

A Physics-Based Microscale Framework for Predicting Vibration-Induced Degradation in Lithium-Ion Batteries

How does vibration reshape a lithium-ion battery from within? This coupled COMSOL model reveals how mechanical loading effect on the carbon-binder network, alters porosity and tortuosity, disrupts ionic and electronic transport, and ultimately affects battery performance.

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Abstract

Mechanical vibrations can accelerate lithium-ion battery degradation by altering electrode microstructure and electrochemical transport. This study presents a physics-based microscale framework linking vibration-induced mechanical damage with electrochemical behaviour in porous electrodes. Cyclic vibration generates stress concentrations that promote particle fracture, carbon binder domain debonding, and electrical contact loss. These changes modify porosity and tortuosity, reduce effective ionic and electronic conductivity, and cause non-uniform current distribution and

increased polarization. The resulting overpotential accelerates solid electrolyte interphase rupture and reformation, lithium inventory loss, impedance growth, and active material isolation. Under severe transport limitations, lithium plating and non-uniform deposition may further accelerate capacity degradation and increase safety risks. The framework establishes a mechanistic connection between vibration-induced microscale damage and battery ageing, supporting predictive degradation modelling, vibration-resilient electrode design, and advanced battery management systems.

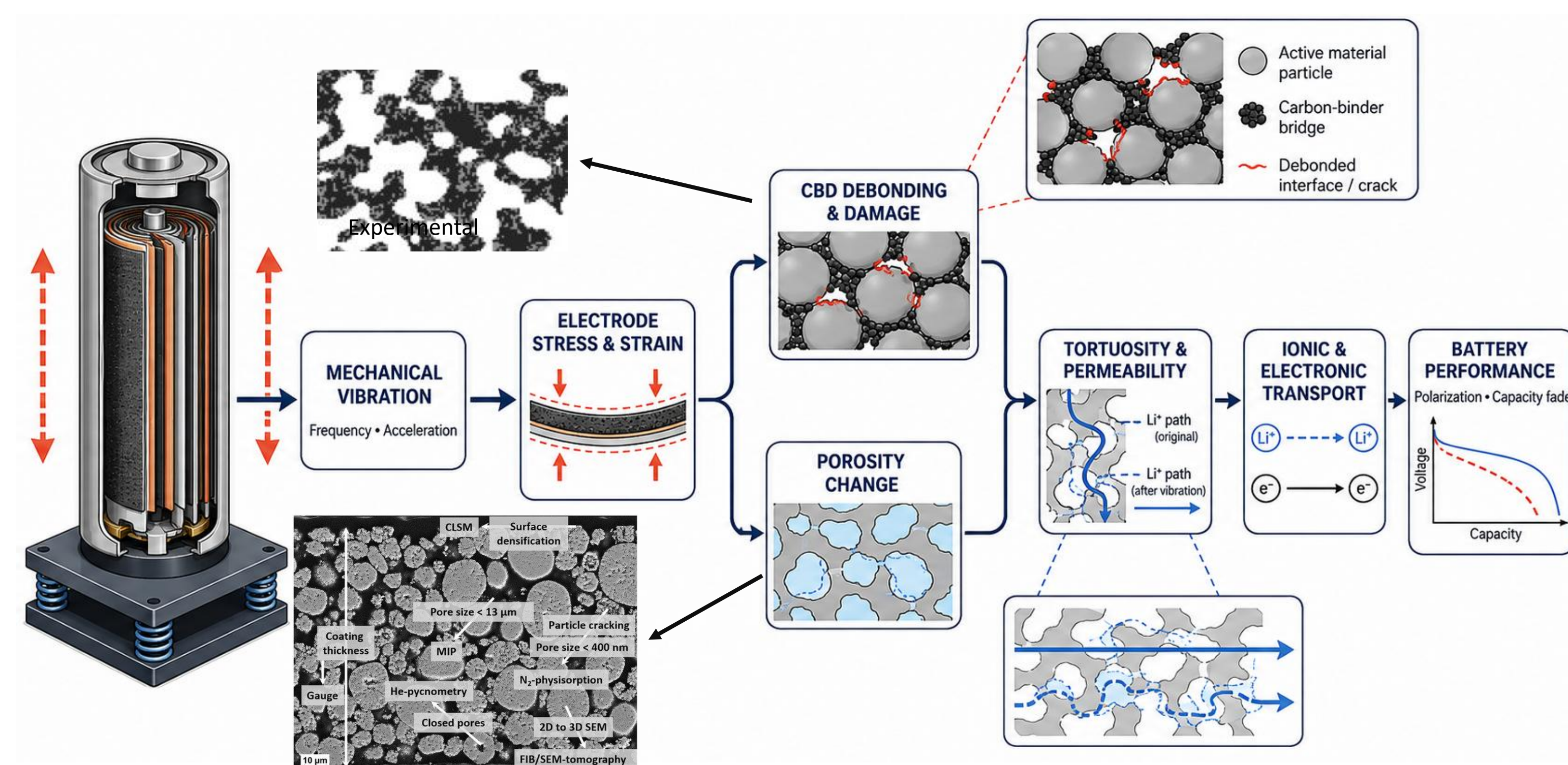


FIGURE 1. Schematic representation of vibration-induced microstructural and transport degradation in a lithium-ion battery. Mechanical vibration, defined by its frequency and acceleration, generates cyclic stress and strain within the electrode layers. Repeated deformation promotes carbon-binder domain (CBD) debonding, interfacial cracking, and changes in electrode porosity.

Methodology

Model component	Governing equation(s)
Vibration-induced total stress	$\sigma_{\text{total}}(r, t) = \sigma_t(r, t) + \frac{mu_0(2\pi f)^2}{A_{\text{surf}}} \sin(2\pi f t)$
