



Review

Cell and interface design strategies for low-pressure operation of solid-state batteries

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ARTICLE INFO

Article history:

Received 15 June 2026

Revised 30 July 2026

Accepted 15 August 2026

Keywords:

Solid-state batteries

Low-pressure operation

Interfacial engineering

Pressure management

ABSTRACT

Solid-state batteries (SSBs) are promising next-generation energy-storage systems because of their potential for improved safety and high energy density. However, their practical implementation remains limited by the strong dependence of electrochemical performance on externally applied stack pressure. Although high stack pressure can improve solid–solid interfacial contact and suppress degradation, it also imposes mechanical, manufacturing, and system-level constraints that are incompatible with practical cell and module designs. This review focuses specifically on the low-pressure operation of lithium-metal-based SSBs—defined here as operation under stack pressures of ≤ 2 MPa—by first examining the electrochemo-mechanical failure modes caused by insufficient mechanical confinement, including cathode-side contact loss and transport heterogeneity, anode-side void formation and current localization, and filament-mediated short-circuiting. Recent cathode, anode, anode-less, and cell-level pressure management strategies are then summarized to clarify how contact retention, transport robustness, Li deposition regulation, and pressure homogenization can reduce the need for high external compression. Finally, future research directions are suggested, including standardized low-pressure benchmarking, operando chemo-mechanical diagnostics, and scalable cell architectures, emphasizing that low-pressure operability should be regarded as a primary design criterion for practical SSBs.

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1. Introduction

Solid-state batteries (SSBs) have attracted considerable attention as next-generation energy storage systems because they offer a pathway toward higher energy density and improved safety compared with conventional lithium-ion batteries (LIBs). Replacing flammable liquid electrolytes with solid electrolytes (SEs) enables the use of lithium metal anodes and more compact cell architectures, both of which are advantageous for enhancing cell-level energy density. Among candidate anode materials, Li metal is widely regarded as the most relevant choice for realizing high energy SSBs because of its exceptionally high theoretical specific capacity (3860 mA h g^{-1}) and low electrochemical potential (-3.04 V vs. SHE , standard hydrogen electrode). Nevertheless, practical operation of Li-metal-based SSBs remains challenging. One of the most critical issues is the strong dependence of electrochemical

performance on externally applied stack pressure, which directly affects interfacial contact, Li plating/stripping behavior, and mechanical stability during cycling [1–7]. Accordingly, this review focuses primarily on Li-metal-based SSBs, particularly in the discussion of anode-side failure mechanisms and interfacial design strategies. However, selected studies employing non-Li-metal counter electrodes are also included when their main contribution lies in cathode-side contact retention and electrolyte–electrode interfacial stabilization, because these strategies provide transferable insight into low-pressure Li-metal-based SSB design.

In the fabrication and operation of SSBs, two distinct forms of mechanical pressure must be considered: fabrication pressure and operating stack pressure. Although complementary, these pressures play fundamentally different roles in determining the contact state within the cell. Fabrication pressure is typically applied during cell assembly, often exceeding 300 MPa, to densify SE pellets and composite electrodes, reduce bulk porosity, and establish grain-to-grain contact within the electrolyte structure as well as contact between active materials and the SE. Importantly, high-pressure fabrication can induce “mechanical welding”

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or interfacial consolidation at solid–solid interfaces, enabling subsequent electrochemical cycling under substantially lower stack pressures (≤ 20 MPa). In contrast, the stack pressure applied during operation acts as a restorative mechanical constraint that maintains these pre-established interfaces and suppresses void formation arising from electrochemically induced volume changes [8–10] (Fig. 1a, b). Without sufficient interfacial consolidation during fabrication, low-pressure operation would be constrained by an inadequate initial contact state.

In many laboratory-scale studies, high stack pressure is employed to stabilize solid–solid interfaces and compensate for the limited point-to-point contact arising from the rigidity of solid components. Mechanical compression increases the real contact area between electrodes and SEs, suppresses interfacial void formation during Li stripping, and lowers interfacial resistance. As a

result, elevated stack pressure often leads to improved apparent electrochemical performance, including higher critical current density (CCD), enhanced cycling stability, and reduced polarization [11]. However, these improvements often arise substantially from externally imposed mechanical constraint rather than from intrinsically stable interfacial chemistry or mechanically robust electrode–electrolyte architectures.

The reliance on high stack pressure presents significant barriers to practical implementation. Sustaining high pressure requires additional mechanical reinforcement structures, such as rigid frames, springs, or external fixtures, which increase system weight and volume and thereby reduce gravimetric and volumetric energy densities at the cell and pack levels. High-pressure operation also increases manufacturing complexity and cost, while introducing engineering challenges such as pressure inhomogeneity across

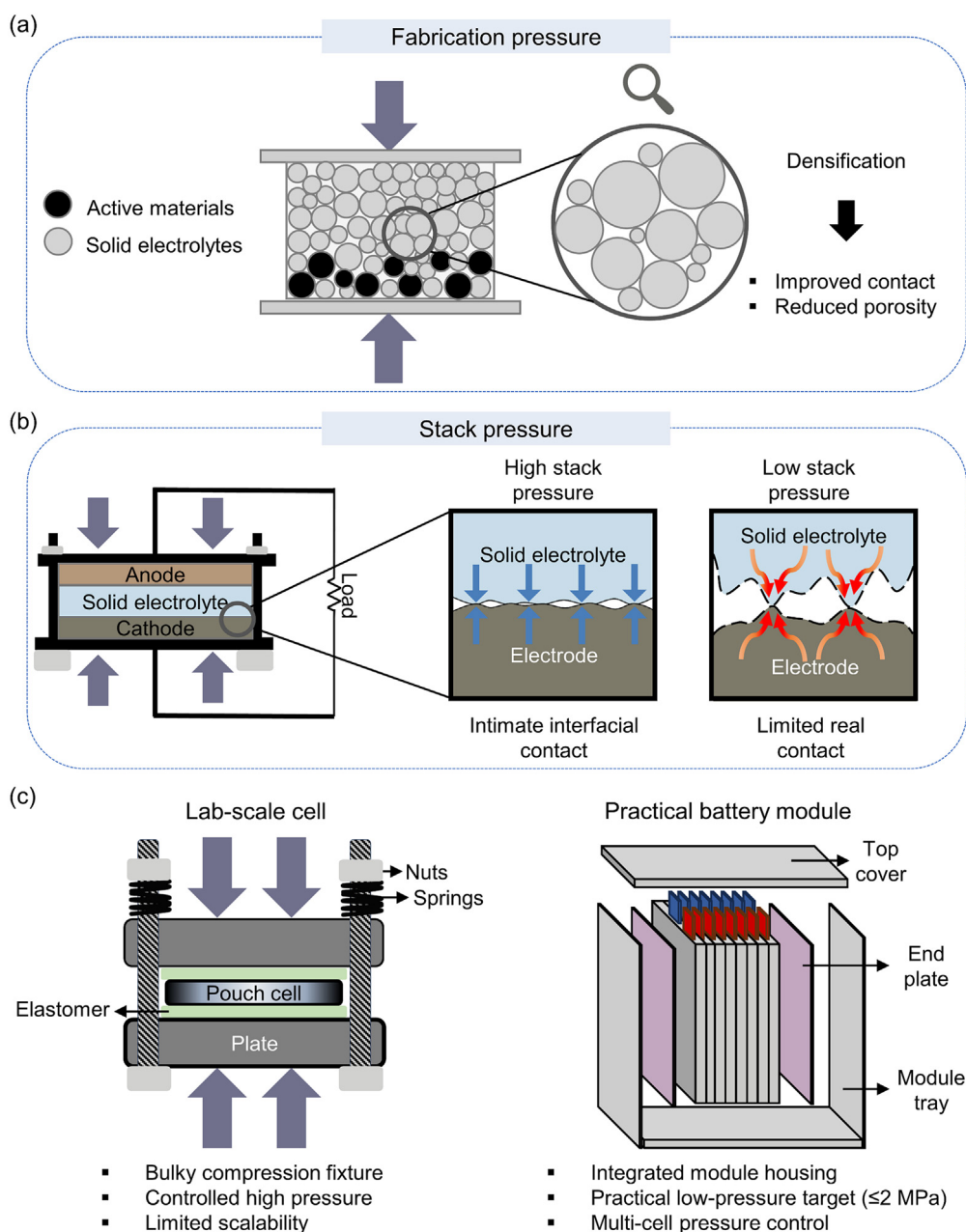


Fig. 1. Schematic illustration of fabrication pressure, operating stack pressure, and module-level pressure constraints in SSBs. (a) Densification and initial solid–solid contact formation under fabrication pressure. (b) Maintenance of electrode–SE interfacial contact under stack pressure, contrasting intimate contact at high pressure with limited real contact at low pressure. (c) Comparison between laboratory-scale cells with high-pressure fixtures and practical battery modules requiring integrated multi-cell pressure management to achieve a practical low-pressure target of ≤ 2 MPa.

large-format cells and long-term mechanical fatigue of structural components [12]. Excessive stack pressure can also lead to undesirable electrochemical and mechanical consequences, including accelerated Li penetration through SEs, microstructural damage within brittle electrolyte frameworks, and internal short circuits. At the pack level, maintaining uniform pressure distribution across multiple cells becomes increasingly difficult, leading to uneven mechanical loading and heterogeneous electrochemical behavior. For these reasons, stable operation under low stack pressure is a key requirement for SSB commercialization. As illustrated in Fig. 1c, this requirement becomes particularly important when transitioning from laboratory-scale cells, in which bulky external fixtures can be used freely, to practical modules, in which pressure must be maintained by integrated housing components. In practical module and pack configurations, uniformly maintainable pressure is typically limited to a few MPa, often ≤ 2 MPa, unless additional reinforcement structures are used [13–15]. Enabling reliable electrochemical performance within this pressure range therefore represents a fundamental design challenge for SSB systems.

Because no universally accepted benchmark currently defines the practical stack pressure for commercial SSBs, this review adopts an operational pressure classification rather than a single absolute threshold. Here, stack pressures of ≤ 2 MPa are regarded as a practically relevant low-pressure regime, whereas pressures of 2–10 MPa are classified as a moderate-pressure regime. Although this range remains higher than the desirable pressure level for practical battery modules, studies in this regime are included because they provide important mechanistic insights into pressure-dependent contact loss and corresponding mitigation strategies. Therefore, unless otherwise specified, “low-pressure SSBs” in this review primarily refers to systems operating at ≤ 2 MPa, while studies up to 10 MPa are considered within the broader scope of pressure-reduction research.

Within this pressure-classification framework, the actual pressure required for stable cycling remains strongly dependent on electrolyte properties, particularly elastic modulus, fracture toughness, and interfacial deformability. For example, the relatively low modulus of sulfide SEs (≈ 20 GPa) allows plastic deformation and interfacial consolidation at pressures that would be insufficient for high-modulus oxide SEs (≈ 150 GPa) [16,17]. Therefore, this review frames low-pressure operation in terms of mechanical compliance, interfacial deformability, and contact retention during cycling. By focusing on strategies that reduce the dependence of interfacial stability on external stack pressure, this review provides a technical roadmap that is particularly relevant to sulfide-based SSBs while offering broader mechanical design principles for other solid-state systems.

To connect this mechanistic perspective with recent experimental progress, Table 1 summarizes representative low-pressure and pressure-reduced SSB demonstrations reported in the literature. Because reported performance is strongly affected by areal loading, cell format, temperature, current density, and pressure-control method, these demonstrations should not be compared solely by cycle retention or operating pressure. Instead, Table 1 serves as a benchmarking framework for evaluating how different material, interface, and cell-level strategies reduce the dependence of SSB performance on high external compression.

2. Pressure-dependent failure evolution under low stack pressure

When the applied stack pressure is insufficient, low-pressure degradation proceeds through coupled failure pathways at the cathode, anode, and full-cell levels. At the local interface, the real

contact area is much smaller than the nominal geometric area because contact occurs only at discrete asperities determined by surface roughness, microstructural irregularities, and limited mechanical compliance. Under a constant applied current, this reduced real contact area amplifies local current density, interfacial resistance, and stress concentration, producing spatially nonuniform electrochemical activity [35–39].

More importantly, pressure sensitivity is governed not only by initial contact formation, but also by contact retention during repeated cycling [40,41]. At the Li metal anode, stripping-induced vacancy accumulation can outpace Li creep or interfacial deformation, causing void formation, contact loss, current localization, and nonuniform Li deposition [42–44]. At the cathode side, chemo-mechanical expansion and contraction of cathode active material (CAM) can induce interparticle rearrangement, interfacial debonding, and loss of ionic/electronic percolation within the composite cathode [45,46]. Therefore, the pressure dependence of SSBs should be understood as an electrochemo-mechanical consequence of insufficient contact retention across dynamically evolving solid–solid interfaces, rather than as a simple requirement for external compression [47,48]. The following sections examine these failure pathways from the cathode and anode perspectives and then discuss their integrated consequences at the full-cell level.

2.1. Cathode-side failure pathway: from CAM volume change to transport-network degradation

On the cathode side, low stack pressure accelerates degradation by weakening the mechanical and transport connectivity within composite electrodes. Unlike the Li metal anode, where failure is dominated by stripping-induced voiding and filament-mediated short-circuiting, cathode-side failure primarily arises from the coupled evolution of active material volume change, CAM–SE contact loss, transport network disruption, and reaction heterogeneity. These processes occur across multiple length scales, from local CAM–SE interfaces to the full cathode thickness, and are schematically summarized in Fig. 2.

2.1.1. Volume-change-driven contact loss

Most intercalation-type cathode materials undergo cyclic lattice breathing during (de)lithiation. Layered oxide cathodes, such as $\text{LiNi}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1}\text{O}_2$ (NCMxyz), exhibit net contraction upon delithiation, generating local strain mismatch with the surrounding rigid SE [49,50]. Under reduced mechanical confinement, these electrochemo-mechanical volume changes cannot be fully accommodated by the limited elasticity of the composite electrode. As a result, the true CAM–SE contact area progressively decreases, making interfacial contact loss and microcracking dominant degradation modes under low stack pressure (Fig. 2a).

Direct visualization of contact loss has been provided by both surface analysis and microscopy. Koerver et al. used NCM811/ β - Li_3PS_4 composite cathodes to demonstrate that NCM811 particles physically detach from the SE during the first charge [51]. Delithiation-induced contraction leaves spherical gaps and imprints of the original particle morphology on the electrolyte surface, indicating that capacity loss arises from both chemical interphase formation and mechanically driven CAM–SE contact loss. Pressure-dependent three-dimensional (3D) X-ray CT analysis of NCM/ $\text{Li}_{10}\text{GeP}_2\text{S}_{12}$ (LGPS) electrodes further supports this interpretation [52]. In the work of Sakka et al., low-pressure conditions produced larger void fractions and limited NCM/LGPS contact area, whereas higher pressure improved the contact area fraction by allowing LGPS to fill voids around rigid NCM particles. Notably, CT analysis also revealed insufficient NCM/LGPS contact in planes perpendicular to the pressure direction, indicating that uniaxial

Table 1

Representative low-pressure and pressure-reduced solid-state battery demonstrations reported in recent literature. Stack pressure values are listed as reported in each study. Systems operating at ≤ 2 MPa are considered low-pressure demonstrations, whereas those operated at 2–10 MPa are included as pressure-reduced studies that provide mechanistic or design insight into reducing pressure dependence.

