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Monolithically integrated NiCo₂Se₄ nanowire–carbon cloth cathode scaffolds for non-planar lithium-sulfur structural-battery integration

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Abstract

Lithium–sulfur (Li–S) batteries are attractive for lightweight structural energy-storage systems because of their high theoretical energy density, but their integration into non-planar components is hindered by sulfur-cathode cracking, interfacial delamination, and contact loss under retained curvature and external loading. Here, we report a monolithically integrated NiCo₂Se₄ nanowire/carbon-cloth cathode scaffold (NCSe@CC) for curvature-retained Li–S pouch-cell integration. Direct growth and selenization of Ni–Co precursor nanowires on woven carbon cloth produce a binder-free, interconnected polar host that combines polysulfide-affinitive NiCo₂Se₄ surfaces with continuous electron-transport pathways along the carbon-fiber network. Compared with sulfur-loaded carbon cloth and precursor-coated carbon cloth, S/NCSe@CC exhibits enhanced polysulfide adsorption, reduced charge-transfer resistance, accelerated sulfur-redox kinetics, and improved electrochemical performance, delivering 1,544 mAh g^{−1} at 0.1 C with a polarization of 0.13 V. The cathode scaffold retains nanowire–fiber integration after 1,000 curvature-conditioning cycles at a radius of 2.5 mm, and pouch cells assembled with conditioned electrodes show discharge behavior comparable to pristine cells. Under cylindrical curvature, the pouch cell retains 94.0% of its flat-state capacity. Integration into cylindrical, oval, square, and drone-leg geometries further verifies electrical operability after geometric insertion and fixation. This work presents a materials-to-architecture strategy for interface-stable Li–S cathode scaffolds in non-planar structural energy-storage components.

Keywords Nickel cobalt selenide nanowires · Lithium-sulfur batteries · Carbon cloth · Curvature-retained cathode · Li–S structural battery integration

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1 Introduction

Lightweight autonomous systems, such as drones and robotic platforms, demand efficient utilization of both mass and volume, yet structural components and electrochemical energy-storage units are typically designed as separate entities, leading to increased packaging overhead and underutilized device space. To address this limitation, structural battery concepts have emerged to integrate mechanical and electrochemical functions within a single system, either by enabling load-bearing components to store energy [1–5] or by embedding electrochemical elements into mechanically functional geometries [6–10]. For non-planar structural forms, such as curved or hollow components, the challenge is not only geometric accommodation but also the retention of electrochemical function under retained curvature and external loading [2, 11]. These conditions impose additional

design requirements beyond those required for conventional planar and freely deformable battery designs.

Previous studies on flexible and stretchable batteries have shown that integrating mechanical functionality with energy storage requires electrode architectures tailored to the specific mode of deformation [12–16]. Structural batteries similarly require architecture-specific integration strategies depending on the prescribed geometry and mechanical loading condition [11, 17, 18]. For non-planar structural forms, geometric conformity alone is therefore insufficient. The electrode architecture must not only maintain interfacial contact and conductive continuity under retained curvature, but also possess sufficient mechanical stiffness and strength to resist fracture, delamination, and contact loss when external mechanical loads are transmitted through the surrounding structural component. To date, such curvature-retained and externally loaded conditions remain largely unexplored, particularly for Li-S cathodes.

Lithium–sulfur (Li–S) chemistry is attractive for high energy density structural battery architectures because sulfur-based conversion reactions offer high theoretical specific capacity and Li–S cells provide high theoretical energy density [19–21]. This chemistry is particularly appealing for lightweight platforms such as drones, where extended operation time must be achieved under strict weight constraints [22]. For weight sensitive aerial platforms, gravimetric energy density is particularly important because the mass of the energy storage system directly affects payload capability and flight endurance [23, 24]. The high specific energy potential of Li–S chemistry therefore makes it a relevant candidate for such applications, although practical implementation additionally requires high sulfur loading, lean electrolyte operation, sufficient rate capability, and long-term cycling stability. However, the practical realization of Li–S batteries remains challenging due to the intrinsically low electronic conductivity of sulfur and Li_2S , the dissolution and shuttling of lithium polysulfides (LiPS), and sluggish sulfur redox kinetics [21, 25]. Consequently, the electrochemical performance of Li–S cathodes is highly dependent on host architecture. An effective sulfur host must provide continuous electronic pathways, accommodate sulfur and its conversion products, and regulate LiPS intermediates, while preserving electrochemical continuity under non-planar, geometry-constrained conditions [20, 21, 25].