Diffusion-induced tangential stress	$\sigma_t(r, t) = \frac{E\Omega}{3(1-\nu)} \left[\frac{2}{R_s^3} \int_0^{R_s} c_s(\rho, t) \rho^2 d\rho + \frac{1}{r^3} \int_0^r c_s(\rho, t) \rho^2 d\rho - c_s(r, t) \right]$
CBD damage	$\frac{\partial D}{\partial t} = k_d \left(\frac{E_v}{E_c} \right)^n (1-D), \quad 0 \leq D \leq 1$ $E_v(x, t) = \int_0^t \max[P_v(x, t), 0] dt$
Porosity including damage/cracking	$\varepsilon_e = \min \left[\varepsilon_{\text{max}}, \max \left(\varepsilon_{\text{min}}, 1 - \frac{1 - \varepsilon_{e,0}}{J} + \varepsilon_{\text{cr,max}} D \right) \right]$
Tortuosity	$\tau = \tau_0 \left(\frac{\varepsilon_e}{\varepsilon_{e,0}} \right)^{1-b} (1 + \beta_D D)$
Effective electrolyte diffusivity	$D_{e,\text{eff}} = D_e \frac{\varepsilon_e}{\tau}$
Effective ionic conductivity	$\kappa_{e,\text{eff}} = \kappa_e \frac{\varepsilon_e}{\tau}$
Effective solid conductivity	$\sigma_{s,\text{eff}} = \sigma_{s,\text{eff},0} (1-D)^m$

Results

The results demonstrate that mechanical vibration can alter electrode porosity, increase tortuosity, and progressively damage the carbon-binder domain network. These microstructural changes disrupt continuous transport pathways, reduce effective ionic diffusivity and electronic conductivity, and increase electrochemical polarization, thereby influencing cell voltage, temperature, and overall battery performance. Under the assumed loading conditions, higher vibration frequency produces greater transport-path disruption and more pronounced degradation of the electrode structure.

The coupled COMSOL model successfully connects mechanical loading, heat generation, electrode deformation, CBD damage, evolving transport properties, and electrochemical response within a unified computational framework. It therefore provides a useful platform for understanding vibration-induced degradation and supporting the design of safer, more durable, and vibration resistant lithium-ion batteries.

Conclusion

The coupled COMSOL model links vibration-induced stress with CBD damage and evolving electrode porosity and tortuosity. These changes influence effective ionic and electronic transport, potentially increasing polarization and affecting battery performance. The framework therefore provides a mechanistic basis for assessing how mechanical loading interacts with electrochemical and thermal behaviour.

