding period: March 2018-2020
 ▪ **USAID Sustainable Higher Education Research Alliances (SHERA)** **Awarded: \$150k**
- [5] **“Predicting Deformation and Failure of Batteries under Mechanical Abuse”**
MIT Industrial Battery Consortium, Phase III Funding period: 2017-2019
Sponsors: AVL, Jaguar-Land Rover, Mercedes-Benz, Murata, PSA Groupe **Awarded: \$1.04M**
 ▪ Technical leader of the research team during the last year of the phase

OTHER GRANT WRITING EXPERIENCES

- [6] **“A digital twin of all solid-state battery cathodes for integrated design optimization of the fabrication process and microstructures”**
LG Chem Proposed period: May 2021 - April 2023
 ▪ Co-PI of the proposal *Proposal in preparation*
- [7] **“Health and Safety Assessment of Second-life Li-ion Batteries for Reusing of Spent EV Packs”**
MIT Energy Initiative Proposed period: June 2020 - May 2022
 ▪ Leading author of the proposal
- [8] **“Data-driven Safety of Li-ion Batteries and its Implication for the Rapidly-growing EV Market”**
MIT Energy Initiative Proposed period: 2019-2021
- [9] **“Defeating Dendrites through Thermo-Mechanical Treatments of Lithium Metal Anodes”**
Department of Energy (DOE) Proposed period: 2018-2021
- [10] **“Development of Computational Failure Models of Li-ion Batteries subjected to Impact, Explosion and Crash Loading for Military Applications”**
Office of Naval Research Proposed period: 2018-2020

RESEARCH EXPERIENCES

- MIT ● **Executive Director of MIT Industrial Battery Consortium** November 2019 - Present
Sponsors: Apple, AVL, Hyundai, Murata, Tesla, Toyota, Volkswagen/Audi/Porsche
 - **Computational mechanics:** Developed high-efficiency battery models and implemented the large-deformation plasticity and fracture theories into finite element and data-driven codes
 - **Industrial standardization:** Standardized safety-focused battery testing and modeling procedures
 - **Next-generation batteries:** Developed models for Li-metal batteries and all-solid-state batteries
- **Postdoctoral Associate** | Chemical Engineering & Mechanical Engineering July 2019 - Present
Co-supervisors: Martin Z. Bazant & Tomasz Wierzbicki
 - **Electro-chemo-mechanics:** Investigated the coupled electrochemical and mechanical effects of Li-ion batteries and solid-state Li-metal batteries
 - **Multiphase porous electrode theory (MPET):** Introduced the poro-plasticity theory of porous media into the MPET theory to predict the pressure and velocity of liquid electrolyte
 - **Data-driven modeling of complex systems:** Applied machine learning algorithms to analyze the big service-life data for battery health and safety prognostics

- **Physics-informed neural network (PINN):** Developed a PINN framework of elastic plates

● **Research Assistant** at Mechanical Engineering August 2015 - June 2019

Advisor: Tomasz Wierzbicki

- **Large-deformation plasticity:** Experimentally characterized the large deformation of the powder coatings of electrodes and developed continuum mechanical models and discrete particle models
- **Structural mechanics:** Developed theoretical models and numerical models of the multi-layered structure of alternating electrodes and separators of lithium-ion battery cells
- **Instability analysis:** Developed an analytical model of stretch-induced wrinkling of a highly orthotropic thin film (a dry-processed polypropylene separator)

Apple **Battery Analyst** at Battery Product Design Team June - August 2018

- **Battery design tool development:** Developed models for battery product reliability

Ford **Research Engineer** at Material Manufacturing July - August 2016

- **Material characterization:** Ductile fracture of aluminum alloys for manufacturing applications

Tsinghua **Research Assistant** | School of Vehicles and Mobility August 2012 - June 2015
Co-advisors: Yong Xia and Qing Zhou

- **Mechanics of materials:** Proposed a general rate-dependent constitutive model and implemented it as a user subroutine; Studied the effect of flow rules on the plastic strain field and onset of fracture

AWARDS AND HONORS

Most-Watched Video Presentation in “Frontiers in Mechanics of Materials” in the Virtual Technical Meeting of the Society of Engineering Science 2020