Flexible carbon architectures based on CNTs, graphene, and related nanocarbons provide attractive platforms for mechanically compliant and non-planar batteries, although their material costs and electrode configurations vary widely (Tables S1 and S2). However, geometric flexibility alone does not provide the load-bearing capability or load-transfer pathway required for multifunctional structural

composites. Carbon fibers are particularly relevant in this context because they are established reinforcing constituents in structural composites and can simultaneously provide continuous electronic pathways as electrode frameworks [26, 27]. Accordingly, woven carbon cloth was selected not simply as a flexible current collector, but as a carbon-fiber framework with a direct pathway toward future structural composite integration. The direct growth of NiCo_2Se_4 nanowires provides LiPS interaction and sulfur-redox functionality without introducing an additional binder-mediated host/current-collector layer. Thus, the principal advantage of NCSe@CC lies in combining Li–S host functionality with a carbon-fiber-based architecture suitable for future multifunctional structural-battery integration. Carbon-based fibrous materials, such as carbon fibers and woven carbon cloths, are attractive scaffolds for structural and multifunctional electrodes due to their low density, high electrical conductivity, and mechanical robustness [27–32]. However, pristine carbon substrates exhibit limited electrochemical activity as cathode materials and thus require incorporation of an active host phase to achieve effective energy-storage functionality [32–35]. In this context, strategies that enable direct growth of the active phase on the carbon fiber framework are particularly advantageous, as they ensure intimate interfacial contact and continuous electron pathways throughout the three-dimensional architecture, while maintaining structural integrity under mechanical deformation.

For this purpose, polar and conductive transition-metal chalcogenides have been widely explored as sulfur-host materials because they can promote LiPS adsorption and sulfur conversion [36–43]. Among them, bimetallic selenides are of particular interest because they combine relatively high electronic conductivity with chemically active polar surfaces [39, 44–47]. However, catalytic activity alone is not sufficient for hollow or curved configurations if the host phase is only physically deposited on the current collector. Under geometric adaptation, such deposited layers cannot preserve continuous host-substrate contact. A nanowire array directly grown on a conductive fibrous scaffold is thus more attractive in this regard because it can provide both interfacial activity and structural continuity. In particular, a Ni–Co selenide host is relevant because the conductive selenide framework and bimetallic surface sites can support both LiPS interaction and redox conversion [48].

Here, we report a Li–S cathode scaffold for non-planar structural battery integration based on NiCo_2Se_4 nanowires directly grown on the surface of woven carbon cloth (NCSe@CC). In this design, the carbon cloth functions as a continuous conductive scaffold, while the integrated NiCo_2Se_4 nanowire network provides polar, electrochemically active interfaces that promote LiPS interaction and accelerate sulfur redox conversion. A precursor-coated carbon cloth

(NCPre@CC) is prepared separately as an intermediate reference to decouple the effects of precursor-derived morphology from those of the selenized nanowire phase. The key advance of this work lies not in developing a new sulfur-host material, but in establishing an electrode architecture that retains electrical output under mechanically constrained non-planar integration. To this end, we systematically evaluate the structural characteristics, LiPS interaction, and planar electrochemical performance of NCSe@CC in comparison with bare carbon cloth (CC) and NCPre@CC, and further assess its stability under repeated curvature conditioning and integration into cylindrical and non-cylindrical hollow configurations, including a drone-leg component.

2 Results and discussion

2.1 Design and structural characterization of NCSe@CC cathode scaffolds

The overall design concept of the NCSe@CC cathode scaffold is illustrated in Fig. 1 and Figure S1. As illustrated in Fig. 1a, this cathode-level design targets non-planar structural components relevant to lightweight autonomous systems. For non-planar structural-battery integration, the cathode must not only accommodate sulfur species and support sulfur-redox reactions, but also preserve host-collector coupling and electron-transport continuity under retained