Cathode SE Anode	Cell type	Operating temp (°C)	Stack pressure (MPa)	Rate	Areal capacity (mA h cm ⁻²) ^a	Cell performance	Design strategy	Ref.
<i>Cathode-side strategies</i>								
NCM811/X10 LPSCI Li-In	Pressure cell	30	0.3	0.2C	≈ 1.22	163 mA h g ⁻¹ / 75% @100 cycles	Crosslinked binder network	[18]
NCM622 LIC/LPSCI Li	Pressure cell	RT	1	$\approx 0.25C$	≈ 5	99% @220 cycles, 98% @530 cycles	Cathode chemo-mechanical stress control	[19]
NCM88-LIC LIC/LPSCI Li	Coin cell	55	2	0.3C	≈ 1.4	201 mA h g ⁻¹ at 0.1C / 80% @278 cycles	Chemically anchored CAM-SE interface	[20]
LTVO/LPSCI LPSCI Li _x In	Pressure cell	50	<0.5	50 mA g ⁻¹	≈ 0.4	220 mA h g ⁻¹ / 90% @270 cycles	Low-strain CAM	[21]
LAZO@LiNiO ₂ LPSCI Li-In	Pressure cell	60	2	0.2C	4.6	76.3% @200 cycles	Coating-assisted interfacial stabilization	[22]
NCM90@TMATFSI LPSCI Li-In	Pressure cell	25	10	0.1C	≈ 2.1	119.6 mA h g ⁻¹ / 82.9% @100 cycles		[23]
NCM83/LPSCI/CNF LPSCI LTO	Pressure cell	30	2	1 mA cm ⁻²	≈ 4.6	182 mA h g ⁻¹ / 85% @500 cycles	TPB regulation	[24]
NCM811-LPSCI LPSCI Li	Pressure cell	30	2	0.1C	≈ 1.3	85.6% @100 cycles	SE microstructure control	[25]
NCM82/LPSCI LPSCI LTO	Pressure cell	60	2	0.5C	5	177 mA h g ⁻¹ , 3.65 mA h cm ⁻² / >80% @500 cycles	Process-integrated cathode/SE architecture	[26]
NCM82/LPSCI LPSCI Si	Pouch	30	5	0.1C		310 Wh kg ⁻¹ , 805 Wh L ⁻¹ / 30 cycles		
<i>Anode-side strategies</i>								
LiNbO ₃ @NCM811 LTO-LPSCI Li	Pressure cell	25	5	0.33C	3.5	86.2% @180 cycles	Dual-functional SE additive	[27]
			2	0.2C	3.75	94.4% @50 cycles		
Li ₄ SiO ₄ @NCM811 LPSCI Li ₇ N ₂ I-Mg/Li	Pressure cell	60	≈ 1	0.5C	2.2	82.4% @350 cycles	Li/SE interlayer engineering	[28]
Li ₂ O-ZrO ₂ @NCM955 LPSCI Ag-C	Pouch	60	2	0.5C	6.8	146 mA h g ⁻¹ , 900 Wh L ⁻¹ / 89% @1000 cycles	Anode-less nucleation regulation	[29]
LiNbO ₃ @NCM811 LPSCI W/Mg	Pouch	25	2	0.3C	3.7	189 mA h g ⁻¹ , 1100 Wh L ⁻¹ / 71.9% @300 cycles		[30]
LiNbO ₃ @NCM811 LPSCI C/Zn	Pouch	45	2	0.33C	4.26	76.7% @400 cycles		[31]
<i>Cell-level strategies</i>								
NCM811 LPSCI Si	Pouch	30	2	0.2C	4	135.4 mA h g ⁻¹ / 47.7% @100 cycles	Isostatic pouch cell holder	[32]
	Pouch (monolayer)		5	0.2C	4	149.7 mA h g ⁻¹ / 77.8% @100 cycles		
	Pouch (bilayer)			0.1C	5	173.6 mA h g ⁻¹ (88.1 mA h) / 83.6% @100 cycles		
LiNbO ₃ @NCM82 LPSCI Graphite	Pouch	30	0 ^b	0.1C	3.1	201.7 mA h g ⁻¹ , ICE 80.3% / 80.7% @100 cycles	Current collector primer layer	[33]
Li ₂ S/LPSCI/AB LPSCI Li _{0.5} In	Pressure cell	RT	10	0.33C	6.8	≈ 800 mA h g ⁻¹ / 78% @350 cycles	Current collector interface engineering	[34]

Abbreviations: LiNi_{0.8}Co_{0.1}Mn_{0.1}O₂ (NCMxyz); styrene-butadiene rubber (SBR)/trimethylolpropane tris(3-mercaptopropionate) (TMPT)/azobisisobutyronitrile (AIBN) mass ratio of 100:10:10 (X10); Li₆PS₅Cl (LPSCI); cathode active material (CAM); Li₃InCl₆ (LIC); room temperature (RT); Li_{8/7}Ti_{12/7}V_{4/7}O₂ (LTVO); Li_xAl_yZn_zO₈ (LAZO); tetramethylammonium bis(trifluoromethanesulfonyl)imide (TMATFSI); carbon nanofiber (CNF); triple-phase-boundary (TPB); Li₄Ti₅O₁₂ (LTO); acetylene black (AB); initial Coulombic efficiency (ICE).

^a Areal capacities not explicitly reported in the literature were estimated from the reported active material loadings and experimentally measured specific capacities.

^b Operated without applied external stack pressure. The pouch cell was consolidated by warm isostatic pressing at 480 MPa and 60 °C prior to cycling.

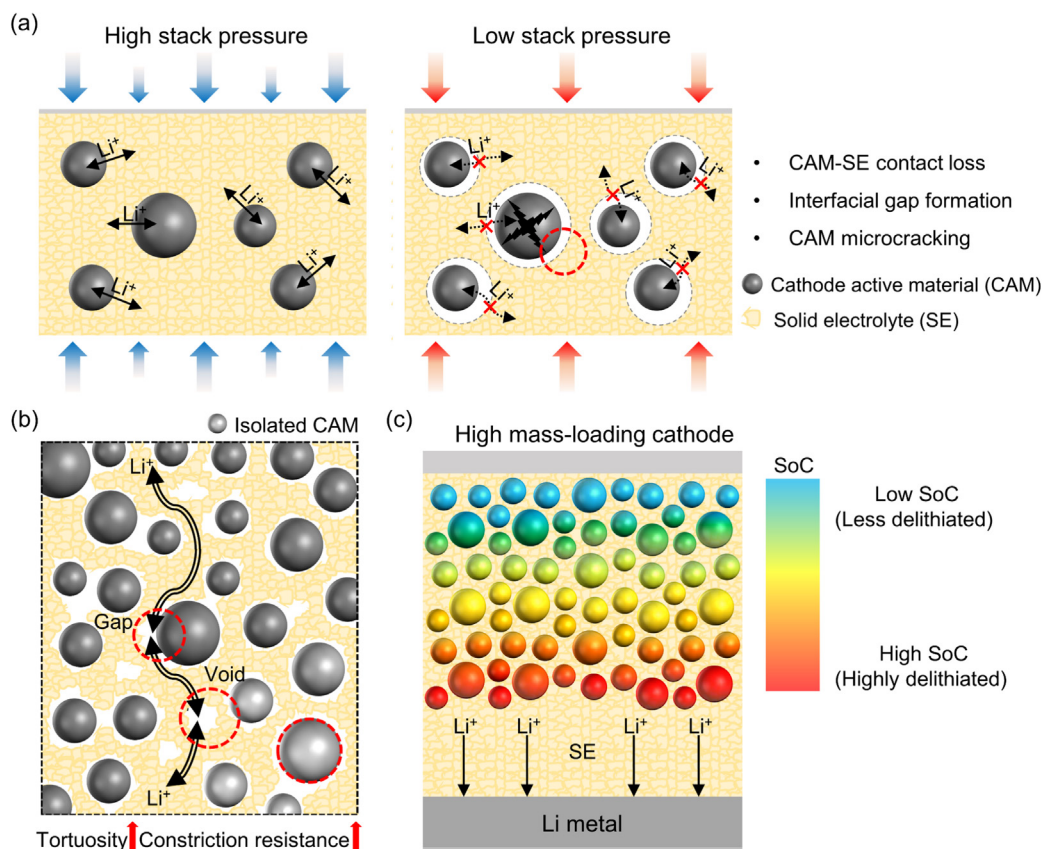


Fig. 2. Schematic illustration of cathode-side failure modes under low stack pressure. (a) Volume-change-driven CAM–SE contact loss, interfacial void formation, and CAM microcracking. (b) Contact-loss-induced disruption of ionic/electronic transport networks. (c) Through-thickness reaction heterogeneity and local state-of-charge (SoC) gradients in high-mass-loading composite cathodes, resulting in preferential reaction near the separator side and underutilization near the current collector side.

loading improves overall contact area but does not guarantee fully conformal 3D CAM–SE contact.

Cathode degradation is further amplified by morphological evolution of the CAM. Liu et al. demonstrated that polycrystalline NCM811 cathodes develop internal microcracks during initial cell pressing, which then propagate during cycling and lead to contact failure with $\text{Li}_{10}\text{SnP}_2\text{S}_{12}$ (LSPS) and conductive additives [53]. This behavior was attributed to anisotropic volume changes and lattice mismatch among randomly oriented grains within secondary particles. In contrast, single-crystal (SC) NCM811 maintained superior structural integrity and more intimate solid–solid contact after cycling.

These observations show that interfacial detachment and CAM cracking are mutually reinforcing failure processes that progressively reduce electrochemically active CAM–SE contact [54]. This pressure-sensitive contact-retention problem is also supported by model-cathode experiments, in which Nb_2O_5 -based cathodes with $\approx 4\%$ expansion exhibited pronounced capacity loss below 2 MPa due to interparticle cracking and solid–solid contact loss, whereas nearly zero-strain $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (LTO)-based cathodes were much less pressure-sensitive [55]. Recent studies on sulfide- and argyrodite-based composite cathodes similarly link active material volume change to interfacial void formation, particle cracking, and CAM–SE contact loss under practical low-pressure conditions [56,57].

2.1.2. Transport network disruption and reaction heterogeneity

As contact loss and microcracking accumulate under reduced mechanical confinement, cathode-side degradation evolves from local interfacial separation into a broader loss of transport connectivity. In this regime, electrode performance is governed not only by the intrinsic conductivities of the CAM, SE, and conductive addi-

tives, but also by whether these phases remain connected as continuous ionic and electronic percolation networks (Fig. 2b). Once CAM–SE contact becomes spatially discontinuous, Li-ion transport is forced through fewer connected pathways, increasing tortuosity, constriction resistance, and local current density. Pressure-dependent 3D X-ray CT analysis of NCM/LGPS cathodes directly supports this interpretation, showing that insufficient pressure increases void fraction, decreases CAM–SE contact area, and produces a composite geometry that is unfavorable for ion transport [52]. Consistently, simulation studies have shown that imperfect contact localizes current and lithium concentration into the remaining active regions, substantially increasing local transport burden [58]. Naik et al. further demonstrated that this effect generates electrochemical hotspots and nonuniform reaction distribution in SC-NCM523/LPSCI composite cathodes, effectively reducing the fraction of CAM connected to the ion-conducting network and lowering overall utilization [59]. Gao et al. similarly showed that, at low pressure, discharge capacity is governed primarily by ion transport through the composite cathode and that volume-change-induced contact loss amplifies transport limitations over repeated cycling [60].

These transport limitations become more severe in high-loading cathodes required for practical cells. In thick composite cathodes, local CAM–SE contact loss and transport constriction can propagate into through-thickness reaction heterogeneity, where different cathode regions evolve toward different local state-of-charge (SoC) (Fig. 2c) [61]. Stavola et al. quantified local lithium content in $\approx 110\text{-}\mu\text{m}$ -thick NCM111/LPSCI composite cathodes and observed substantial lithiation gradients during C/10 cycling, which were attributed to dynamically evolving tortuosity, particularly in the SE phase [62]. Ji et al. also observed

preferential lithiation from the SE membrane side toward the current collector side in a high-mass-loading NCM811 cathode with an areal loading of 33 mg cm^{-2} and a thickness of $\approx 180 \text{ }\mu\text{m}$, identifying ion-flux imbalance as a key origin of reaction gradients in thick composite cathodes [63]. Similar reaction-front behavior was observed by Bradbury et al. using operando neutron imaging in solid-state Li–S cathodes, further supporting that sluggish macroscopic ion transport can drive spatially nonuniform reaction [64].

Transport-based descriptions provide a useful framework for interpreting thickness-scale heterogeneity. Bernges et al. analyzed Li_2FeS_2 solid-state cathodes with increasing areal loading and electrode thickness using effective ionic/electronic transport properties and the δ -parameter from porous electrode theory [65]. In this framework, low effective conductivity, high current density, and increasing electrode thickness promote nonuniform reaction-rate distributions. When ionic transport is more limiting than electronic transport, reaction preferentially occurs near the separator side, where Li^+ supply is more accessible, leading to low utilization at the current collector side.

Therefore, preserving local CAM–SE contact is necessary but not sufficient for low-pressure cathode operation. Even if selected regions retain acceptable contact, the cathode can still fail to use its full active material inventory when ionic pathways are constricted and reaction is not uniformly distributed across the electrode depth. The cathode-side failure pathway under low stack pressure can thus be summarized as a progression from local contact loss and transport constriction to through-thickness reaction heterogeneity, ultimately appearing as resistance growth, increased polarization, early voltage-limit termination, and incomplete active material utilization.

2.2. Anode-side failure pathway: from Li stripping voids to localized Li deposition

On the anode side, low stack pressure destabilizes Li plating/stripping by weakening the mechanical continuity of the Li/SE interface. In contrast to cathode-side degradation, which is governed primarily by contact loss and transport disruption within the composite electrode, anode-side failure proceeds through a sequential coupling of interfacial voiding, current localization, and filament-mediated short-circuiting. During stripping, insufficient pressure limits the ability of Li to replenish the receding interface, leading to void formation and loss of active contact area. During subsequent plating, the remaining contact patches carry disproportionately high local current, promoting nonuniform Li deposition and filament growth through the SE. These coupled failure modes are schematically summarized in Fig. 3.

2.2.1. Creep-limited interfacial void formation

Under reduced mechanical confinement, the dominant degradation mode of lithium metal anodes is the loss of conformal Li/SE contact during stripping through the nucleation and growth of interfacial voids. During stripping, each extracted Li atom leaves behind a vacancy. When these vacancies cannot be removed sufficiently rapidly through diffusion or pressure-assisted plastic deformation (i.e., creep), they accumulate at the interface and evolve into pores or voids. Interfacial voiding is therefore not merely a geometric defect, but a dynamic imbalance between electrochemical Li removal and mechanical/diffusive replenishment at the receding interface [66]. This process is intrinsically dependent on both stack pressure and stripping rate (Fig. 3a).

The ability of Li to replenish the receding interface is affected by the stress-relief kinetics of the confined Li layer. Because Li has a low melting temperature, it operates at a high homologous temperature near room temperature, allowing creep to dominate its

deformation over a wide range of battery-relevant conditions [67]. During stripping, void closure therefore depends on whether Li can creep fast enough to compensate for the electrochemical recession of the Li/SE interface. However, this creep-mediated contact recovery is not determined by nominal stack pressure alone. The effective deformation of Li is also influenced by stripping rate, Li thickness, interfacial friction, and the characteristic length scale of surface defects or voids [68]. This thickness dependence becomes particularly important in thin Li and anode-less configurations. Duan et al. showed that geometric confinement introduces lateral shear and multiaxial stress states that suppress Li creep deformation, causing thinner Li layers to require substantially higher stack pressure to maintain conformal contact [69]. Thus, confined or thin Li can exhibit insufficient creep-mediated stress relaxation even under externally applied pressure, causing stripping-induced voids to persist and evolve into mechanically stable non-contact regions.

Experimental studies consistently show that interfacial instability emerges when electrochemical stripping exceeds the transport and deformation capability of Li. Wang et al. identified a current-dependent critical stack pressure in $\text{Li/Li}_7\text{La}_3\text{Zr}_2\text{O}_{12}$ (LLZO) cells and confirmed that the resulting sharp voltage increase primarily originates from the stripping-side contact loss [70]. Similarly, Krauskopf et al. and Hänsel et al. concluded that Li becomes morphologically unstable once vacancy diffusion and creep can no longer sustain the stripping flux [71,72]. Complementing these studies, Zhang et al. developed a 3D time-dependent contact model showing that, at sufficiently low stripping rates, creep and stripping can cooperatively smooth interfacial asperities and maintain contact, whereas vacancy accumulation leads to dynamic contact instability at higher rates [73].

Operando and impedance-resolved studies further reveal that void formation is spatially heterogeneous and progressively cumulative rather than transient. Haslam et al. distinguished a quasi-stable stripping regime, in which partial contact loss remains tolerable, from an unstable regime characterized by abrupt voltage rise once lithium replenishment becomes critically insufficient [74]. Their impedance and distribution of relaxation times (DRT) analysis showed that higher stack pressure delays void growth and reduces the severity of interfacial contact loss. Consistently, operando SEM imaging by Zhao et al. directly visualized the evolution of numerous small voids into a single interfacial gap that ultimately delaminates the interface [75]. Roach et al. further showed that pre-existing voids close primarily through pressure-driven creep, confirming that contact recovery is mechanically limited rather than instantaneous [76]. Once such gaps form under low pressure, contact recovery becomes highly limited.

Although the creep response is governed by the mechanical properties and microstructure of Li itself, the effective confinement imposed on Li depends on the SE. Rigid oxide electrolytes such as LLZO provide strong normal constraint but are less conformal, making the Li/SE interface sensitive to asperities, surface defects, and grain boundaries [77]. Higher pressure or interfacial modification may therefore be required to maintain contact, although excessive local stress can promote electrolyte fracture or Li intrusion. In contrast, sulfide electrolytes are softer and more deformable, which can facilitate interfacial consolidation under moderate pressure; however, their lower fracture resistance and residual porosity can still allow pressure-assisted Li penetration through connected defects [78]. Thus, different SEs do not fundamentally change the need for creep-mediated Li contact recovery, but they alter the boundary conditions for creep by changing interfacial conformity, friction, defect geometry, and fracture resistance. Because this review focuses on sulfide-based SSBs, oxide-based examples are considered only where they clarify transferable mechanical principles governing Li/SE confinement.