Battery Safety Young Researcher Award, Journal of Electrochem. Energy Convers. Storage 2020
Three recipients to recognize the most promising young researchers in the battery safety modeling community

Award for Outstanding Self-finance Students Abroad, the Chinese government 2019
Fifty recipients out of 150,000 Chinese graduate students in the New England Area

Keck Travel Award in Thermal Sciences, MIT Mechanical Engineering 2019

Outstanding Oral Presentation, Society of Automotive Engineer 2018

Top Grade Award, Tsinghua University 2015
The most prestigious honor, ten recipients each year out of 31,500 graduate students

National Fellowship, Tsinghua University 2014
Ranked #1 in School of Vehicles and Mobility

Best Bachelor’s Thesis Award, Tsinghua University 2012

Top Prize of the Challenge Cup, Tsinghua University 2012
Most prestigious scientific competition, ranked #1, leading author of this team honor

TEACHING AND MENTORING EXPERIENCES

MIT ● **Guest Lecturer** February - May 2020

Course: MIT 2.081J. Plates and Shells (Graduate)

Guest Lecture: “Advanced Topics on Plate Buckling”

- Derivation of the Föppl–von Kármán (FvK) equations using energy methods
- Application of FvK equations in an everyday example – stretch-induced wrinkling
- Introduction of more examples in engineering over multiple scales

- **Supervisor of Master Thesis** November 2018 - present
 - **LT Chris Reynolds**. “Generating a large experimental databank of the coupled electrochemical and mechanical effects of Li-ion cells for potential data-driven prognostic application.” Expected in 2021
 - **Tobias Sedlatschek**. “Characterization of the plasticity and fracture behavior of lithium under various stress states with particular emphasis on its microstructural evolution.” 2020
 - **Marco Miguel Koch**. “Testing and modeling the mechanical behavior of lithium-ion pouch cells under in-plane compression.” 2019
- **Supervisor of Bachelor Thesis** May 2020 - present
 - **Zachery W Kutschke**. “Modeling the internal short circuit of lithium-ion battery cells with physics-informed neural network algorithms.” 2020
- **Mentor of Ph.D. students**
 - **Zhexin Pan**, Visiting Ph.D. student, Tsinghua University, 2019-2020
 - **Wei Li**, Visiting Ph.D. student, Tsinghua University, 2018-2019
 - **Hailing Luo**, Visiting Ph.D. student, Tsinghua University, 2017-2018
- **Mentor of MS and undergraduate students**
 - **Rui Luo**, Undergraduate Summer Intern, Tsinghua University, 2019
 - **LT Nathaniel J. Byrd**. Course 2N Master Student, MIT, 2017-2018
 - **Zihao Qin**, Master student, Tsinghua University, 2014-2017
- Tsinghua Teaching Assistant** January - May 2015
 - **Massive Open Online Course (MOOC):** Fundamentals of Automotive Crash Safety
 - Lectures were given in English to international students
- **Teaching Assistant** September 2013 – January 2014
 - **Course:** Impact Dynamics || Laboratory
- **Mentor and Leader of the Formula Students Racecar Team** 2011 - 2013

PUBLICATIONS (= Authors with equal contributions; * Corresponding author.)

I have published 16 journal articles as the first author or corresponding author (4 more in preparation), 2 review articles in major journals (2 more under review), 8 journal articles as a co-author (1 more under review), and 4 conference proceedings.

Journal articles as first author or corresponding author

- [1] **J. Zhu** & M. Z. Bazant, “Learning plastic yield and flow from small experimental data.” *In preparation*.
- [2] **J. Zhu**, W. Li, M. Z. Bazant, “Mechanics of granular-metal multi-layered structures: a semi-analytical model driven by optimization algorithm.” *In preparation*.
- [3] W. Li, M. Z. Bazant, **J. Zhu***, “Physics-informed neural network implementation of a poro-mechanical model for lithium-ion batteries.” *In preparation*.
- [4] T. Wierzbicki*, Y. Liu, W. Li, **J. Zhu***, “Effect of receptors on the resonant and transient harmonic vibration of SARS-CoV-2.” *Journal of the Mechanics and Physics of Solids*. (2021) 150 104369
- [5] W. Li, M. Z. Bazant, **J. Zhu***, “A physics-guided neural network framework of elastic plates: comparison of governing equations-based and energy-based approaches.” (2020) *Submitted to Computer Methods of Applied Mechanics and Engineering*. Under revision. Preprint online: arXiv: 2010.06050.
- [6] T. Sedlatschek, J. Lian, W. Li, M. Jiang, T. Wierzbicki, M. Z. Bazant, **J. Zhu*** “Characterization of the plasticity and fracture behavior of pure lithium under various stress states with particular emphasis on its microstructural evolution.” *Acta Materialia*. (2021) 208 116730