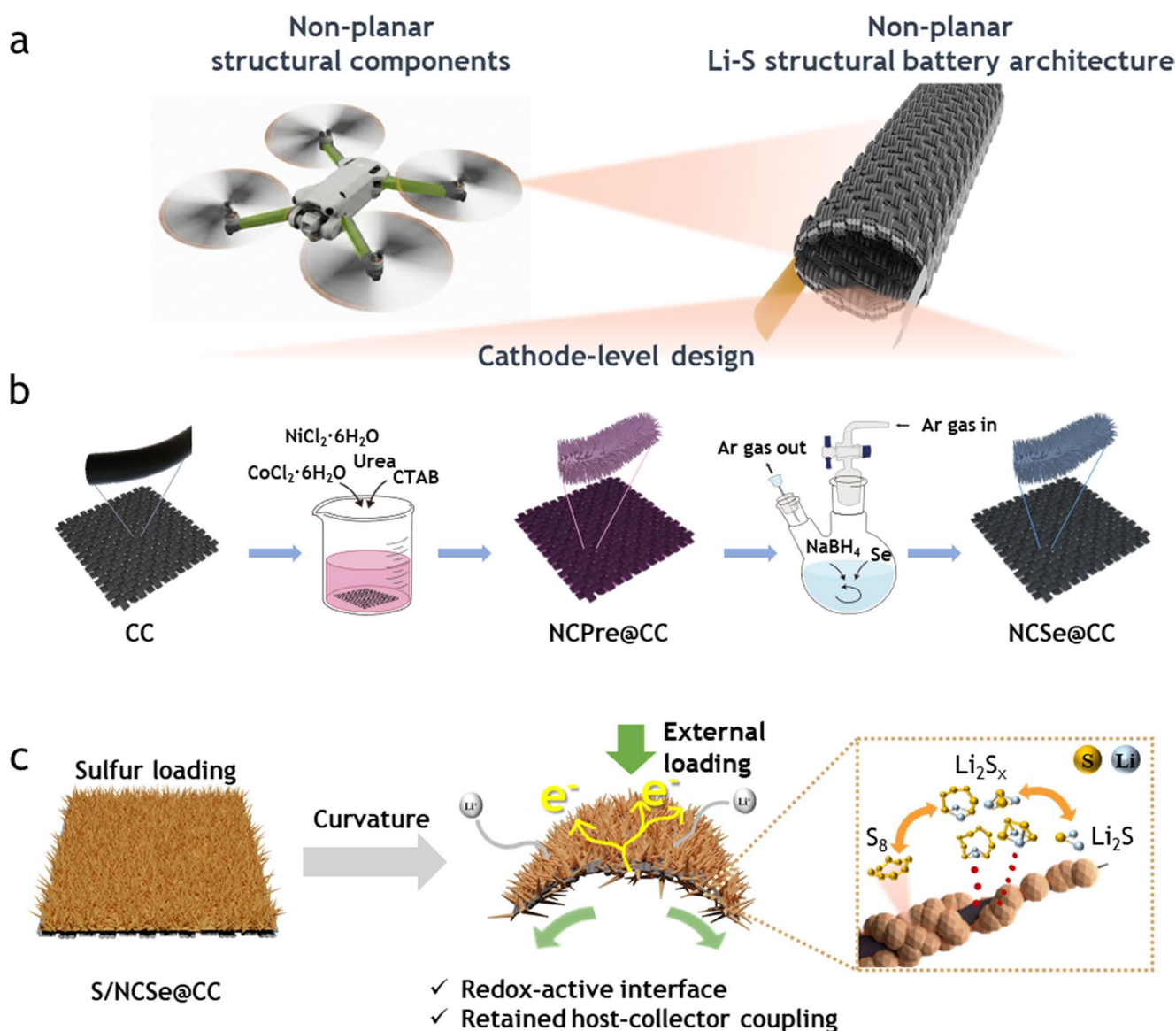


Fig. 1 Cathode scaffold design for non-planar Li-S structural battery architectures. **a** Application context for cathode-level design in non-planar structural components. **b** Fabrication route of NCSe@CC

through Ni-Co precursor growth on carbon cloth followed by selenization. **c** Functional design of sulfur-loaded NCSe@CC scaffold (S/NCSe@CC) under constrained curvature and external loading

curvature and external loading. Compared with particle/binder-based sulfur cathodes, which can suffer from contact loss within the active layer under curvature, and conformal sulfur coatings on carbon fabrics, which provide geometric conformity but limited redox-active host interfaces, the directly integrated S/NCSe@CC architecture is designed to combine redox-active interfaces with retained host-collector coupling under constrained curvature (Fig. 1c; Figure S1). In this architecture, woven carbon cloth serves as the conductive fibrous framework, while the directly grown NiCo_2Se_4 nanowire layer provides a polar and electrochemically active sulfur-host surface.