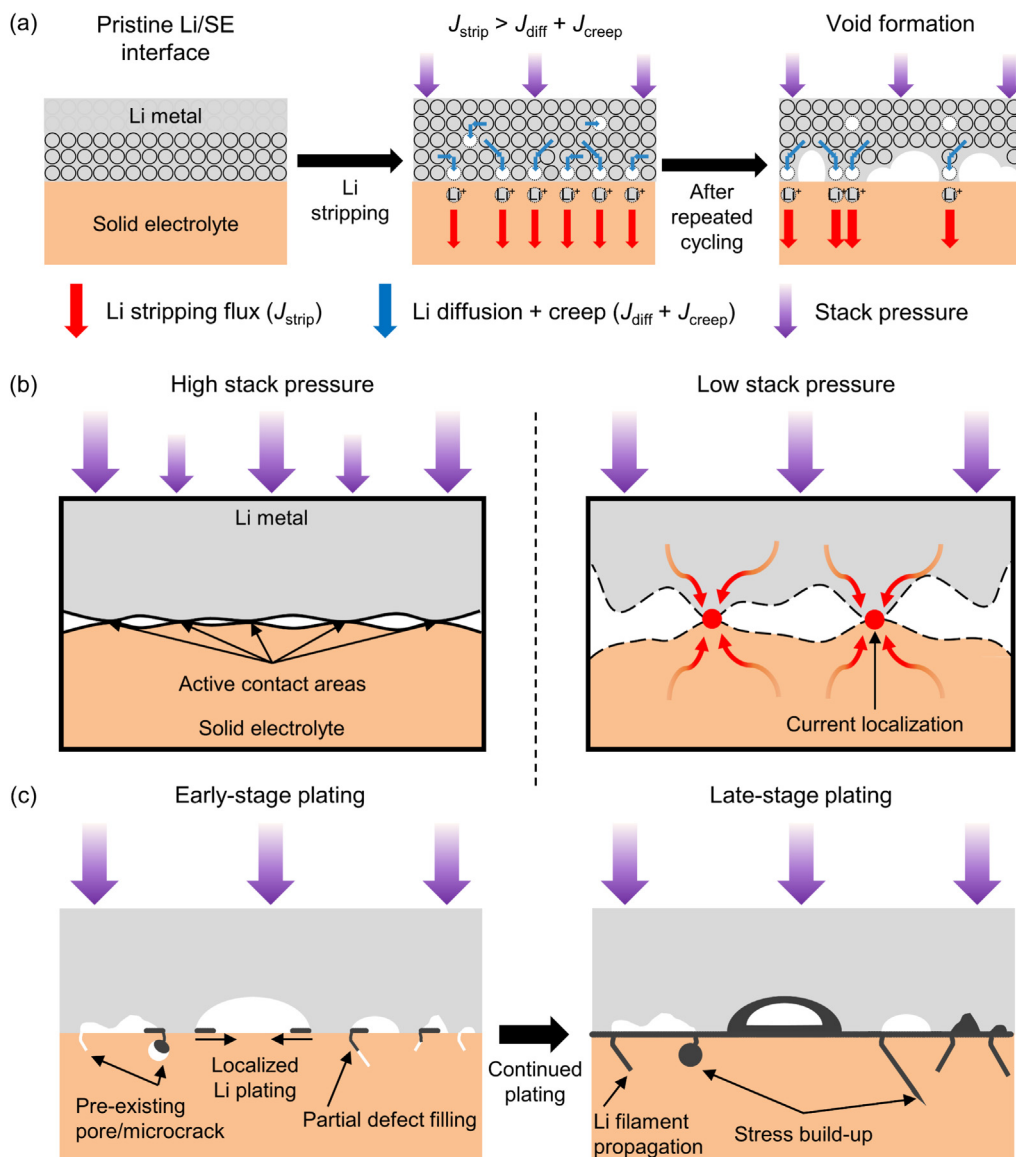


Fig. 3. Schematic illustration of anode-side failure evolution under low stack pressure. (a) Interfacial void formation during Li stripping when Li removal exceeds diffusion- and creep-mediated interfacial recovery. (b) Comparison of distributed active contact under high stack pressure with current localization at residual contact patches under low stack pressure. (c) Localized Li plating into pre-existing pores and microcracks during early-stage plating, followed by stress build-up and Li filament propagation during continued plating.

Collectively, these studies establish that stripping-induced void formation under low stack pressure is governed by the competition between electrochemical Li recession and creep-mediated contact recovery. When Li creep, vacancy diffusion, and pressure-assisted deformation cannot sustain the stripping flux, interfacial voids evolve into mechanically persistent non-contact regions. These regions reduce the true Li/SE contact area, increase local current density at the remaining contact patches, and provide the mechanistic basis for CCD limitations, Li filament nucleation, and short-circuit-related failure discussed in the following section.

2.2.2. Current localization and filament-mediated short-circuiting

As stripping-induced voids accumulate, the Li/SE interface evolves into a discontinuous contact landscape in which residual contact patches coexist with non-contacting regions. Low initial stack pressure produces a similar sparse “point-plane” contact geometry even before cycling [79,80], so that, under a constant applied current, electrochemical flux becomes concentrated at the remaining active contact areas rather than being distributed

uniformly across the nominal interface (Fig. 3b). The resulting current amplification can be severe. Raj et al. showed that current lines strongly crowd at void edges, such that a nominal current density of 0.5 mA cm^{-2} can generate local edge currents exceeding $1,000 \text{ mA cm}^{-2}$ [81].

This current amplification directly affects the experimentally measured CCD. Kasemchainan et al. showed that the stripping-side critical current can remain substantially lower than the plating threshold under insufficient confinement [82]. In Li/Li₆PS₅Cl/Li cells, the maximum current density avoiding stripping-induced failure increased from 0.2 mA cm^{-2} at 3 MPa to 1.0 mA cm^{-2} at 7 MPa, whereas the plating threshold remained approximately 2.0 mA cm^{-2} at both pressures. These results indicate that the apparent CCD under low stack pressure is often governed not by intrinsic electrolyte limitations alone, but by pressure-dependent effective-area loss and the resulting amplification of local current density. Fuchs et al. further argued that, under such interface-controlled conditions, the measured CCD becomes highly sensitive to extrinsic testing parameters, including the applied current–time

profile, transferred charge, resting intervals, and stack pressure [83]. Consequently, CCD values obtained under low-pressure conditions reflect pressure-dependent effective-area loss and the evolving interfacial contact state, and cannot be interpreted as intrinsic electrolyte limitations.

The terminal anode-side failure mode under low stack pressure is the conversion of localized Li deposition into filamentary penetration through the SE, ultimately resulting in progressive short-circuit behavior (Fig. 3c). Raj et al. provided a direct electrochemical link between interfacial voids and filament nucleation in $\text{Li}_{6.4}\text{-La}_3\text{Zr}_{1.4}\text{Ta}_{0.6}\text{O}_{12}$ (LLZTO)-based cells, detecting void growth at approximately two-thirds of the current density required for dendrite-induced shorting, indicating that filament formation evolves directly from the contact-defect state rather than arising as an independent instability [81]. Mechanistically, Ning et al. demonstrated that Li initially deposits into subsurface pores and microcracks. Once these defects are filled, continued plating generates internal stress because Li extrusion by viscoplastic flow becomes kinetically limited, and filament propagation proceeds through wedge-driven crack opening within the SE [84]. Similarly, Gao et al. showed using in situ TEM that Li eruption under strong mechanical constraint can generate hydrostatic pressures of several GPa and fracture even single-crystal LLZO, whereas weaker mechanical constraint promotes Li extrusion with substantially reduced electrolyte fracture [85]. Together, these studies indicate that filament initiation is governed not only by localized current amplification, but also by the ability of deposited Li to dissipate stress without mechanically opening fracture pathways.

Experimental observations in low-pressure cells further support this stress-coupled failure mechanism. Operando stress measurements combined with microscopy revealed that Li/polyethylene oxide (PEO)–lithium bis(trifluoromethanesulfonyl)imide (LiTFSI)–LLZTO hybrid SE/Li cells cycled under 3 MPa develop interfacial microvoids, heterogeneous stress distributions, and eventual dendritic growth [86]. Likewise, stress mapping in cycled LLZTO showed preferential Li deposition in tensile-stress regions, followed by crack extension and repeated void refilling during subsequent cycles [87]. In sulfide systems, operando pressure and X-ray CT measurements further linked large internal stress fluctuations with spiderweb-like cracking and enhanced filament penetration [88]. These studies indicate that insufficient pressure promotes contact loss and current localization, whereas excessive pressure may also accelerate crack-assisted Li penetration within pre-existing defects.

Electrochemically, filament-mediated failure under low pressure often evolves progressively rather than appearing as an immediate hard short circuit. Counihan et al. distinguished transient soft shorts, in which ionic and electronic currents coexist through unstable filamentary pathways, from irreversible hard shorts that permanently collapse the cell voltage [89]. Wang et al. similarly described this intermediate regime as “soft breakdown,” characterized by charge-curve fluctuation, low Coulombic efficiency, and failure to reach the upper cut-off voltage [90]. Consistently, Ping et al. observed reversible short-circuit behavior in garnet-based cells, where voltage fluctuations during charging temporarily disappeared during discharge or rest, indicating repeated shorting and unshorting events, which have been attributed to transient filament dissolution and reformation driven by Joule heating, local melting, corrosion, and replating [91]. Consequently, low-pressure cells may retain apparently reasonable galvanostatic profiles even after electronically leaky pathways have already formed. Early warning signs can instead include abnormal voltage noise, transient polarization fluctuations, overcharge behavior, and Coulombic-efficiency loss [92]. Short-circuiting under low stack pressure should therefore be understood as a progressive failure trajectory involving defect-assisted initiation, stress-coupled prop-

agation, transient soft shorting, and eventual irreversible electrical collapse.

2.3. Cell-level amplification through temporal pressure relaxation and spatial pressure heterogeneity

While the failure mechanisms described in Sections 2.1 and 2.2 are defined at individual electrode/electrolyte interfaces, their severity in practical cells is governed by how stack pressure evolves in time and space. Temporally, the nominal stack pressure is not a fixed boundary condition. Because cycling-induced electrode volume changes are mechanically constrained, conventional fixed-volume cells convert these volume changes into MPa-scale pressure fluctuations [93], comparable to, or exceeding, the upper limit of the practically relevant low-pressure regime (≤ 2 MPa). In addition, the effective load can decrease gradually over prolonged operation as fixtures and packaging components undergo mechanical fatigue and stress relaxation. A cell assembled within the low-pressure regime can therefore drift below the pressure required for interfacial contact retention during operation, re-triggering the contact loss, void formation, and current localization processes described above even when the initial pressure appears adequate.

Spatially, pressure uniformity degrades with increasing cell format. In small pellet-type cells, a nearly uniform load can be applied readily, whereas in larger cells, electrode thickness variation, surface roughness, plate deflection, and uneven fastening loads produce increasingly nonuniform pressure distributions. Under rigid uniaxial plates, cell edges and locally non-flat regions can experience substantially reduced or even negligible pressure [32]. The resulting pressure heterogeneity promotes uneven ionic flux, degraded interlayer contact, and local stress concentration. These spatial variations couple directly to the local failure pathways described in Sections 2.1 and 2.2. Under-pressurized regions become preferential sites for contact loss, reaction heterogeneity, and current localization, whereas locally over-pressurized regions can accelerate crack-assisted Li penetration. In multilayer pouch-type stacks, both the areal homogeneity of pressure and its maintenance throughout cycling become progressively more difficult to guarantee, while the reinforcement structures required to sustain higher loads impose substantial mass, volume, and manufacturing cost penalties at the module level [94]. Consequently, results obtained from small, rigidly constrained laboratory cells may systematically understate the severity of low-pressure failure in large-format cells. These temporal and spatial amplification effects define the cell-level design requirements addressed in Section 5, which discusses pressure application and control, mechanical buffering and compliance layers, and stack architectures that improve pressure homogeneity.

Fig. 4 consolidates these mechanisms and the strategies that address them into a single framework, linking the dominant low-pressure failure modes at the cathode, anode, and cell/module levels to their corresponding design strategies through four unifying functions: contact retention, transport robustness, Li deposition regulation, and pressure homogenization. This figure serves as a roadmap for Sections 3–5, in which each correspondence is developed in detail, and is revisited in Section 6.

3. Cathode-side design strategies

The failure mechanisms discussed in Section 2 indicate that low-pressure operation is ultimately limited by whether solid–solid interfaces can remain mechanically and electrochemically stable under weak confinement [95]. However, the manifestation of this problem differs between the anode and cathode. Anode-side degradation is dominated by Li stripping-induced void-

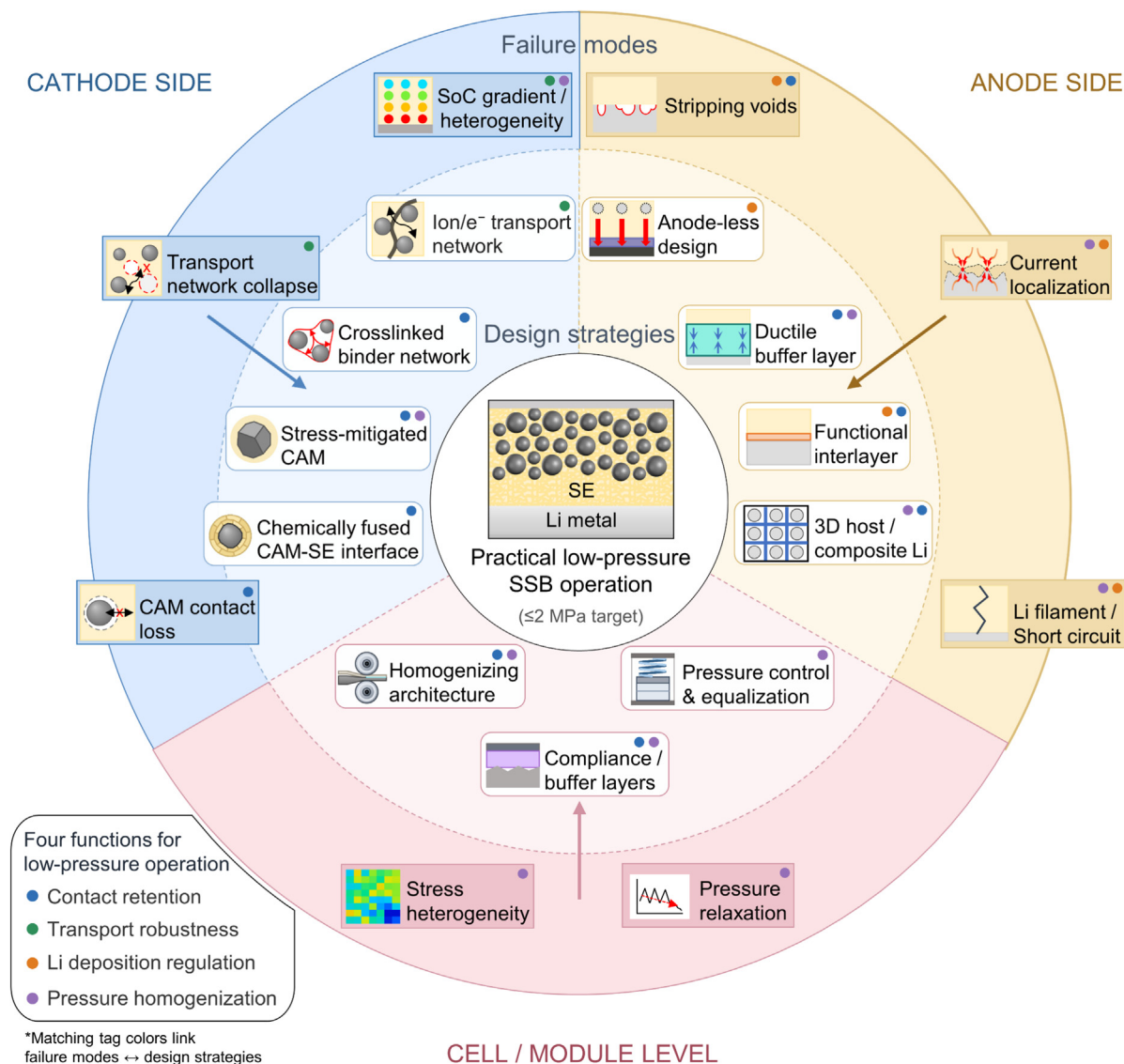


Fig. 4. Summary of the pressure-sensitive failure modes (outer ring) and corresponding design strategies (inner ring) discussed in this review, organized into cathode-side, anode-side, and cell/module-level domains and converging toward practical low-pressure operation (≤ 2 MPa). Tag colors denote the governing factors that each failure mode involves and each strategy addresses: interfacial contact (blue), ion/electron transport (green), Li plating/stripping (orange), and stress/pressure distribution (purple).

ing, current localization, and filament-mediated short-circuiting, whereas cathode-side degradation involves CAM–SE contact loss, disruption of ionic/electronic percolation, and interfacial reactions within a mechanically evolving composite electrode [96]. Cathode-side design should therefore stabilize both interfacial contact and transport continuity during cycling. In this context, SEs are not merely ion-conducting fillers, but structural and interfacial components whose particle morphology, deformability, chemical compatibility, and spatial distribution directly influence contact retention, stress distribution, and reaction uniformity [97]. Accordingly, electrolyte-related strategies are discussed together with cathode architecture and interface engineering, rather than as a separate design category.

3.1. Contact-stable composite architectures

For low-pressure operation, composite cathode design should prioritize not only the formation of initial CAM–SE contact, but also its retention during repeated cycling. Under weak mechanical confinement, cathode degradation is driven by CAM volume change,

interfacial debonding, particle rearrangement, and loss of percolating reaction pathways. Recent model studies suggest that the positive electrode can strongly influence full-cell behavior under low stack pressure, while practical areal capacities exceeding 5 mA h cm^{-2} can still be achieved at room temperature and 1 MPa when cathode chemo-mechanics are properly managed [19]. Therefore, contact-stable cathode architectures should be evaluated by their ability to suppress interfacial separation under realistic loading and reduced external pressure, rather than by initial conductivity or capacity alone. Representative cathode-side strategies for improving contact stability are summarized in Fig. 5.