- [7] W. Li & **J. Zhu***, “A large deformation and fracture model of lithium-ion battery cells treated as a homogenized medium.” *Journal of the Electrochemical Society* (2020) 167(12) 120504.
- [8] J. Lian, M. M. Koch, W. Li, T. Wierzbicki, **J. Zhu***, “Mechanical deformation of lithium-ion pouch cells under in-plane loads–Part II: numerical simulation.” *Journal of the Electrochemical Society* (2020) 167(9) 090556
- [9] **J. Zhu***, M. M. Koch, W. Li, T. Wierzbicki, “Mechanical deformation of lithium-ion pouch cells under in-plane loads–Part I: experimental investigation.” *Journal of the Electrochemical Society* (2020) 167(9) 090533
- [10] Z. Pan, **J. Zhu***, H. Xu, T. Sedlatschek, X. Zhang, W. Li, T. Gao, Y. Xia, T. Wierzbicki, “Microstructural deformation patterns of a highly orthotropic polypropylene separator of lithium-ion batteries: Mechanism, model, and theory.” *Extreme Mechanics Letters* (2020) 37 100705
- [11] W. Li[–], **J. Zhu[–]***, Y. Xia, M. Gorji, T. Wierzbicki, “Data-driven safety envelope of lithium-ion batteries for electric vehicles.” *Joule* (2019) 3(11) 1-13
- [12] **J. Zhu[–]***, W. Li[–], T. Wierzbicki, Y. Xia, J. Harding, “Deformation and failure of lithium-ion batteries treated as a discrete layered structure.” *International Journal of Plasticity* (2019) 121 293-311
- [13] **J. Zhu***, H. Luo, W. Li, T. Gao, Y. Xia, T. Wierzbicki, “Mechanism of strengthening of battery resistance under dynamic loading.” *International Journal of Impact Engineering* (2019) 131 78-84
- [14] **J. Zhu**, T. Wierzbicki, K. Pack, S. Roggeband, “Characterization of the cyclic loading in the tube expansion process.” *International Journal of Mechanical Sciences* (2019) 150 112-126
- [15] **J. Zhu[–]***, W. Li[–], Y. Xia, E. Sahraei, “Testing and modeling the mechanical properties of the granular materials of graphite anode.” *Journal of the Electrochemical Society* (2018) 165(5) A1160-A1168
- [16] **J. Zhu***, X. Zhang, H Luo, E. Sahraei, “Investigation of the deformation mechanisms of lithium-ion battery components using in-situ micro tests.” *Applied Energy* (2018) 224 251-266
- [17] **J. Zhu***, X. Zhang, T Wierzbicki, “Stretch-induced wrinkling of highly orthotropic thin films.” *International Journal of Solids and Structures* (2018) 139-140 238-249
- [18] **J. Zhu**, X. Zhang, E. Sahraei, T Wierzbicki, “Deformation and failure mechanisms of 18650 battery cells under axial compression.” *Journal of Power Sources* (2016) 336 332-340
- [19] **J. Zhu**, Y. Xia, Q. Zhou, T Wierzbicki, “A rate-dependent model for metals based on a master curve of normalized hardening behavior of DP steels.” *Journal of Dynamic Behavior of Materials* (2016) 2(2)
- [20] **J. Zhu**, Y. Xia, H. Luo, G. Gu, Q. Zhou, “Influence of flow rule and calibration approach on plasticity characterization of DP780 steel sheets using Hill48 model.” *International Journal of Mechanical Sciences* (2019) 150 112-126