The NCSe@CC scaffold was prepared through a two-step growth and selenization process (Fig. 1b). A Ni-Co precursor nanowire layer was first grown on the surface of carbon cloth to form NCPre@CC, followed by selenization to produce the NiCo_2Se_4 nanowire-integrated carbon cloth scaffold. This direct-growth strategy is intended to avoid weakly attached active layers and to establish intimate contact between the redox-active host phase and the conductive carbon-fiber framework. The morphology of the prepared hosts was first examined to verify direct formation of a nanowire-integrated scaffold on the carbon-cloth framework.

Bare carbon cloth consists of smooth woven fibers (Fig. 2a), whereas NCPre@CC shows dense nanowire coverage along the carbon fibers (Fig. 2b). After selenization, the nanowire morphology is retained on the woven carbon cloth, forming a continuous three-dimensional fibrous/nanowire architecture (Fig. 2c, d). Such a three-dimensional nanowire architecture can provide a host framework with exposed reaction interfaces.

The structural conversion of the precursor into the selenide phase was then examined by X-ray diffraction. After selenization, the X-ray diffraction (XRD) pattern of NCSe@CC is consistent with the standard diffraction peaks of NiCo_2Se_4 (PDF No. 01-081-4822, indexed as NiCo_2Se_4), whereas bare carbon cloth shows no corresponding selenide phases (Figures S2 and S3). The nanowire structure of NiCo_2Se_4 was further confirmed by TEM analysis (Fig. 2e). In the HRTEM analysis, a lattice spacing of 0.535 nm is observed, which confirms the characteristic (001) plane of NiCo_2Se_4 (Fig. 2f). The formation of Ni-Co selenide phase was further ascertained by the scanning transmission electron microscopy energy dispersive x-ray spectroscopy (STEM-EDS), which shows that Ni, Co, and Se elements were distributed uniformly throughout the nanowire structure (Fig. 2g–i). These observations confirm direct formation of a selenized nanowire scaffold on the carbon-cloth framework. This architecture integrates the active host phase directly with the fibrous current collector, which is

advantageous for maintaining structural continuity during adaptation to hollow curved configurations.

2.2 LiPS interaction and sulfur-redox behavior of the nanowire host

Cyclic voltammetry was first used to examine whether the nanowire-coated host alters sulfur-redox kinetics and LiPS interaction. S/NCPre@CC and S/NCSe@CC exhibit more clearly resolved Li-S conversion peaks than sulfur loaded carbon cloth (S/CC), with the most distinct behavior observed for S/NCSe@CC (Fig. 3a), where R1 and R2 correspond to the stepwise reduction from sulfur to soluble polysulfides and then to $\text{Li}_2\text{S}_2/\text{Li}_2\text{S}$, and O1 corresponds to the reverse oxidation process [21, 25]. In addition, S/NCSe@CC shows the smallest peak separation, consistent with reduced polarization [49].

The scan-rate-dependent CV response was then examined to determine whether this difference is accompanied by faster sulfur-redox kinetics. The CV curves of S/NCSe@CC collected at different scan rates show a systematic increase in peak current while retaining the overall redox profile (Fig. 3b). The scan-rate-dependent CV curves of S/CC and S/NCPre@CC (Figure S4), together with the impedance response of S/NCPre@CC and S/NCSe@CC (Figure S5), support the same trend. The Nyquist plots show a smaller semicircle for S/NCSe@CC than for S/NCPre@CC electrode, consistent with reduced interfacial resistance and more favorable sulfur-redox kinetics (Figure S5). To further examine the influence of the electrode architecture, a conventional particulate NiCo_2Se_4 control (S/NCSeP) was prepared by coating NiCo_2Se_4 powder/PVDF onto Al foil, followed by the same sulfur-loading procedure used for S/NCSe@CC. The S/NCSeP electrode exhibited a characteristic impedance of approximately 10 k Ω before the scan-rate-dependent CV measurement (Figure S6). By comparison, S/NCSe@CC exhibited a substantially lower characteristic resistance of approximately 72 Ω under the electrochemical impedance spectroscopy (EIS) condition shown in Figure S5. The difference was also evident in the scan-rate-dependent CV response. S/NCSeP showed poorly resolved sulfur oxidation and reduction features (Figure S7), whereas the directly grown S/NCSe@CC architecture retained distinct sulfur-redox peaks over the investigated scan-rate range (Fig. 3b). These results indicate that the directly integrated NiCo_2Se_4 nanowire architecture provides more favorable interfacial charge transport and sulfur-redox behavior than the conventional powder-coated NiCo_2Se_4 electrode configuration. For quantitative comparison, the O1 peak current was plotted against the square root of scan rate (Fig. 3c). According to the Randles-Sevcik relationship, the slope