One direct strategy is to chemically reinforce the CAM–SE interface. Liu et al. introduced an in situ recrystallization strategy to form a chemically fused interface between Ni-rich NCM and Li_3InCl_6 (LIC), improving resistance to interfacial debonding under low-pressure operation (Fig. 5a) [20]. The resulting freestanding NCM88–LIC composite cathode delivered $\approx 200 \text{ mA h g}^{-1}$ at 0.1C and ≈ 2 MPa with an areal capacity of $\approx 1.4 \text{ mA h cm}^{-2}$ corresponding to a CAM loading of $\approx 6.9 \text{ mg cm}^{-2}$, retaining 80% of its capacity

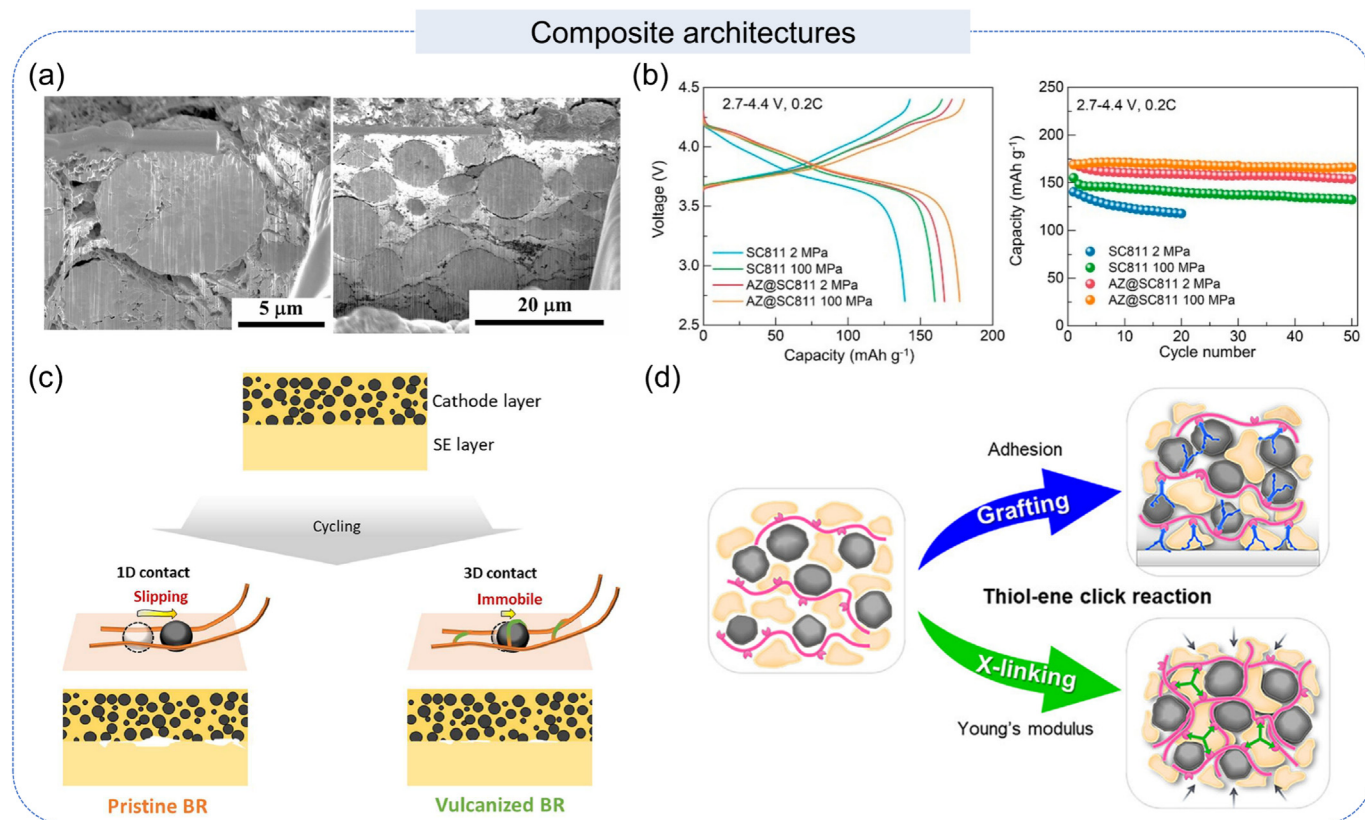


Fig. 5. Cathode-side design strategies for low-pressure SSBs, encompassing contact-stable composite cathode architectures that retain CAM–SE contact under low stack pressure. (a) Chemically fused NCM83–LIC interfaces formed by in situ recrystallization, with cross-sectional SEM micrographs comparing a dry-mixed cathode after 5 cycles (left) and an in situ recrystallized cathode after 100 cycles (right), showing suppressed interfacial debonding. Reproduced with permission from Ref. [20]. Copyright 2025, Elsevier. (b) Stress-mitigated AZ@SC811 design, with charge–discharge profiles and cycling performance at 0.2C under stack pressures of 2 and 100 MPa, showing reduced pressure sensitivity of cathode utilization. Reproduced with permission from Ref. [98]. Copyright 2023, American Chemical Society. (c) An in situ vulcanized BR binder forming a three-dimensional elastic scaffold that suppresses particle slippage and electrode delamination under reduced pressure. Reproduced with permission from Ref. [99]. Copyright 2022, Elsevier. (d) Slurry-applicable thiol–ene modification of SBR combining adhesion-enhancing grafting and crosslinking-induced reinforcement to maintain electrode integrity. Reproduced from Ref. [18] under the CC BY 4.0 license. Copyright 2026, The Author(s). Published by Wiley-VCH.

after 278 cycles and 54% after 1500 cycles at 0.3C and 55 °C. This work demonstrates that the SE can function not only as an ionic conductor, but also as an interfacial reaction mediator and mechanically tolerant contact phase at the CAM–SE boundary.

A second approach is to reduce the chemo-mechanical driving force for contact loss within the CAM itself. Zhao et al. designed an Al/Zr-decorated single-crystal NCM811 cathode (AZ@SC811) to mitigate cathode stress evolution while maintaining fast ion transport within the composite (Fig. 5b) [98]. Under 2 MPa, the cathode delivered $166.7 \text{ mA h g}^{-1}$ at 0.2C with 90.8% capacity retention after 50 cycles. This corresponds to $\approx 94\%$ of the capacity measured under 100 MPa ($177.2 \text{ mA h g}^{-1}$), whereas the undecorated counterpart retained only $\approx 87\%$ (139.3 vs. $160.0 \text{ mA h g}^{-1}$), indicating that the stress-mitigated CAM design substantially reduces the pressure sensitivity of cathode utilization. This example illustrates that low-pressure stability can be improved by designing CAMs that undergo less mechanically disruptive volume change, thereby preserving both interfacial contact and transport continuity.

Binder design provides a more processing-oriented route to contact-stable cathodes. Kwon et al. reported a wet-slurry process in which in situ vulcanization produced a 3D butadiene rubber (BR) binder network that suppressed particle slippage and delamination under reduced pressure (Fig. 5c) [99]. Cathodes containing the networked binder delivered 165 mA h g^{-1} vs. 151 mA h g^{-1} relative to pristine BR at 2 MPa, 30 °C, and 0.1C, and pouch-type NCM/LTO full cells operated without external pressure delivered 153 vs.

121 mA h g^{-1} at 0.2C while retaining 72.8% vs. 61.8% of their capacity after 150 cycles.

Park et al. extended this concept beyond cohesion enhancement by using slurry-applicable thiol–ene click chemistry to introduce adhesion-enhancing grafts and crosslinking-induced reinforcement into styrene–butadiene rubber (SBR) (Fig. 5d) [18]. In single-crystalline NCM|LPSCI|(Li–In) half cells at 0.3 MPa and 30 °C, the crosslinked binder delivered 163 mA h g^{-1} with 75% retention after 100 cycles, compared with 133 mA h g^{-1} and 67% for unmodified SBR. Notably, crosslinking proved more critical than adhesion enhancement, and the performance difference between modified and pristine binders became negligible at 70 MPa, confirming that mechanical reinforcement of the binder network specifically targets low-pressure operation. From a processing perspective, the in situ click chemistry route also avoids separate synthesis and redispersion of highly polar or crosslinked binders, reducing risks of solubility mismatch and slurry gelation.

Interfacial coatings can also improve cathode-side contact stability, although their relevance depends strongly on the demonstrated pressure regime. Wang et al. introduced a TMATFSI-based organic ionic plastic crystal coating on NCM90, which suppressed cathode–electrolyte interfacial side reactions and reduced interfacial resistance [23]. The coated cathode retained 82.9% of its capacity after 100 cycles at 10 MPa, whereas the uncoated NCM90 retained only 35.8% under identical conditions, indicating that coating-assisted interfacial stabilization can relax the pressure requirement relative to highly pressurized cells. However, because

10 MPa remains above the strict low-pressure range emphasized in this review, this example is better viewed as a moderate-pressure relaxation strategy rather than a fully low-pressure solution.

Collectively, contact-stable composite cathodes can be classified into four design categories: chemically anchored CAM–SE interfaces, stress-mitigated CAM architectures, crosslinked binder networks, and coating-assisted interfacial stabilization. These strategies demonstrate that low-pressure cathode operation requires dynamic contact retention, rather than merely high initial interfacial contact. For practical implementation, however, such approaches should ultimately be evaluated not only by capacity retention, but also by operating pressure, areal loading, inactive material fraction, electrode thickness, and compatibility with scalable electrode fabrication. In this respect, the four categories differ considerably in maturity and generality. Chemically fused interfaces provide strong adhesion but are specific to the CAM and SE chemistry pair employed, and their extension to sulfide systems remains unverified. Stress-mitigated CAM architectures reduce the chemo-mechanical driving force for contact loss at its source, but longer cycling and high-areal-capacity validation are necessary. Crosslinked binder networks are the most compatible with existing slurry-based manufacturing and have achieved the lowest demonstrated operating pressures, although demonstrations to date involve moderate CAM loadings of $\approx 8\text{--}10\text{ mg cm}^{-2}$, and their effectiveness in thick, high-areal-capacity cathodes remains to be verified. Coating-assisted stabilization is broadly applicable across CAM chemistries, but its benefit under strictly low-pressure conditions remains to be demonstrated because reported examples are limited to the moderate-pressure regime. The following subsection considers the complementary requirement of maintaining robust ionic and electronic transport pathways under the same low-pressure conditions.

3.2. Transport-robust electrode engineering

Beyond retaining CAM–SE contact, low-pressure composite cathodes must maintain continuous ionic and electronic transport pathways as external mechanical confinement is reduced. This requirement becomes increasingly important in thick, high-areal-loading cathodes, where even partial disruption of the ion-conducting network can cause substantial increases in polarization and incomplete CAM utilization. Transport-robust electrode engineering therefore aims to construct composite cathodes in which ionic percolation, electronic conduction, and reaction distribution remain stable under reduced stack pressure. In this context, the morphology and spatial organization of the SE phase are particularly important, because SE particle size, packing behavior, dispersion uniformity, and interfacial coverage collectively determine whether the cathode maintains a percolating, low-tortuosity ion transport network during cycling. Fig. 6 illustrates approaches to transport-robust electrode engineering.

One effective strategy is to tailor the particle-size distribution and spatial arrangement of the SE within the cathode composite. Zhou et al. demonstrated that replacing coarse LPSCI with fine-particle LPSCI produced a more homogeneous electrolyte distribution around NCM811 particles, leading to improved CAM utilization and reduced tortuosity (Fig. 6a) [25]. The fine-LPSCI composite exhibited a median tortuosity of 1.21, compared with 1.84 for the coarse-LPSCI analogue, together with lower cathode charge transfer resistance and improved low-pressure cycling stability. At 2 MPa, the fine-LPSCI cathode retained 85.6% of its capacity after 100 cycles, compared with only 63.3% for the coarse-LPSCI cathode, indicating that homogeneous SE distribution can reduce the pressure sensitivity of cathode transport.

A second strategy is to regulate electronic pathways and triple-phase-boundary (TPB) chemistry so that electronic conduction is

maintained without accelerating sulfide decomposition. In thick, coating-free Ni-rich NCM cathodes employing LPSCI, Wang et al. showed that the relevant transport problem is not only the presence of ionic and electronic pathways, but also the spatial distribution of carbon at CAM–carbon–SE junctions (Fig. 6b) [24]. By replacing high-surface-area Ketjen black (KB) with low-surface-area carbon nanofibers, they suppressed oxidative decomposition at TPBs while preserving electronic percolation in a $\approx 110\text{-}\mu\text{m}$ -thick cathode with a CAM loading of $\approx 25\text{ mg cm}^{-2}$. Under 2 MPa, 1 mA cm^{-2} , and $30\text{ }^\circ\text{C}$, the coating-free cathode delivered an initial areal capacity of $\approx 4.6\text{ mA h cm}^{-2}$ and retained 85% of its capacity after 500 cycles, with an average capacity loss of 0.03% per cycle, roughly 12 times lower than that of the otherwise identical Ketjen black cathode (0.35% per cycle). This result shows that low-pressure operation of thick cathodes requires not only continuous transport pathways, but also chemically sustainable TPB architectures that limit parasitic reactions at electronically connected sulfide interfaces.

A third approach is to integrate cathode and electrolyte fabrication into a mechanically integrated architecture. Lee et al. developed a co-rolling dry process that simultaneously formed a thin SE layer and a high-loading positive electrode, producing an intimate and mechanically reinforced SE–positive electrode interface (Fig. 6c) [26]. This architecture enabled a $50\text{ }\mu\text{m}$ SE layer and a 5 mA h cm^{-2} positive electrode containing 80 wt% active material, while maintaining $>80\%$ capacity retention after 500 cycles at 2 MPa and $60\text{ }^\circ\text{C}$. Compared with freestanding counterparts, the co-rolled film showed a smaller capacity loss upon reducing the stack pressure from 75 to 2 MPa (8.5% vs. 13.2%) and a markedly lower interfacial void fraction after cycling under 2 MPa, as quantified by image analysis of cross-sectional SEM images. The same strategy was extended to an Si-anode all-solid-state pouch cell delivering 310 Wh kg^{-1} and 805 Wh L^{-1} at $30\text{ }^\circ\text{C}$ and 5 MPa, highlighting how cathode processing strategies can be linked directly to stack-level performance metrics.

Collectively, transport-robust electrode engineering can be classified into three design categories: SE microstructure control for low-tortuosity ionic percolation, TPB regulation for chemically stable electronic conduction, and process-integrated cathode/SE architectures that preserve transport continuity under reduced pressure. These studies demonstrate that low-pressure cathode performance is governed not only by the intrinsic conductivity of individual components, but also by the spatial stability of the full reaction network. The three categories differ in industrial readiness, however. SE particle size control and TPB regulation can be implemented with conventional composite processing, although fine sulfide powders increase moisture sensitivity and handling requirements, which raises processing cost even when no new chemistry is introduced. Co-rolled and dry-processed architectures offer the most direct route to stack-level performance metrics, but depend on dry-film equipment whose large-area uniformity and throughput are still maturing. Together with the contact-retention strategies discussed in Section 3.1, transport-robust electrode engineering thus defines the cathode-side design requirements for maintaining mechanically stable and electrochemically accessible reaction pathways under low stack pressure.

From a cathode-design perspective, future studies should move beyond demonstrating improved cycling at a single pressure and instead quantify how contact retention, tortuosity, reaction heterogeneity, and interfacial resistance evolve with stack pressure, cathode loading, and electrode thickness. Particular attention should be given to thick, high-areal-capacity cathodes, where local improvements in CAM–SE contact may not necessarily translate into homogeneous utilization through the electrode depth. Establishing these relationships will be essential for identifying cathode architectures that remain effective under practical low-pressure conditions.

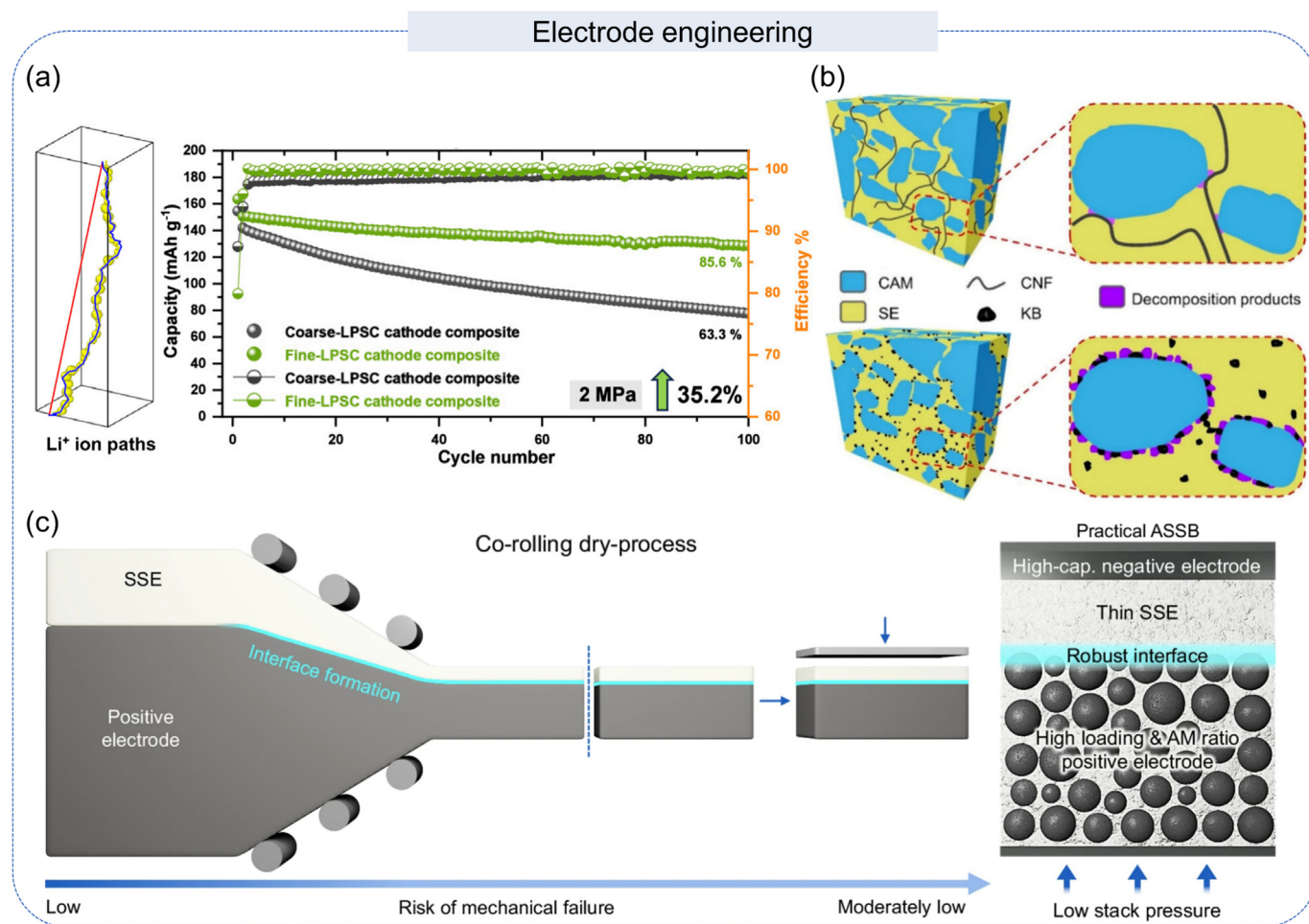


Fig. 6. Transport-robust cathode engineering under low stack pressure. (a) Simulated Li^+ transport pathways and 2 MPa cycling performance of coarse- and fine-LPSCI composites, showing reduced tortuosity and improved stability through homogeneous SE distribution. Adapted with permission from Ref. [25]. Copyright 2025, American Chemical Society. (b) Schematics of CNF- and KB-based coating-free cathodes, illustrating TPB regulation that preserves electronic percolation and suppresses oxidative SE decomposition. Reproduced from Ref. [24] under the CC BY 4.0 license. Copyright 2026, The Author(s). Published by American Chemical Society. (c) Co-rolling dry process for an integrated SE-positive electrode film with a thin SE layer, high-loading positive electrode, and robust low-pressure interface. Reproduced from Ref. [26] under the CC BY 4.0 license. Copyright 2025, The Author(s). Published by Springer Nature.