Review and Perspective articles in major journals

- [21] H. Xu, **J. Zhu**, D. Finegan, X. Lu, P. Shearing, M. Z. Bazant. “Learning and designing heterogeneous microstructures for Li-ion battery applications: microscopic imaging, predictive modeling, and machine learning.” (2020) Invited review article by *Advanced Energy Materials*, under review.
- [22] **J. Zhu[–]**, I. Mathews[–], D. Cogswell, B. Xing, T. Sedlatschek, W. Li, N. Kantareddy, M. Z. Bazant, T. Wierzbicki, “Retired electric vehicles: end-of-life or a second life?” (2020) *Joule*. Under Review
- [23] D. Finegan, **J. Zhu**, X. Feng, M. Keyser, W. Li, M. Z. Bazant, S. J. Cooper, “The application of data-driven methods and physics-based learning for improving battery safety.” *Joule*. In press
- [24] **J. Zhu**, T Wierzbicki, W. Li, “A review of safety-focused mechanical modeling of commercial lithium-ion batteries.” *Journal of Power Sources* (2018) 378 153-168

Co-authored journal articles

- [25] T. Tancogne-Dejean, M. Gorji Bandpay, **J. Zhu**, D. Mohr, “Recurrent Neural Network Plasticity Model of Lithium-ion Battery Cells.” *International Journal of Plasticity*. Under review
- [26] J. Lian, T. Wierzbicki, **J. Zhu**, W. Li, “Prediction of shear crack formation of Lithium-ion batteries under rod indentation: Comparison of seven failure criteria.” *Engineering Fracture Mechanics* (2019) 217 106520
- [27] W. Li, Y. Xia, **J. Zhu**, H. Luo, “SOC-dependence of the mechanical behavior of lithium-ion batteries: a result of internal stress.” *Journal of the Electrochemical Society* (2018) 165(7) A1537-A1546
- [28] S.H. Chung, T. Tancogne-Dejean, **J. Zhu**, H. Luo, T. Wierzbicki, “Failure in lithium-ion batteries under transverse indentation loading.” *Journal of Power Sources* (2018) 389 148-159
- [29] H. Luo, **J. Zhu**, E. Sahraei, Y. Xia, “Adhesion strength of the cathode in lithium-ion batteries under combined tension/shear loadings.” *RSC Advances* (2018) 8(8) 3996-4005
- [30] X. Zhang, **J. Zhu**, E. Sahraei, “Degradation of battery separators under charge–discharge cycles.” *RSC Advances* (2017) 7(88) 56099-56107
- [31] Z. Qin, **J. Zhu**, W. Li, Y. Xia, Q. Zhou, “System ringing in impact test triggered by upper-and-lower yield points of materials.” *International Journal of Impact Engineering* (2017) 108 295-302
- [32] Y. Xia, **J. Zhu**, K. Wang, Q. Zhou, “Design and verification of a strain gauge-based load sensor for medium-speed dynamic tests with a hydraulic test machine.” *International Journal of Impact Engineering* (2016) 88 139-152
- [33] Y. Xia, **J. Zhu**, Q. Zhou, “Verification of a multiple-machine program for material testing from quasi-static to high strain-rate.” *International Journal of Impact Engineering* (2015) 86 284-294

Conference proceedings

- [34] **J. Zhu***, X. Zhang, T. Wierzbicki, G. Chen, Y. Xia, “Structural designs for electric vehicle battery pack against ground impact.” *SAE Technical Papers* (2018)
- [35] Z. Qin, **J. Zhu**, W. Li, Y. Xia, Q. Zhou, “Experimental and numerical analysis of the system ringing in intermediate strain rate tests.” *ASME International Mechanical Eng. Congress & Exposition* (2016) 9
- [36] W. Li, **J. Zhu**, Y. Xia, Q. Zhou, “Testing and modeling the effect of strain-rate on plastic anisotropy for a traditional high strength steel.” *ASME International Mechanical Eng. Congress & Exposition* (2015)
- [37] **J. Zhu**, Y. Xia, G. Gu, Q. Zhou, “Extension of non-associated Hill48 model for characterizing dynamic mechanical behavior of a typical high-strength steel sheet.” *ASME International Mechanical Eng. Congress & Exposition* (2014) 9 V009T12A097-V009T12A097

PRESENTATIONS (* Invited talks)