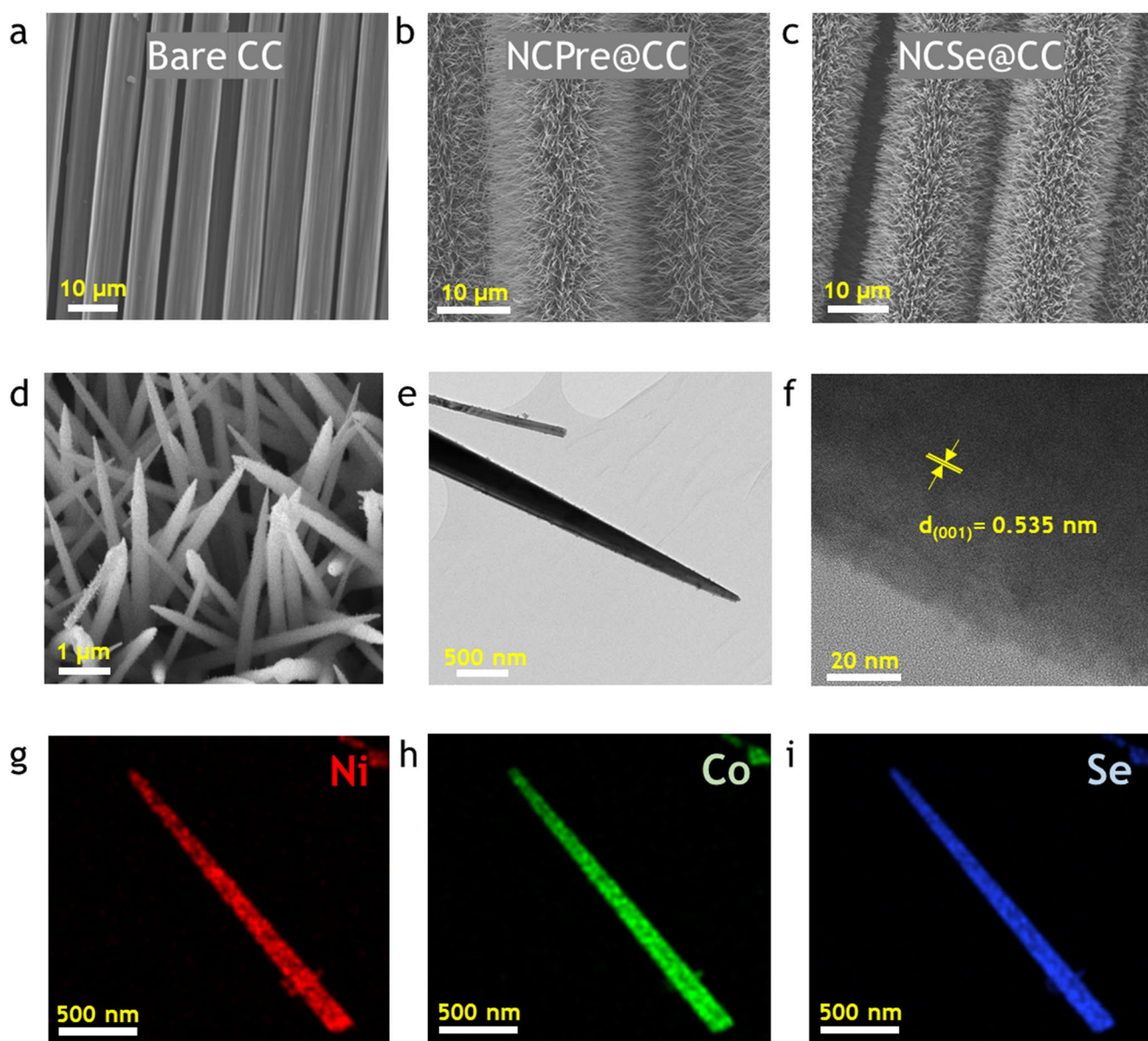


Fig. 2 Morphological characterization of the NiCo_2Se_4 nanowire-coated carbon cloth (NCSe@CC). **a–c** SEM images of bare CC, NCPRe@CC, and NCSe@CC. **d** High-magnification SEM image of