4. Anode-side design strategies

The anode side presents one of the most pressure-sensitive interfaces in SSBs because Li plating and stripping occur directly at a mechanically constrained Li/SE boundary. As discussed in Section 2.2, insufficient stack pressure promotes stripping-induced void formation, loss of active contact area, current localization, and, ultimately, filament-mediated short-circuiting [100]. Therefore, anode-side design strategies must reduce the dependence of Li cycling on external mechanical confinement by stabilizing Li transport, interfacial contact, and deposition morphology under limited pressure.

The strategies discussed in this section are classified according to the location at which anode-side contact retention is engineered. Section 4.1 examines pressure-tolerant anode architectures that distribute Li transport, electrochemical reaction, and mechanical deformation throughout a 3D or composite anode volume rather than concentrating them at a planar Li/SE boundary. Section 4.2 addresses functional interlayers inserted at a pre-existing Li/SE interface to improve chemical compatibility, regulate ionic and electronic transport, accommodate local deformation, and preserve contact during Li stripping and plating. Representative pressure-tolerant anode architectures and Li/SE interlayer

strategies are summarized in Fig. 7. Section 4.3 then considers anode-less SSBs as the limiting case of anode-side contact regulation. Unlike the preceding configurations, anode-less cells contain no excess Li reservoir. The Li/SE interface must therefore be formed in situ during the first charge and repeatedly reconstructed during subsequent cycling. Accordingly, the anode-less configuration is not intrinsically a pressure-mitigation strategy, but provides a stringent test of whether interfacial and architectural design can sustain reversible Li cycling without mechanical compensation from excess Li.

4.1. Pressure-tolerant anode architectures

One route to mitigating low-pressure anode failure is to move Li plating/stripping away from a vulnerable planar Li/SE interface and distribute the reaction within a 3D or composite anode framework. Compared with flat Li metal foils, such architectures can increase the effective reaction area, reduce local current density, accommodate volume change, and preserve electrochemical accessibility even when partial contact loss occurs. Thus, 3D anode design should be understood not simply as surface area enhancement, but as a means of redistributing reaction, transport, and stress under limited stack pressure.

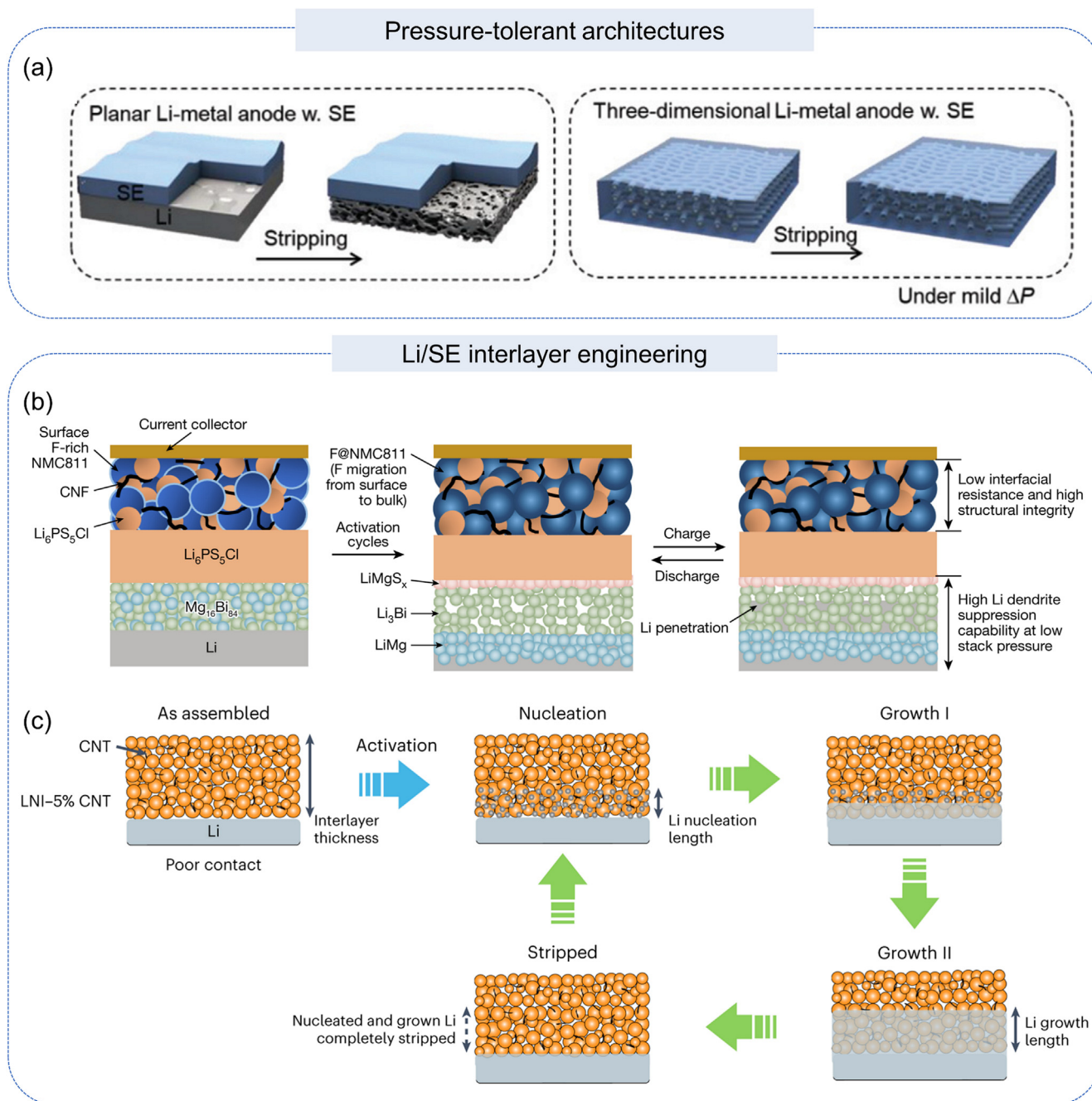


Fig. 7. Anode-side design strategies for low-pressure Li-metal-based SSBs. (a) Pressure-tolerant three-dimensional Li-metal host architectures that redistribute Li plating/stripping and preserve Li/SE contact under low stack pressure. Reproduced with permission from Ref. [102]. Copyright 2022, Wiley-VCH. (b) Activation-induced transformation of a $\text{Mg}_{16}\text{Bi}_{84}$ interlayer into a multifunctional LiMgS_x - Li_3Bi - LiMg architecture for interfacial passivation, regulated Li transport, adhesion, and accommodation of Li-volume evolution. Reproduced with permission from Ref. [104]. Copyright 2023, Springer Nature. (c) A porous $\text{Li}_7\text{N}_2\text{I}$ -CNT interlayer that regulates Li nucleation, growth, and reversible stripping through a controlled balance of lithiophobicity, ionic and electronic conductivities, and porosity. Reproduced with permission from Ref. [28]. Copyright 2024, Springer Nature.

Alexander et al. demonstrated this concept using a porous mixed ion- and electron-conducting (MIEC) garnet framework supporting a thin, dense Ta-doped LLZO separator [101]. The porous host was estimated to provide an approximately 40-fold larger Li/SE contact area than a planar interface, thereby reducing the local interfacial current density by a similar factor. The resulting MIEC trilayer reached a critical current density of 100 mA cm^{-2} and sustained Li plating/stripping at up to 60 mA cm^{-2} with 30 mA h cm^{-2} transferred per cycle at room temperature without applied stack pressure. This substantially exceeded the 10 mA cm^{-2}

cycling rate previously achieved using non-MIEC porous garnet architectures.

A more directly pressure-relevant example was reported by Ren et al., who designed a hollow Ag/carbon-fiber scaffold combined with a sulfide/polymer composite electrolyte (Fig. 7a) [102]. The hollow scaffold reached a critical current density of 4.8 mA cm^{-2} , compared with 0.8 mA cm^{-2} for a dense carbon-paper host, while a planar electrode exhibited substantial polarization above 0.4 mA cm^{-2} . The architecture was subsequently validated in a high-Ni pouch cell containing onefold excess Li at an operating

stack pressure of 320 kPa. The cell retained 90.5% of its capacity after the first 100 cycles at 0.2C charge and 0.4C discharge. After increasing the discharge rate to 1C while maintaining charging at 0.2C, it retained 83% after 200 cycles. These results show that the 3D host simultaneously enlarges the reaction area and accommodates plating-induced volume change, enabling relatively high-rate pouch cell cycling under sub-MPa confinement.

Fuchs et al. approached anode architecture from a composite-Li perspective by dispersing carbon nanotubes (CNTs) directly into Li metal [103]. At 100 $\mu\text{A cm}^{-2}$, pure Li reached the depletion cutoff after only 1.2 mA h cm^{-2} , whereas the optimized Li–CNT30 composite delivered approximately 25 mA h cm^{-2} , representing a greater than 20-fold increase in stripping capacity. The CNT network maintained electronic contact with LLZO after depletion of the initially planar Li/SE interface and redirected Li dissolution into the electrode volume. The measurements were conducted under nominally pressure-free conditions. However, the authors clarified that the clamps used to maintain current-collector contact exerted an unquantified pressure below 1 MPa after the electrode had initially been attached to LLZO at approximately 30 MPa. Moreover, a substantial fraction of the additional stripping capacity was accessed at polarization above 0.5 V, limiting its direct translation to practical full-cell operation.

These studies show that pressure-tolerant anode architectures reduce the reliance of Li cycling on a single planar interface. Whether implemented as a mixed-conducting ceramic framework, a hollow lithiophilic scaffold, or a composite Li host, the central design principle is to distribute current, Li transport, and mechanical deformation across a larger volume. Such architectures therefore mitigate current constriction and stripping-induced contact loss, providing a structural pathway toward stable Li metal cycling under reduced stack pressure. Nevertheless, these benefits carry practical costs that need to be quantified. The pore volume and host mass required for stress accommodation directly reduce the volumetric and gravimetric energy density gains that motivate the use of Li metal anodes. Rigid ceramic frameworks are also difficult to reconcile with roll-to-roll lamination and pouch-type stacking, and scalable fabrication routes for 3D hosts have yet to be demonstrated. Among the examples above, only the Ag/carbon-fiber scaffold has been validated in a pouch-format cell, while other works have yet to report low-pressure demonstrations at practical areal capacities. Future studies should therefore report the host volume fraction, inactive mass, electrode-level density, and compatibility with continuous film processing so that 3D architectures can be compared with planar Li on a cell-relevant gravimetric and volumetric basis.

4.2. Interlayer engineering at the Li/SE interface

A second route to pressure-tolerant anode operation is to introduce a functional interlayer at the Li/SE interface. An effective interlayer should regulate where Li nucleates, maintain rapid ionic transport while limiting electron leakage toward the SE, accommodate Li-volume changes, and preserve contact during stripping. Because these functions depend strongly on SE chemistry and mechanics, the following discussion focuses on sulfide-compatible interlayers and distinguishes direct low-pressure demonstrations from moderate-pressure or mechanistic studies.

Wan et al. introduced a $\text{Mg}_{16}\text{Bi}_{84}$ interlayer between Li and LPSCl (Fig. 7b) [104]. During activation, the interlayer transformed into a multifunctional $\text{LiMgS}_x\text{--Li}_3\text{Bi--LiMg}$ architecture, in which LiMgS_x passivated the sulfide surface, porous Li_3Bi accommodated Li growth, and LiMg maintained adhesion between the Li_3Bi framework and the Li anode. Mg migration also generated free volume within the Li_3Bi framework, thereby accommodating volume evolution and reducing interfacial resistance. Combined with an F-

rich cathode treatment, this design enabled an NCM811 cell to deliver an areal capacity of 7.2 mA h cm^{-2} at 2.55 mA cm^{-2} and a LiNiO_2 cell to reach 11.1 mA h cm^{-2} with a cell-level energy density of 310 Wh kg^{-1} at 2.5 MPa. These results demonstrate pressure-reduced operation at practically relevant areal capacities, although the contribution of the anode interlayer cannot be fully separated from that of the simultaneous cathode modification.

Wang et al. developed porous $\text{Li}_7\text{N}_2\text{I--CNT}$ and $\text{Li}_7\text{N}_2\text{I--Mg}$ interlayers that regulate Li growth through a controlled balance of lithiophobicity, ionic and electronic conductivities, and porosity (Fig. 7c) [28]. The optimized $\text{Li}_7\text{N}_2\text{I--CNT}$ interlayer directed Li plating to the Li/interlayer boundary and enabled reversible penetration into and extraction from the porous framework, achieving a critical current density of 4.0 mA cm^{-2} at 4.0 mA h cm^{-2} and stable cycling for more than 600 h at 25 °C under approximately 1 MPa. To reduce the inactive interlayer thickness, an 18.5 μm $\text{Li}_7\text{N}_2\text{I--Mg}$ interlayer was designed with a gradient electronic conductivity generated by Mg migration. In a full cell containing a 20 μm Li anode, this interlayer enabled an areal capacity of 2.2 mA h cm^{-2} and 82.4% capacity retention after 350 cycles at 0.5C and 60 °C. This study provides the clearest direct low-pressure demonstration among the interlayers considered here, although the elevated operating temperature and added interlayer volume remain important practical constraints.

Shen et al. introduced a hierarchical Si/C (H–Si/C) interlayer in which Si self-lithiation generated an ion-conducting Li–Si alloy phase, while the carbon coating established a continuous electronic network [105]. The resulting homogenization of ionic and electronic transport stabilized Li deposition and maintained compact contact with the sulfide SE. NCM811/LPSCl/H–Si/C@Li cells retained 70.28% of their initial capacity after 800 cycles at 0.5C and 30 °C, with an average Coulombic efficiency of 99.93%. At a higher areal capacity of 3.4 mA h cm^{-2} , the cells retained 80.9% of their capacity after 200 cycles and were also demonstrated at 6.9 mA h cm^{-2} for 15 cycles at 60 °C. Although the stack pressure of 15 MPa used in this work is above the low-pressure regime established in this review, it provides mechanistic evidence that adaptive ion–electron transport regulation can stabilize the Li/sulfide–SE interface.

Cheng et al. addressed stripping-side void formation using a 15 μm graphitized CNT/fluorinated-graphite interlayer (LNT10F) [106]. Lithiation produced LiC_x within the graphitized CNT network and LiF from the fluorinated-graphite component, providing rapid Li transport together with chemical passivation of the sulfide interface. The effective Li diffusion coefficient increased from $2.99 \times 10^{-10} \text{ cm}^2 \text{ s}^{-1}$ for bare Li to $9.62 \times 10^{-10} \text{ cm}^2 \text{ s}^{-1}$ with the optimized interlayer. At 0.5 mA cm^{-2} and 5 MPa, the critical delithiation capacity increased from 6.60 to 12.96 mA h cm^{-2} , while an NCM9 full cell retained more than 91% of its capacity after 100 cycles at 0.3C and room temperature. Although this pressure lies in the moderate-pressure regime, the results directly demonstrate that accelerating Li transport and preserving interfacial contact can delay stripping-induced void formation.

Taken together, these studies demonstrate that effective interlayers must coordinate chemical stabilization, charge-carrier transport, and mechanical contact retention. Among the present examples, direct operation within the ≤ 2 MPa regime is demonstrated most clearly by the $\text{Li}_7\text{N}_2\text{I}$ -based interlayers, whereas the $\text{Mg}_{16}\text{Bi}_{84}$ interlayer requires cycle retention verification at practically relevant areal capacity and operating temperature. The LNT10F and H–Si/C studies remain in the moderate-pressure regime and require explicit low-pressure verification. Future studies should therefore report operating pressure, temperature, Li thickness, areal capacity, interlayer thickness and mass, and activation-induced phase evolution to permit meaningful assessment of interlayer practicality and scalability.

4.3. Contact regulation in anode-less solid-state batteries

The pressure-tolerant architectures and interlayers discussed in Sections 4.1 and 4.2 generally operate in the presence of a pre-existing Li reservoir. Anode-less solid-state batteries (ALSSBs), also termed anode-free solid-state batteries, remove this reservoir by assembling the negative electrode without excess Li metal and plating cathode-derived Li onto a current collector or interfacial host during the first charge. This configuration can increase gravimetric and volumetric energy density, but it is not intrinsically a strategy for mitigating anode-side contact failure. On the contrary, it represents the most demanding boundary condition for contact retention because the Li/SE interface must be created in situ, displaced during every cycle, and reconstructed without excess Li to compensate for isolated or irreversibly consumed deposits [107].