- [1*] “Electro-Chemo-Mechanics of Li-ion Batteries: from Physics-based to Data-Driven.”. *TAMU OCEAN Engineering Seminars*. Virtual seminar, 2021
- [2*] “Electro-Chemo-Mechanics of Li-ion Batteries: from Physics-based to Data-Driven.”. *Machine Learning of Batteries Workshop by National Renewable Energy Laboratory*, Virtual seminar, 2021
- [3*] “Safety modeling of Li-ion batteries: from physics-based to data-driven.” 2021 *MRS Spring Meeting & Exhibit*. Invited to be presented in Seattle, Washington
- [4] “Physics-guided machine learning model of Li-ion battery systems involving multiple scales, physics, and phases.” *2020 Virtual MRS Spring/Fall Meeting & Exhibit*.
- [5*] “A physic-guided machine learning framework for elastic plates and shells.” *Engineering and Applied Science Forum*, Virtual webinar. 2020

- [6] “Large-deformation plasticity and fracture behavior of pure lithium under various stress states.” *57th Annual Technical Meeting of the Society of Engineering Science*, Virtual Conference, 2020
- [7*] “Decoupled modeling of the mechanics and electrochemistry of batteries.” *Automotive Battery Safety Conference*, Virtual Conference. 2020
- [8] “Mechanism of strengthening of battery resistance under dynamic loading.” *56th Annual Technical Meeting of the Society of Engineering Science*, Washington University, St. Louis, MO, USA. 2019
- [9] “Recent progress of mechanical modeling program of lithium-ion batteries at ICL-MIT.” *ASME International Mechanical Engineering Congress & Exposition*. Pittsburgh, PA, USA 2018
- [10] “Modeling the granular/metal multi-layered structure of lithium-ion batteries.” *18th U.S. National Congress for Theoretical and Applied Mechanics*, Chicago, IL, USA 2018
- [11] “Failure in lithium-ion batteries under transverse indentation loading.” *ASME International Mechanical Engineering Congress & Exposition*. Tampa, FL, USA. 2017
- [12] “Stretch-induced Wrinkling of a Highly orthotropic thin film.” *The 54th Annual Technical Meeting of the Society of Engineering Science*. Northeastern University, Boston, MA, USA. 2017
- [13] “Deformation and failure mechanisms of 18650 battery cells under axial compression.” *ASME International Mechanical Engineering Congress & Exposition*. Phoenix, AZ, USA. 2016

ISSUED PATENTS

- [1] Y. Xia, X. Lai, L. Ma, S. Lin, L. Zeng, **J. Zhu**, L. Wang, Q. Zhou, “A force sensor for tension tests”. Chinese patent for invention. ZL 2013 1 0435523.4. 01-15-2014.
- [2] J. Zhang, X. Yang, C. Ma, S. Xu, **J. Zhu**, Z. Yang. “Turnover-style integrated Child Safety Seat”. Chinese patent for invention. ZL 2012 1 0052308.1. 03-01-2012.

ACADEMIC COMMUNITY SERVICE

Conference Organizer

- Symposium of “Mechanical Failure of Lithium-ion Batteries: from Materials to Structures” in **International Congress on Fracture (ICF15) 2022** (delayed) To be held in Atlanta, GA, U.S.
- **Six Consecutive Meetings of the Battery Consortium.** **1)** June 19, 2018, Coventry, Jaguar-Land Rover, UK; **2)** November 9, 2018, MIT, Cambridge, MA, U.S.; **3)** June 20, 2019, Eco Polytechnics, Paris, France. **4)** November 12-13, 2019, MIT, Cambridge, MA, U.S.; **5)** June 18, 2020, virtual meeting; **6)** November 20, 2020, virtual meeting
- **Symposium of Impact Mechanics and Crash Protection**, 2017. Beijing, China.

Journal Reviewer

Mechanics- & physics-related

- International Journal of Solids and Structures
- Mechanics of Materials
- Experimental Mechanics
- International Journal of Plasticity
- International Journal of Impact Engineering
- Journal of the Mechanical Behavior of Biomedical Materials
- Engineering Fracture Analysis
- SN Applied Sciences

Energy & Electrochemistry-related

- Joule
- Advanced Materials
- Advanced Energy Materials
- Applied Energy
- Energy Technology
- Acta Materialia
- Journal of Power Sources
- Journal of Energy Storage
- Energy Storage Materials
- Journal of the Electrochemical Society
- Journal of Electrochemical Energy Conversion and Storage
- Current Opinion in Electrochemistry