References

- [1] F. L. E. Usseglio-Viretta *et al.*, "Resolving the discrepancy in tortuosity factor estimation for Li-ion battery electrodes through micro-macro modeling and experiment," *Journal of The Electrochemical Society*, vol. 165, no. 14, pp. A3403–A3426, 2018, doi: [10.1149/2.0731814jes](https://doi.org/10.1149/2.0731814jes)
- [2] G. Blanco, M. Alberghini, A. Bertinetti, and A. Tommasi, "Electrochemomechanical simulations of 3D-resolved solid-state lithium battery cells," presented at the COMSOL Conference 2023, Munich, Germany, Oct. 25, 2023. [Online]. Available: [COMSOL](https://www.comsol.com/conference).
- [3] Beuse, T., Fingerle, M., Wagner, C., Winter, M., & Börner, M. (2021). Comprehensive Insights into the Porosity of Lithium-Ion Battery Electrodes: A Comparative Study on Positive Electrodes Based on LiNi0.6Mn0.2Co0.2O2 (NMC622). *Batteries*, 7(4), 70.

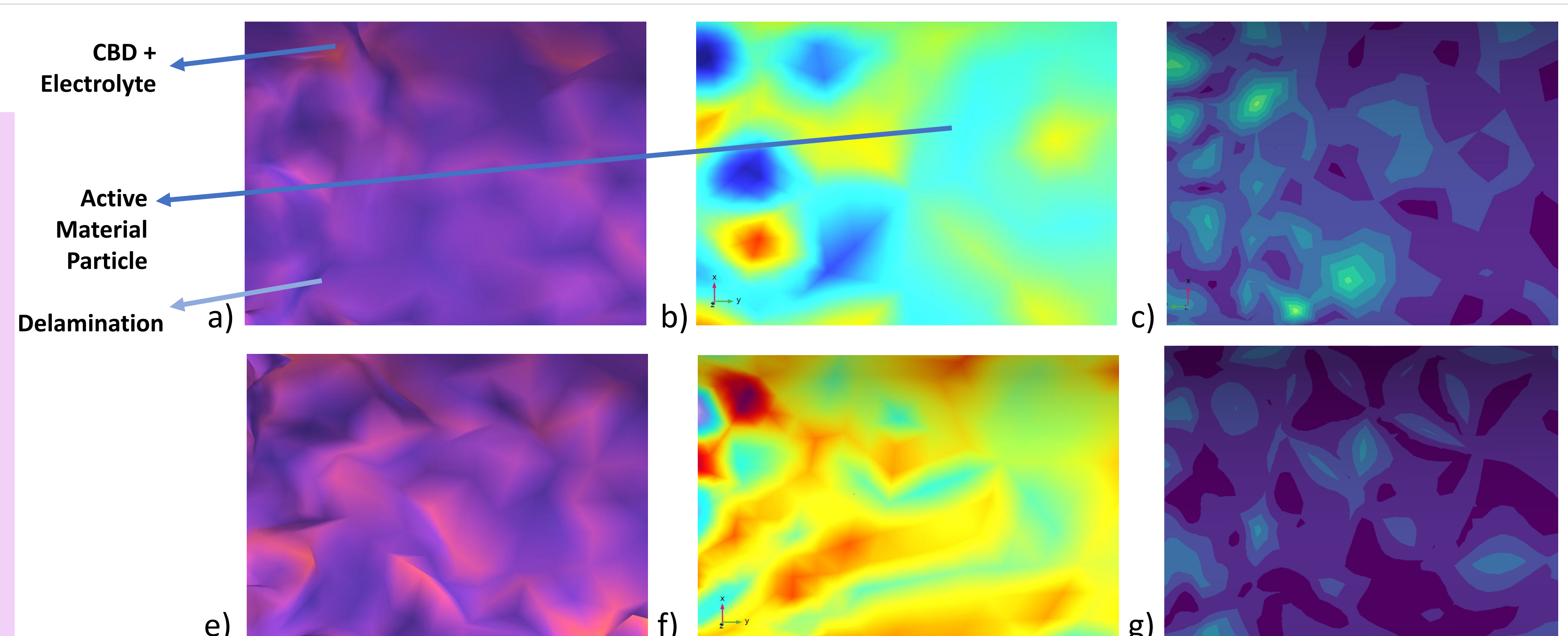


FIGURE 2. Microscale behavior of Negative electrode 50Hz, 1g vibration a) CBD damage b) Effective Transport c) tortuosity. Microscale behavior of Negative electrode 50Hz, 2g vibration d) CBD damage e) Effective Transport f) tortuosity