The inclusion of anode-less cells in this section is therefore based not on the configuration itself, but on the contact-regulation functions required for it to operate. Successful anode-less designs employ interlayers, modified current collectors, and adaptive alloy hosts to control where Li nucleates, maintain electron transport as the Li layer recedes, accommodate deposition-induced thickness changes, and limit current localization at stripping-generated contact defects. Anode-less cells can thus be regarded as a stringent test of whether anode-side design can autonomously preserve Li inventory and interfacial contact under limited mechanical confinement. Representative contact-regulation strategies for low-pressure anode-less SSBs, encompassing Li nucleation and deposition regulation and stripping-side contact preservation, are summarized in Fig. 8.

Among the early demonstrations of this concept, Lee et al. reported a silver–carbon composite layer to regulate Li deposition in an anode-less sulfide-based cell (Fig. 8a) [29]. The Ag–C layer acted not merely as a current collector modification, but as an alloy-forming nucleation matrix that guided reservoir-free Li formation at the anode side. Combined with an argyrodite-type sulfide electrolyte, a high-Ni cathode with a specific capacity above 210 mA h g⁻¹ and areal capacity above 6.8 mA h cm⁻², and warm isostatic pressing to improve contact, the resulting 0.6 A h pouch cell achieved an energy density above 900 Wh L⁻¹, Coulombic efficiency above 99.8%, and 89% capacity retention over 1000 cycles under a stack pressure of 2 MPa. This demonstration, however, was obtained at an elevated operating temperature of 60 °C.

A more explicitly low-pressure-oriented design was reported by Oh et al., who introduced a lithio-amphiphilic nanobilayer composed of a lithiophobic W top layer and a lithiophilic Mg bottom layer with a total thickness of only 230 nm (Fig. 8b) [30]. This bilayer separated two key interfacial functions: the lower Mg layer facilitated uniform Li nucleation through its strong Li affinity, while the upper W layer confined dense Li deposition underneath it by imposing a high interfacial energy against Li. As a result, the bilayer enabled short-circuit-free cycling at high current density and supported a pouch-type full cell with an energy density of 1100 Wh L⁻¹ and 71.9% capacity retention after 300 cycles at room temperature under 2 MPa. This study shows that low-pressure anode-less operation depends not only on lowering the Li nucleation barrier, but also on controlling the location and density of Li deposition.

A recent approach extended nucleation control from a static interlayer to a self-regenerating one by embedding the nucleation agent within the SE itself. Choi et al. coated an Ag-substituted argyrodite layer (Li_{5.4}Ag_{0.6}PS₅Cl) onto the current collector beneath an undoped argyrodite separator, forming an SE bilayer (Fig. 8c) [108]. During charging, Ag⁺ was electrochemically exsolved as nanoscale lithiophilic seeds along grain boundaries and pores, and these seeds alloyed with Li to guide the growth of a compact Li layer between the SE bilayer and the current collector. Upon

stripping, the Ag species returned to the electrolyte layer, so the nucleation matrix was regenerated in each cycle rather than being consumed or displaced together with the Li deposit. A pouch-type full cell operated at 2.0 MPa and 60 °C delivered an areal capacity of 7.0 mA h cm⁻² at 0.7 mA cm⁻² with 95.0% capacity retention after 50 cycles and a volumetric energy density of 1312 Wh L⁻¹ excluding packaging materials, and stable operation was also demonstrated at 30 °C with 87.4% retention after 50 cycles. This result indicates that deposition-site regulation need not rely on a fixed or sacrificially consumed interlayer, although the reported cycle numbers remain modest compared with interlayer-based cells.

Jun et al. proposed a structurally adaptive approach using Mg particles as a “breathing” anode framework for Li-free all-solid-state batteries [109]. In their design, a Li concentration gradient from the Mg particle surface to the core promotes Li redistribution and deposition between Mg particles. The anode-side interface therefore behaves as an evolving alloy framework rather than a static planar current collector. This breathing behavior allows the interparticle spacing to change during repeated plating/stripping, providing a route to accommodate Li morphology evolution while maintaining interfacial contact. The full cell with an NCM cathode retained Coulombic efficiency above 99.9% over 1000 cycles at 30 °C, and capacity retention reached 80% after 500 cycles when a sacrificial Li₃N additive in the cathode compensated the initial Li loss. These full-cell demonstrations were, however, conducted under 30 MPa, and the corresponding half cell sustained 99 cycles with an average Coulombic efficiency of 98% when the pressure was reduced to 5 MPa. The breathing framework thus validates stripping-tolerant contact retention as a design principle, but its capability in the practically relevant low-pressure regime remains to be demonstrated at the full-cell level.

A complementary route preserves stripping-side contact through mechanical compliance placed directly at the anode interface. Oh et al. demonstrated this concept in anode-less sulfide SSBs using a dual thin-film anode composed of an Mg upper layer and a Ti₃C₂T_x MXene buffer layer underneath (Fig. 8d) [110]. The Mg layer lowered the kinetic barrier for Li (de)alloying, while the ductile MXene layer [111] suppressed void formation and maintained interfacial contact at 2 MPa. In half-cell plating and stripping tests at 2 MPa, the initial Coulombic efficiency increased from 60.8% for bare Mg to 75.4% for the MXene/Mg design, and the lifespan before short-circuiting was extended from 130 to 380 h. Post-cycling analysis showed that the MXene/Mg interface remained substantially flatter than Mg alone, while internal porosity after 10 cycles decreased from ≈28% for bare Mg to 6% for the MXene/Mg design. This result demonstrates that stripping-induced contact loss can be mitigated at the electrochemically active interface itself, rather than only through the packaging- and fixture-level compliance strategies discussed in Section 5.

Overall, ALSSBs rely on interfacial architectures that perform two complementary functions: (i) regulating where and how densely Li nucleates and deposits during charging, and (ii) preserving interfacial contact during stripping. Nevertheless, the absence of excess Li makes these systems especially sensitive to irreversible Li loss, contact discontinuity, and nonuniform deposition. Moreover, the most extended demonstrations still depend on elevated temperature or on pressures above the practically targeted low-pressure regime, and room-temperature operation at 2 MPa has so far been achieved with shorter cycle lives than the elevated-temperature counterparts. Thus, in the context of low-pressure operation, anode-less configurations should not be regarded simply as energy-density-enhancing designs, but as demanding tests of whether interfacial and architectural engineering can sustain reversible Li cycling with minimal external mechanical compensation.

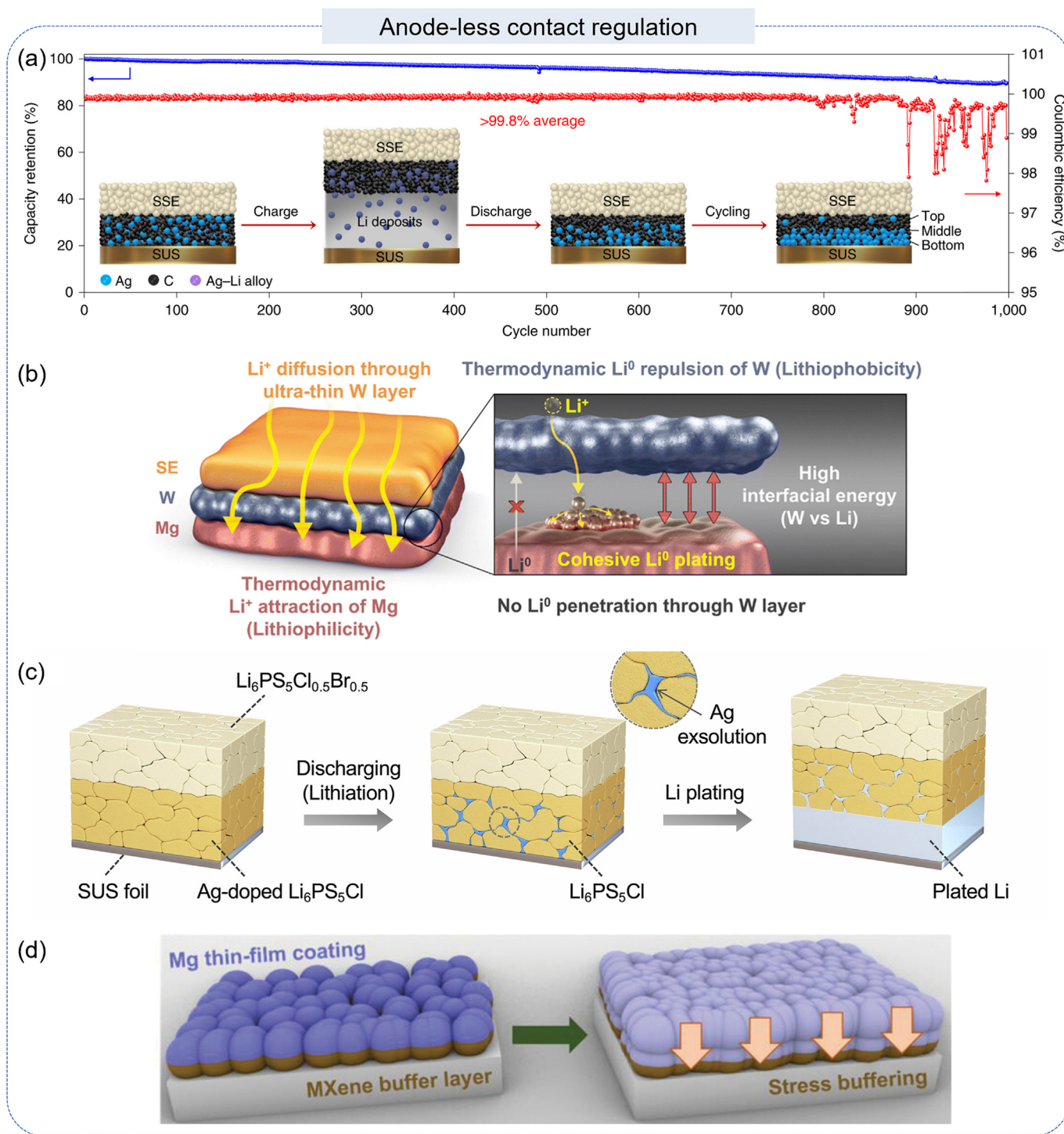


Fig. 8. Contact-regulation strategies for low-pressure anode-less SSBs. (a) An Ag–C composite layer acting as an alloy-forming nucleation matrix for uniform Li deposition and stable cycling for 1000 cycles at 2 MPa. Adapted with permission from Ref. [29]. Copyright 2020, Springer Nature. (b) A lithio-amphiphilic W/Mg nanobilayer in which lithiophilic Mg promotes uniform Li nucleation and lithiophobic W confines dense Li deposition beneath the W layer. Reproduced with permission from Ref. [30]. Copyright 2024, Royal Society of Chemistry. (c) An Ag-substituted Li-argyrodite bilayer enabling reversible Ag exsolution and regeneration of nanoscale lithiophilic nucleation sites during Li plating/stripping. Reproduced with permission from Ref. [108]. Copyright 2025, The Author(s). Published by Springer Nature. This material is excluded from the Creative Commons license governing this article. (d) An MXene/Mg dual thin-film electrode in which Mg–Li (de)alloying regulates Li deposition and a ductile MXene buffer preserves interfacial contact during stripping. Adapted with permission from Ref. [110]. Copyright 2023, Wiley-VCH.

From an anode-design perspective, the key challenge is to decouple reversible Li plating/stripping from the need for continuous external mechanical compensation. Future work should therefore evaluate whether 3D hosts, interlayers, compliant buffers, and

anode-less current collectors can maintain stable Li morphology and interfacial contact under realistic areal capacities, lean Li inventory, and limited stack pressure. In particular, interface analysis should be coupled with full-cell performance evaluation,

because stable voltage profiles alone may not reveal gradual contact loss, nonuniform Li deposition, or irreversible Li inventory loss during cycling. Such combined analysis will be essential for identifying anode-side designs that are truly compatible with practical low-pressure operation.

5. Cell-level design and stack-level pressure management

The cathode- and anode-side strategies discussed above aim to stabilize local interfaces under reduced mechanical confinement. Although such component-level approaches can substantially improve low-pressure performance, their effectiveness ultimately depends on how pressure is applied, transmitted, and maintained at the full-cell level. In practical SSBs, as described in Section 2.3, the nominal stack pressure does not necessarily represent the actual local pressure experienced across the cell. Instead, pressure evolves temporally with electrochemical volume changes and varies spatially owing to cell geometry, electrode roughness, current collector rigidity, and local differences in interfacial conformity.

Cell-level design must therefore address how pressure is controlled and homogenized across multilayer architectures. Poorly regulated pressure can either fail to maintain solid–solid contact under weak confinement or generate local stress concentrations that accelerate cracking, delamination, Li penetration, or nonuniform reaction. Conversely, optimized pressure fixtures, compliant layers, and pressure-homogenizing stack architectures can convert external pressure into a more uniform and reversible interfacial contact state. This section discusses three stack-level approaches that counter these cell-level amplification effects: pressure application and control strategies that regulate the global mechanical

boundary condition and its temporal evolution, mechanical buffering layers that locally accommodate stress and thickness variation, and architecture-enabled strategies that improve pressure homogeneity and stress distribution within the cell stack.

5.1. Pressure application and control strategies

Pressure application and control strategies address the global mechanical boundary condition of the cell, including how the applied load is regulated during cycling and how pressure is distributed across the stack, thereby countering the temporal pressure fluctuation and relaxation described in Section 2.3. Conventional fixed-volume laboratory cells can convert electrochemical volume change into large pressure fluctuations. In contrast, optimized pressure-control systems aim to maintain stable and spatially uniform operating pressure while accommodating dimensional changes during cycling. Recent studies have therefore moved beyond simply increasing uniaxial load to focus on dynamic pressure accommodation, regulated pressure application, and electrode-specific pressure partitioning. Fig. 9 presents representative pressure-control strategies.

One approach is to introduce controlled compliance into the pressure fixture so that cycling-induced volume changes are absorbed by the fixture rather than fully translated into stack-pressure fluctuations. Lee et al. developed a dual-sensor-equipped variable-volume cell and showed that conventional fixed-volume assemblies can generate MPa-scale pressure variations during cycling (Fig. 9a) [112]. By incorporating compression springs, the pressure fluctuation was reduced to the hundred-kPa scale because part of the mechanical displacement was accommo-

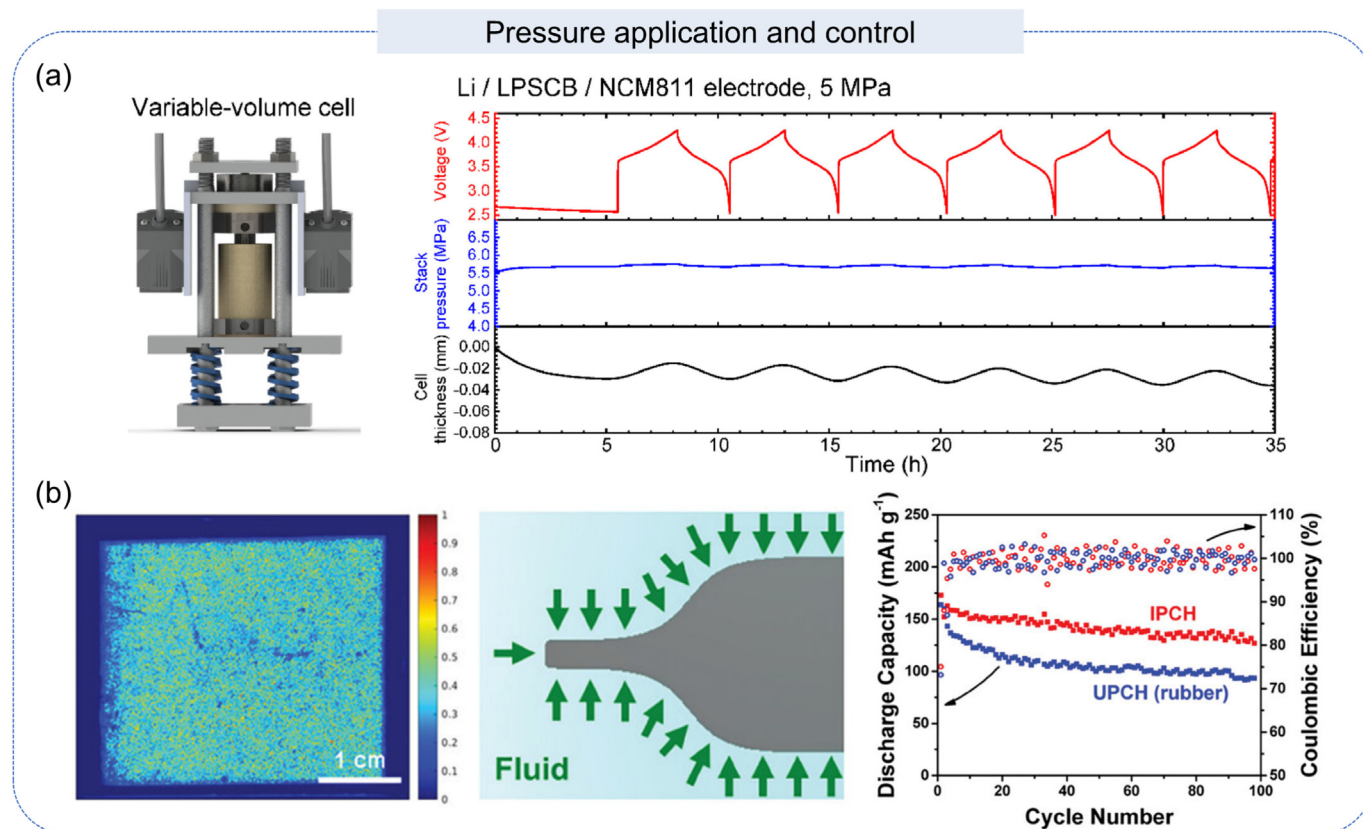


Fig. 9. Cell- and stack-level pressure-management strategies for low-pressure SSBs. (a) Spring-assisted, dual-sensor-equipped variable-volume cell and corresponding voltage, stack-pressure, and cell-thickness profiles at an initial pressure of 5 MPa, showing accommodation of cycling-induced volume changes and suppression of pressure fluctuations to the hundred-kPa scale. Reproduced with permission from Ref. [112]. Copyright 2024, Elsevier. (b) Color-mapped pressure distribution, fluid-mediated isostatic loading, and cycling performance of pouch-type SSBs using an isostatic pouch cell holder (IPCH) and a rubber-gasket uniaxial pouch cell holder (UPCH) at 5 MPa, demonstrating more uniform and accurately controlled pressure with the IPCH. Reproduced with permission from Ref. [32]. Copyright 2024, Wiley-VCH.

dated by spring deformation. This result emphasizes that an optimized pressure setup should not only impose the desired initial pressure, but also maintain the operating pressure within a narrow range as the cell expands and contracts during cycling.

Another strategy is to improve the spatial uniformity and controllability of pressure in pouch-type cells. Chen et al. introduced an IPCH to overcome the limitations of conventional uniaxial fixtures, including nonuniform pressure distribution, poor accommodation of electrode volume changes, and unstable cycling pressure (Fig. 9b) [32]. By using air as the pressurizing medium, the holder imposed a more uniform and accurately controlled external pressure on pouch-type SSBs. In NCM811|LPSCI|Si pouch cells cycled between 1 and 5 MPa, increasing pressure improved cycling performance, and 2 MPa was identified as the minimum pressure required for optimal operation in that system. The same architecture was extended to a 100 mA h bilayer pouch cell, which delivered a first-cycle Coulombic efficiency of 76.9%, a discharge capacity of 173.6 mA h g⁻¹ (88.1 mA h), and 83.6% capacity retention after 100 cycles. This work demonstrates that pressure-control hardware can act as an enabler of pouch cell scale-up, rather than merely as a test fixture.

Pressure management can also be improved by decoupling the mechanical requirements of different electrodes. Doerrer et al. demonstrated an asymmetric pressure design in which a calibrated uniaxial load maintained the anode at 2.5 MPa, while a compression spring limited the cathode pressure to 0.2 MPa [113]. The pressure asymmetry was maintained because friction between the SE pellet and mold wall suppressed pressure transmission, as verified experimentally and by finite-element modeling. Under this configuration, SC-NCM/LPSCI cathodes delivered discharge capacities above 200 mA h g⁻¹, and even a high-loading cathode of 8.7 mA h cm⁻² could be cycled at a cathode pressure of 0.2 MPa. This study demonstrates that practical pressure management may require electrode-specific pressure windows rather than a single uniform load applied across the entire stack.

Taken together, these studies show that pressure management in practical SSBs must account for cycling-induced pressure evolution, spatial pressure uniformity, and electrode-specific mechanical requirements. Thus, the relevant design target is not simply the nominal pressure applied at the beginning of cycling, but the ability to maintain appropriate, spatially controlled, and temporally stable pressure throughout operation.

5.2. Mechanical buffering and compliance layers

Mechanical buffering and compliance layers provide local adaptability within the stack by accommodating surface roughness, layer misalignment, and cycling-induced thickness changes that cannot be fully resolved by external pressure control alone. Unlike the fixture-level strategies discussed in Section 5.1, these layers operate closer to electrochemically active interfaces and redistribute local stress before it develops into severe contact loss or nonuniform current distribution. Their role is therefore not simply to soften the stack, but to convert heterogeneous local contact into a more uniformly loaded and reversibly contacted interface. Representative buffering layers and pressure-homogenizing architectures are summarized in Fig. 10.

Thorpe et al. demonstrated this concept by introducing a thin elastomeric interlayer behind the current collector in anode-less sulfide cells to compensate for plate roughness and angular misalignment (Fig. 10a) [114]. The silicone elastomer promoted a more uniform stress distribution across the anode-less interface, improving Li plating coverage from 49% to 70% after plating to 2 mA h cm⁻² and increasing Coulombic efficiency from 89% to 94%. By combining experiments with finite-element simulations, the study showed that packaging-level mechanical compliance

can homogenize interfacial pressure without directly modifying interfacial chemistry. This result highlights that pressure nonuniformity can originate from macroscopic cell and fixture imperfections, not only from electrode or electrolyte materials.

A second class of compliance layers combines mechanical buffering with electronic functionality. Cao et al. introduced a conductive carbon felt elastic layer in anode-less all-solid-state cells, where the felt self-adjusted the anode-side pressure during cycling while maintaining Li/SE contact during stripping (Fig. 10b) [115]. The carbon felt simultaneously provided electronic conduction and released pressure accumulated during Li plating, producing a self-regulated internal pressure response. As a result, the first-cycle Coulombic efficiency increased from 58.4% to 83.7%, accompanied by more than a tenfold improvement in cycling stability. This example shows that a compliance layer can function as an electro-mechanically active structural component rather than a passive mechanical cushion.

Taken together, mechanical buffering and compliance layers can be classified by their operating length scale and functionality. Elastomeric homogenizers address packaging-level pressure nonuniformity, and conductive elastic layers couple stress accommodation with current collection. Compliance can also be placed directly at the electrochemically active interface, as exemplified by the ductile MXene/Mg buffer discussed in Section 4.3, which suppresses stripping-induced contact loss at its origin rather than at the packaging level. Across these approaches, the central design principle is to endow the stack with local mechanical adaptability, allowing interfacial contact to be retained under practical confinement without relying solely on higher external pressure.

5.3. Strategies for pressure homogeneity and stress distribution

Beyond external pressure regulation and dedicated compliance layers, pressure homogeneity can also be improved by designing electrode/electrolyte architectures that transmit load more uniformly and suppress poorly contacted regions from the outset (Fig. 10c, d). This approach shifts the focus from how pressure is applied to how the stack receives and distributes that pressure, addressing the spatial pressure nonuniformity and scale-up effects described in Section 2.3. Accordingly, electrode/electrolyte manufacturing routes, current collector interfaces, dry-processing methods, and integrated bonding strategies can all serve as upstream pressure-management tools by improving interfacial coverage, adhesion, and mechanical continuity before cycling begins.

For larger cell formats, Grandjean et al. showed that pressure tolerance is strongly coupled to the electrode/electrolyte manufacturing route and cell architecture. In their sulfide-based NCM/LPSCI/nanosilicon system, 10 cm² all-coated pouch cells cycled under 1 MPa outperformed pelletized cells cycled under >100 MPa [116]. The improved behavior was attributed to better densification, enhanced microstructural homogeneity, and lower resistance in the sheet-type architecture. This comparison illustrates that low-pressure operation cannot be evaluated independently of cell format; when the electrode/electrolyte architecture is made more homogeneous and better matched to pouch-scale assembly, the operating pressure required for stable cycling can be substantially reduced.

Current collector modification provides a more localized approach to improving pressure transmission and interfacial adhesion. Oh et al. introduced a primer layer of carbon conductive agent and polyvinylidene fluoride between the electrode and the current collector, which raised the interfacial adhesion force from 1.56 to 2.45 N at the Al collector and from 1.62 to 2.50 N at the Cu collector and allowed the inactive binder content to be reduced [33]. The improved adhesion lowered the cathode and anode interfacial resistances by 91.4% and 88.8%, and a 40 × 30 mm² pouch full cell

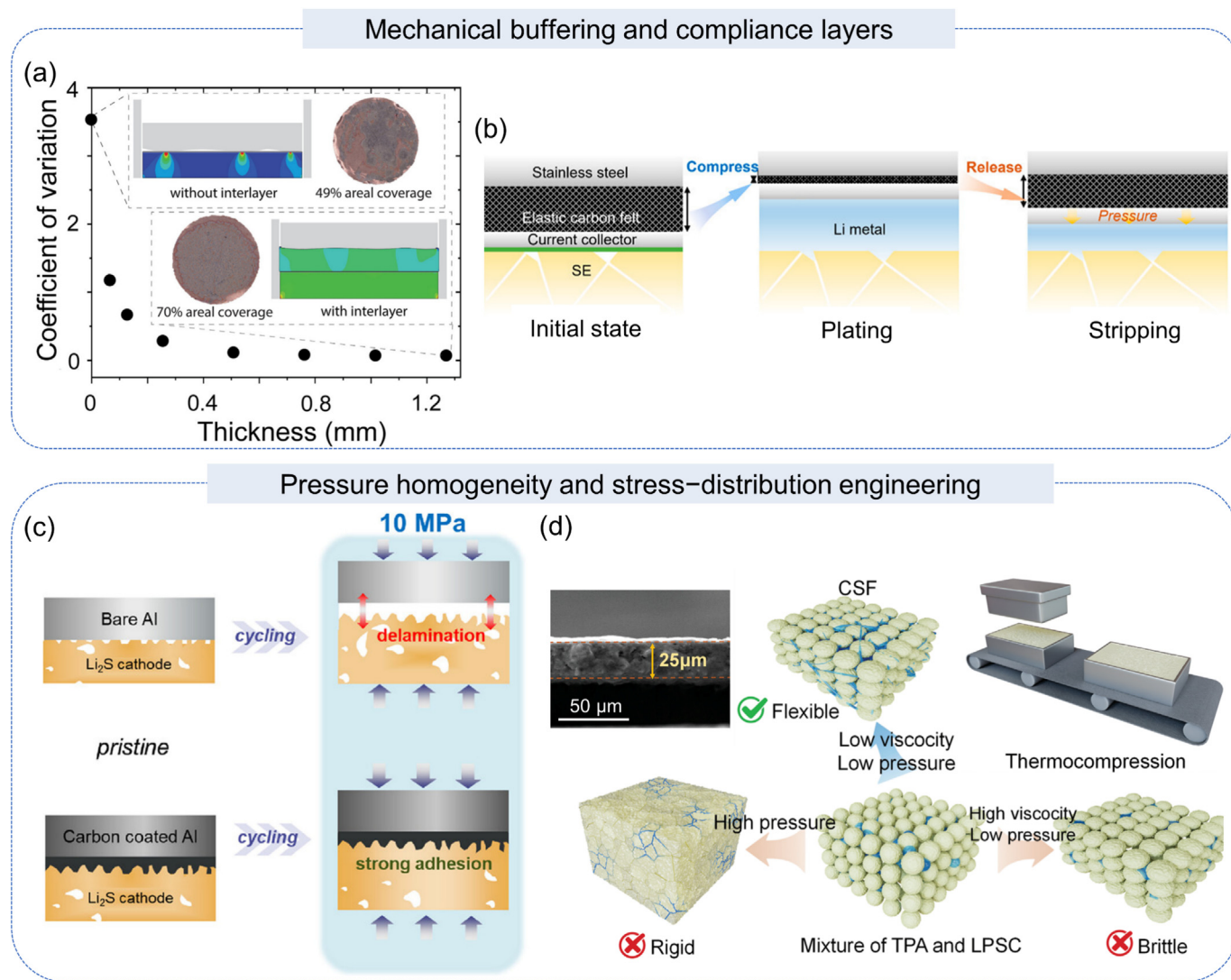


Fig. 10. Mechanical buffering and pressure-homogenizing architectures for low-pressure SSBs. (a) Simulated interfacial-stress variation and Li-plating images for silicone interlayers of different thicknesses, showing mitigation of local pressure inhomogeneity caused by surface roughness and angular misalignment. Reproduced with permission from Ref. [114]. Copyright 2025, Elsevier. (b) Schematic of a conductive carbon felt elastic layer that compresses during Li plating and releases during Li stripping to self-regulate anode-side pressure and maintain Li/SE contact. Reproduced from Ref. [115] under the CC BY 4.0 license. Copyright 2023, The Author(s). Published by American Chemical Society. (c) Schematic comparison of Li_2S cathodes on bare and carbon-coated Al current collectors before and after cycling at 10 MPa, showing suppressed delamination and retained cathode–collector adhesion through the carbon-based primer layer. Reproduced from Ref. [34] under the CC BY 4.0 license. Copyright 2026, The Author(s). Published by Wiley-VCH. (d) Solvent-free fusion-bonding process and cross-sectional SEM image of a flexible composite sulfide film (CSF) formed from low-viscosity thermoplastic polyamide (TPA) and LPSCI by low-pressure thermocompression, showing how binder viscosity and applied pressure govern film flexibility. Adapted with permission from Ref. [118]. Copyright 2024, Wiley-VCH.

operated at 30 °C without any external stack pressure delivered 201.7 mA h g^{−1} in the first cycle with an initial Coulombic efficiency of 80.3% and 80.7% capacity retention after 100 cycles, compared with 182.0 mA h g^{−1}, 75.6%, and 64.8% for the uncoated cell. Because the cell was consolidated by warm isostatic pressing at 480 MPa and 60 °C before cycling, this result also illustrates that fabrication pressure and operating pressure can be decoupled when the collector interface is engineered. Park et al. demonstrated the same principle at the cathode–collector interface in all-solid-state Li–S cells, where carbon-primed Al foil reduced interfacial resistance, improved cathode adhesion, and stabilized cycling relative to unmodified collectors (Fig. 10c) [34]. Those results were obtained at 10 MPa, however, so this study falls within the moderate-pressure regime and indicates how collector surface chemistry and topology govern the conversion of an applied load into electrochemically active contact.

A second route is to improve contact coverage during electrode fabrication, so that the applied pressure is not primarily consumed

in closing mesoscale gaps during operation. Lee et al. showed that dry-processed cathodes can exploit shear-force-induced deformation of the SE to increase cathode contact coverage [117]. Dry-processed electrodes reached an average coverage of 67.2%, compared with 30.6% for pellets and 33.3% for wet-processed electrodes, and this higher coverage was directly associated with improved rate capability and cyclability. From a stack-level perspective, improved initial contact coverage places the cell in a more homogeneous mechanical state before cycling, reducing the dependence of later performance on locally concentrated pressure.

Integrated bonding and co-rolling approaches further extend this concept by forming electrode/electrolyte laminates with stronger mechanical continuity. Hu et al. developed a fusion-bonding route in which a thermoplastic polyamide/LPSCI network was formed by thermocompression at a fabrication pressure of ≤5 MPa and 140 °C, enabling ultrathin sulfide films (≤25 μm) with built-in stress dissipation and strong adhesion to thick cathodes (Fig. 10d) [118]. The resulting integrated batteries were

Table 2

Critical comparison of the design strategy categories discussed in Sections 3–5 for low-pressure SSB operation. Strategies are grouped by the cell component at which they act, and each category is annotated with the primary failure pathway (Section 2) that it targets.

Strategy category (section)	Representative designs [Ref.]	Operating temp (°C)	Stack pressure (MPa)	Representative performance	Advantages	Limitations, processing, and scalability
Cathode-side strategies (Section 3)						
Chemically anchored CAM–SE interfaces (3.1) <i>Targets: volume-change-driven CAM–SE contact loss (2.1.1)</i>	In situ recrystallized, chemically fused NCM88–LIC interface [20]	55	≈2	201 mA h g ^{−1} at 0.1C with 1.4 mA h cm ^{−2} (6.9 mg cm ^{−2}); 80% retention after 278 cycles (54% after 1500) at 0.3C	Strong interfacial adhesion; SE serves as reaction mediator and mechanically tolerant contact phase	Specific to the CAM–SE chemistry pair employed, extension to sulfide SEs unverified
Stress-mitigated CAM architectures (3.1) <i>Targets: CAM volume change and microcracking (2.1.1)</i>	Al/Zr-decorated single-crystal NCM811 (AZ@SC811) [98]	30	2	166.7 mA h g ^{−1} at 0.2C, 90.8% retention after 50 cycles; ≈94% of the capacity measured at 100 MPa (vs. ≈87% for undecorated CAM)	Reduces the chemo-mechanical driving force at its source; preserves both contact and transport continuity	Cycling demonstrated over 50 cycles, long-term and high-areal-capacity validation still required
Crosslinked binder networks (3.1) <i>Targets: particle slippage and interfacial debonding (2.1.1)</i>	In situ vulcanized 3D BR network [99]; thiol–ene click-crosslinked SBR [18]	30	0.3–2; pouch cells without external pressure	NCM/LTO pouch cell: 153 mA h g ^{−1} at 0.2C and 72.8% retention after 150 cycles under no external operating pressure; 163 mA h g ^{−1} with 75% retention after 100 cycles at 0.2C and 0.3 MPa	Most compatible with slurry-based manufacturing; lowest demonstrated operating pressures; in situ chemistry avoids binder redispersion and slurry gelation	Demonstrations limited to moderate CAM loadings (≈8–10 mg cm ^{−2}), effectiveness in thick, high-areal-capacity cathodes unverified
Coating-assisted interfacial stabilization (3.1) <i>Targets: interfacial side reactions and contact degradation (2.1.1)</i>	TMATFSI organic ionic plastic crystal coating on NCM90 [23]	25	10 (moderate regime)	82.9% retention after 100 cycles vs. 35.8% for uncoated NCM90	Broadly applicable across CAM chemistries; suppresses interfacial side reactions and resistance growth	Benefit under strictly low-pressure (≤2 MPa) conditions not yet demonstrated, currently a moderate-pressure relaxation strategy
SE microstructure control (3.2) <i>Targets: transport network disruption (2.1.2)</i>	Fine-particle LPSCI distribution in NCM811 composite [25]	30	2	Median tortuosity 1.21 vs. 1.84 (coarse LPSCI); 85.6% vs. 63.3% retention after 100 cycles	Implementable with conventional composite processing; lowers pressure sensitivity of cathode transport	Fine sulfide powders increase moisture sensitivity and handling requirements, raising processing cost
Triple-phase-boundary (TPB) regulation (3.2) <i>Targets: transport disruption and TPB-driven SE decomposition (2.1.2)</i>	Low-surface-area CNFs replacing Ketjen black in thick, coating-free NCM cathode [24]	30	2	≈4.6 mA h cm ^{−2} (≈110 μm, ≈25 mg cm ^{−2}); 85% retention after 500 cycles; capacity loss 0.03%/cycle (≈12 × lower than Ketjen black)	Enables thick, coating-free cathodes using conventional composite processing	Demonstrated with an LTO counter electrode (Table 1), transfer to Li-metal full cells to be confirmed
Process-integrated cathode/SE films (3.2) <i>Targets: contact loss, transport disruption, and interfacial voiding (2.1.1–2.1.2)</i>	Co-rolled dry-processed positive electrode–SE film [26]	60; 30 for pouch cell	2; 5 for pouch cell	5 mA h cm ^{−2} at 80 wt% CAM; >80% retention after 500 cycles at 0.5C; capacity loss on 75 → 2 MPa reduction 8.5% vs. 13.2% (freestanding); pouch 310 Wh kg ^{−1} / 805 Wh L ^{−1}	Embeds contact robustness during fabrication; directly linked to stack-level performance metrics	Depends on dry-film equipment whose large-area uniformity and throughput are still maturing
Anode-side strategies (Section 4)						
3D and composite anode host architectures (4.1) <i>Targets: creep-limited voiding and current localization (2.2.1–2.2.2)</i>	MIEC garnet framework [101]; hollow Ag/carbon-fiber scaffold [102]; Li–CNT composite anode [103]	RT	Pressure-free to sub-MPa (pouch cell at 320 kPa)	CCD up to 100 mA cm ^{−2} (MIEC trilayer); pouch cell 90.5% retention after 100 cycles at 320 kPa; >20-fold increase in one-way stripping-to-depletion capacity (≈25 vs. 1.2 mA h cm ^{−2} at 0.1 mA cm ^{−2} , Li–CNT)	Distributes current, Li transport, and deformation over an electrode volume; largest demonstrated CCD gains; lowest demonstrated operating pressures	Pore volume and host mass reduce volumetric/gravimetric energy density, rigid ceramic frameworks incompatible with roll-to-roll lamination, only the Ag/C-fiber scaffold pouch-validated
Li/SE interlayer engineering (4.2) <i>Targets: stripping-induced voids, electron leakage, and filament nucleation (2.2.1–2.2.2)</i>	Mg ₁₆ Bi ₈₄ conversion interlayer [104]; porous Li ₇ N ₂ I–CNT/Mg [28]; hierarchical Si/C [105]; graphitized CNT/fluorinated-graphite (LNT10F) [106]	80 for [104]; 25 and 60 for [28]; 30 for [105]; RT for [106]	≈1 (Li ₇ N ₂ I); 2.5–15 for other examples	Up to 11.1 mA h cm ^{−2} and 310 Wh kg ^{−1} at 2.5 MPa; 2.2 mA h cm ^{−2} with 82.4% retention after 350 cycles; 3.4 mA h cm ^{−2} with 80.9% retention after 200 cycles; >91% after 100 cycles at 0.3C	Coordinates chemical stabilization, charge-carrier transport, and contact retention at the existing Li/SE interface	Long-term cycling at high loading unverified for [104]; only Li ₇ N ₂ I systems verified within ≤2 MPa; elevated temperature and added interlayer volume remain constraints

(continued on next page)

Table 2 (continued)

Strategy category (section)	Representative designs [Ref.]	Operating temp (°C)	Stack pressure (MPa)	Representative performance	Advantages	Limitations, processing, and scalability
Anode-less: nucleation and deposition regulation (4.3) <i>Targets: current localization and nonuniform Li deposition (2.2.2)</i>	Ag–C nucleation layer [29]; lithio-amphiphilic W/Mg nanobilayer [30]; Ag-exsolving SE bilayer [108]	60 for [29,108]; 25 for [30]	2	900 Wh L ⁻¹ , 89% retention after 1000 cycles at 0.5C; 1100 Wh L ⁻¹ , 71.9% after 300 cycles at 0.3C; 1312 Wh L ⁻¹ , 95.0% after 50 cycles at 0.1C	Among the highest reported volumetric energy-density values; controls where and how densely Li deposits without excess Li	Longest lifetimes require 60 °C, RT 2 MPa operation shows shorter cycle life, especially sensitive to irreversible Li loss and contact discontinuity
Anode-less: stripping-side contact preservation (4.3) <i>Targets: stripping-induced contact loss (2.2.1)</i>	Breathing Mg-particle anode [109]; ductile MXene/Mg dual thin-film anode [110]	30 for [109]; 25 for [110]	5 for half cell and 30 for full cell [109]; 2 for [110]	Average CE 98% over 99 cycles at 5 MPa and CE >99.9% over 1000 cycles at 30 MPa (breathing framework); Initial CE 60.8 → 75.4% and short-circuit-free lifespan 130 → 380 h in half cell and 30 cycles at 0.1C in full cell	Mitigates stripping-induced contact loss at the electrochemically active interface itself	Low-pressure capability not yet demonstrated at the full-cell level; validation largely at half-cell scale
Cell-level strategies (Section 5) Pressure application and control (5.1) <i>Targets: temporal pressure fluctuation and relaxation (2.3)</i>	Spring-assisted variable-volume cell [112]; isostatic pouch cell holder [32]; electrode-specific asymmetric loading [113]	40 for [112]; 30 for [32,113]	5 for [112]; 1–5 for [32]; 2.5/0.2 (anode/cathode) for [113]	Springs held stack pressure at 98.94% and capacity at 91.73% over 65 cycles, vs. 80.00% and 75.82% in a volume-fixed cell; 100 mA h bilayer pouch, 83.6% retention after 100 cycles; 8.7 mA h cm ⁻² cathode with initial CE of 87% under asymmetric anode/cathode pressure of 2.5/0.2 MPa Li plating coverage 49 → 70% at 2 mA h cm ⁻² and initial CE 89 → 94%; initial CE 58.4 → 83.7% with >99.5% CE for the first 30 cycles	Maintains temporally stable, spatially controlled pressure; enables electrode-specific pressure windows; can act as a pouch scale-up enabler	Pressure-control components add inactive mass, volume, and manufacturing cost at the module level; retention at 2 MPa falls to 47.7% vs. 77.8% at 5 MPa [32]
Mechanical buffering and compliance layers (5.2) <i>Targets: local stress heterogeneity (2.3)</i>	Elastomeric interlayer behind the current collector [114]; conductive carbonfelt elastic layer [115]	RT	≈5 (nominal, finite-element) for [114]; 7.5 for [115]	Li plating coverage 49 → 70% at 2 mA h cm ⁻² and initial CE 89 → 94%; initial CE 58.4 → 83.7% with >99.5% CE for the first 30 cycles	Homogenizes local pressure without modifying interfacial chemistry; can couple stress accommodation with current collection	Demonstrated over first-cycle plating to ≈30 cycles; creep and stress relaxation of the compliant layers uncharacterized
Manufacturing- and architecture-enabled contact homogeneity (5.3) <i>Targets: spatial pressure nonuniformity and scale-up effects (2.3)</i>	Sheet-type pouch architecture [116]; carbon-coated current collector [34]; dry-processed contact coverage [117]; fusion-bonded cathode/SE laminates [118]	RT for [34,116]; 25 and 60 for [117]; 30 and 50 for [118]	1 for [116] (10 cm ² pouch); 10 for [34]; not reported for [117] (three screws, 11 N m torque); 30–80 for [118]	10 cm ² pouch: 79% retention after 160 cycles; ≈800 mA h g ⁻¹ with 78% retention after 350 cycles in a Li ₂ S Li _{0.5} In half-cell; contact coverage 67.2% vs. 30.6% (pellet) / 33.3% (wet-processed); ≤25 μm sulfide film enabling 390 Wh kg ⁻¹ / 1020 Wh L ⁻¹	Improves interfacial coverage and adhesion before cycling; supports scalable sheet and pouch formats	Current collector benefit demonstrated only at 10 MPa and at half-cell level; fusion-bonded cells operated at 30–80 MPa; the 1 MPa pouch demonstration reaches only 104 Wh kg ⁻¹ at C/20; relies on manufacturing routes rather than components addable to an existing cell

Abbreviation: Coulombic efficiency (CE).

demonstrated in long-life, bipolar, and pouch-type formats, highlighting that pressure homogeneity can be improved by strengthening the laminate itself rather than by simply increasing external load. The co-rolling dry process discussed in Section 3.2 achieves a similar effect from the electrode-fabrication side, embedding interfacial robustness into the positive electrode/SE laminate before cell assembly.

Overall, these studies show that pressure homogeneity is not only a fixture-level problem, but also a manufacturing and architecture-design problem. Current collector engineering can improve adhesion and reduce local interfacial resistance, dry processing can increase initial contact coverage, and bonded or co-rolled architectures can suppress poorly contacted regions under reduced pressure. These strategies complement the global pressure-control approaches of Section 5.1 and the local compliance-layer approaches of Section 5.2 by making the stack intrinsically less sensitive to pressure gradients.

From a cell-engineering perspective, future low-pressure SSB studies should report not only the nominal stack pressure, but also how pressure is applied, distributed, and maintained during cycling. Practical evaluation should include pressure evolution, fixture compliance, local pressure homogeneity, inactive mass and added manufacturing cost associated with pressure-control components, and compatibility with multilayer pouch cell formats. Such reporting is necessary because the same nominal pressure can represent very different mechanical boundary conditions depending on cell geometry, fixture design, and manufacturing route.

To consolidate the strategies discussed in Sections 3–5, Table 2 compares the principal design categories in terms of their targeted failure pathways, demonstrated pressure and temperature conditions, representative performance, advantages, and current limitations. Two cross-cutting observations emerge from this comparison. First, although operation within the practically relevant ≤ 2 MPa regime has been demonstrated in most categories, these demonstrations typically rely on compensating conditions such as elevated temperature, moderate areal loading, or small cell formats, and several categories, including coating-assisted stabilization and most interlayer designs, remain confined to the moderate-pressure regime. Second, the strategies are complementary rather than interchangeable. Component-level designs reduce the pressure required to stabilize individual interfaces, whereas cell-level designs determine whether that pressure is actually delivered uniformly and maintained throughout cycling. Low-pressure operability therefore emerges from the co-design of active materials, interfaces, electrode architectures, and pressure-management systems, rather than from any single modification.

6. Conclusions and perspectives

SSBs are often evaluated under externally applied stack pressure because solid–solid interfaces cannot self-adjust like liquid-wetted interfaces. This review emphasizes that the pressure sensitivity of SSBs should not be interpreted simply as a need for mechanical compression. Rather, it reflects the inability of dynamically evolving solid–solid interfaces to maintain sufficient real contact area, homogeneous current distribution, and mechanically stable reaction pathways under limited confinement. When stack pressure is insufficient, the reduced real contact area leads to current constriction, local stress concentration, and progressive interfacial degradation. High stack pressure can therefore improve apparent performance by mechanically compensating for these instabilities, but it does not by itself solve the underlying limitations of the cell architecture. In this sense, high pressure relocates the burden of contact retention from the cell to the external fix-

ture, whereas low-pressure operability requires that this burden be absorbed by the cell itself. This correspondence between failure modes and design strategies, organized by the four unifying functions of contact retention, transport robustness, Li deposition regulation, and pressure homogenization, is summarized in Fig. 4.

The failure modes discussed in this review show that low-pressure degradation is intrinsically coupled across materials, interfaces, and cell architecture, and that it proceeds as a distinct causal sequence at each level. On the cathode side, lattice breathing and volume mismatch of cathode active materials promote CAM–SE contact loss, microcracking, disruption of ionic/electronic transport networks, and through-thickness reaction heterogeneity in thick composite electrodes. On the anode side, Li stripping under weak confinement causes creep-limited interfacial void formation, current localization at residual contact patches, and filament-mediated short-circuiting when subsequent Li deposition becomes sufficiently nonuniform. At the cell level, these interfacial mechanisms are amplified by temporal pressure fluctuation and relaxation, together with spatial pressure nonuniformity that creates locally under- and over-pressurized regions. As cell format increases, these effects make contact loss, reaction heterogeneity, current localization, and crack-assisted Li penetration more difficult to control than in small, rigidly constrained laboratory cells. These degradation pathways become even more critical in thin-Li and anode-less configurations, where the Li inventory is limited and interfacial contact must be regenerated reversibly during every cycle. Stable low-pressure operation therefore requires more than chemically stable interfaces; it requires mechanically adaptive cell architectures that preserve real contact area, suppress transport bottlenecks, stabilize Li deposition, and homogenize stress and electrochemical reactions across the full cell.

Recent progress indicates that this goal can be approached through multiscale design at three complementary levels: (i) cathode-side strategies that combine contact-stable composite architectures—chemically anchored CAM–SE interfaces, stress-mitigated CAM architectures, crosslinked binder networks, and coating-assisted interfacial stabilization—with transport-robust electrode engineering based on SE microstructure control, triple-phase-boundary regulation, and process-integrated cathode/SE architectures; (ii) anode-side strategies comprising pressure-tolerant 3D or composite Li architectures, functional interlayers for coordinated chemical, transport, and mechanical stabilization, and anode-less designs using nucleation-guiding layers, self-regenerating nucleation seeds, and ductile buffer layers; and (iii) cell-level strategies involving pressure-control hardware, elastomeric compliance layers, current collector surface engineering, dry-process contact optimization, and bonded laminate architectures. Collectively, these approaches show that the central design principle for low-pressure SSBs is shifting from externally forcing contact to intrinsically retaining contact through interface, electrode, and stack-level co-design. To translate this concept into practical cell technologies, however, the field must define more clearly how low-pressure operability should be evaluated and compared.

Cycling performance at a single nominal pressure is insufficient to establish practical relevance because pressure tolerance depends strongly on areal capacity, electrode thickness, cell format, temperature, current density, fabrication pressure, and pressure evolution during cycling. Future studies should therefore report coupled metrics, including operating pressure window, active-material loading, areal capacity, electrolyte thickness, cell format, pressure-control method, inactive-mass penalty, and scalability to multilayer or pouch cell configurations. Such standardized reporting would enable fairer comparison among different strategies and help distinguish truly pressure-tolerant cell designs from demonstrations that rely on hidden mechanical or

architectural advantages or on compensating conditions such as elevated operating temperature, moderate areal loading, or small cell formats.

A second priority is to move from component-level optimization toward coupled chemo-mechanical full-cell design. Low-pressure instability does not originate from a single weak interface, but from the coupled evolution of contact loss, stress accumulation, transport constriction, and morphology-dependent reaction heterogeneity across the entire stack. Accordingly, improved operando and spatially resolved characterization tools will be essential. Techniques capable of tracking pressure evolution, local contact area, interfacial void formation, Li morphology, cathode transport pathways, and stress distribution during cycling will be particularly valuable, and spatially resolved pressure mapping across large-format cells is required to connect interfacial mechanisms to the pressure heterogeneity that emerges only upon scale-up. These diagnostics are also important for interpreting commonly reported metrics such as critical current density, which can be strongly influenced by evolving contact area, current–time protocol, transferred charge, rest periods, stack pressure, and interfacial morphology rather than by intrinsic SE properties alone.

A third direction is to align low-pressure design more closely with scalable manufacturing and realistic cell assembly. Strategies that perform well in small pellet cells may not translate directly to pouch or multilayer formats if they require excessive inactive components, complex processing, high fabrication pressure, or precise laboratory-scale fixtures. Conversely, recent studies show that manufacturing routes themselves can function as pressure-management strategies by improving contact coverage, adhesion, laminate integrity, and pressure homogeneity before cycling begins. For practical SSBs, low-pressure operation should therefore be evaluated together with process compatibility, throughput, cost, solvent tolerance, dry-room compatibility, multilayer stacking, and module-level pressure distribution.

Ultimately, low-pressure operation should be regarded as a primary design criterion for practical SSBs rather than a secondary testing condition. The goal is not necessarily to eliminate mechanical pressure entirely, but to reduce the required pressure to a practically manageable range of ≤ 2 MPa while ensuring that interfaces remain mechanically and electrochemically stable throughout cycling. Achieving this target will require integrated co-design of active materials, SEs, interfacial layers, electrode microstructures, current collectors, compliance elements, and pressure-control architectures. By embedding contact retention, transport robustness, Li deposition regulation, and pressure homogenization into the cell itself, future SSBs can move closer to high-energy, scalable, and mechanically practical operation without relying on excessive external compression.

CRediT authorship contribution statement

Taegeun Park: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Sojeong Kim:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Young-Gi Lee:** Resources, Funding acquisition. **Jinwoo Lee:** Validation, Supervision. **Seok Hun Kang:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the Technology Innovation Program (RS-2024-00449747) through the Korea Planning & Evaluation Institute of Industrial Technology (KEIT) funded by the Ministry of Trade, Industry & Energy (MOTIE, South Korea), and by the Nano & Material Technology Development Program (RS-2026-25542167) through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (MSIT, South Korea).

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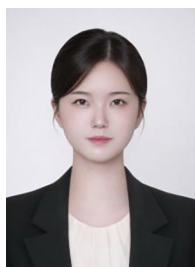
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