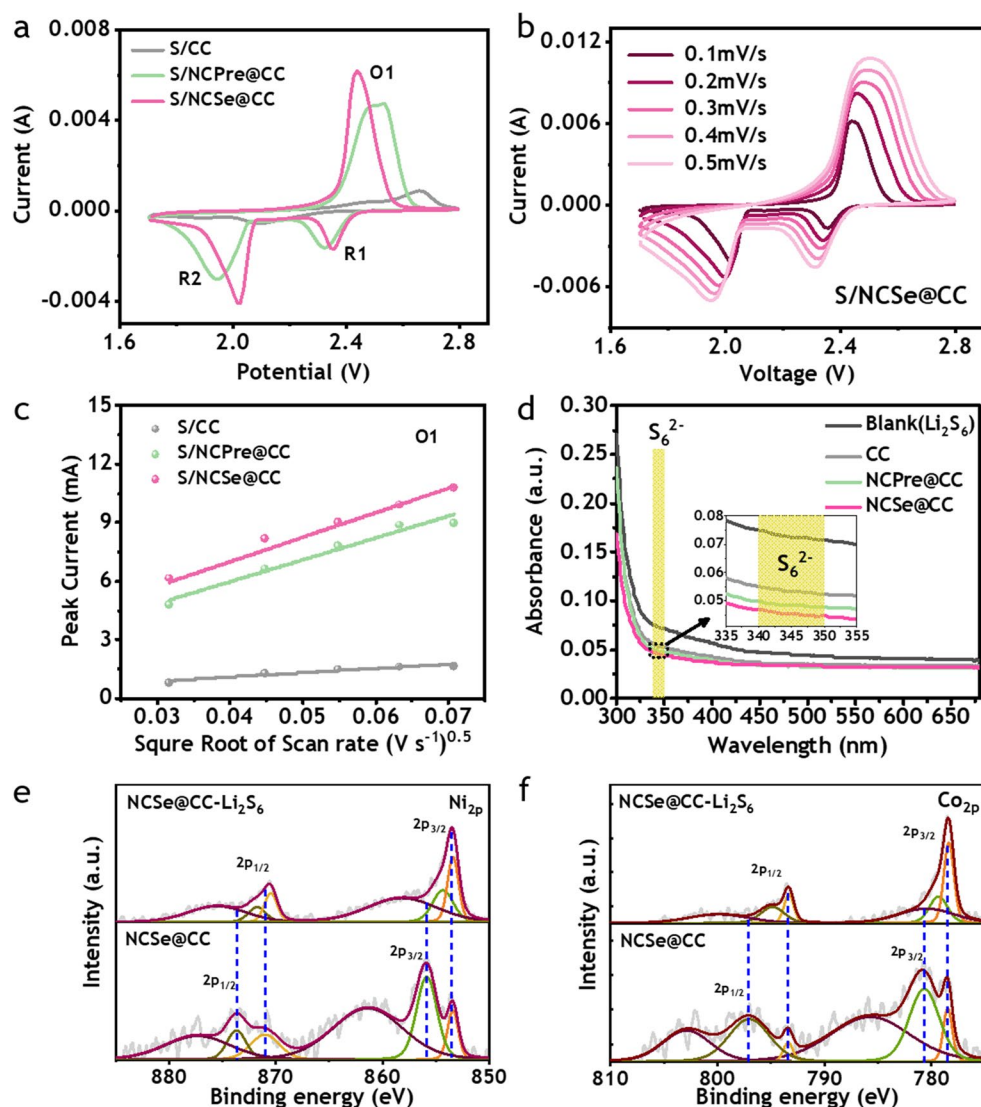
NCSe nanowires grown on carbon cloth fibers. **e** TEM image and **(f)** HRTEM images of an individual NiCo_2Se_4 nanowire. **g–i** STEM–EDS elemental mapping of the Ni, Co, and Se in the NCSe nanowire

is proportional to the diffusion-related electrochemical response under the tested conditions [50, 51]. From the linear fitting, S/NCSe@CC shows the highest apparent Li^+ diffusion coefficient of $7.26 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1}$, compared with $6.97 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1}$ for S/NCPRe@CC and $1.38 \times 10^{-8} \text{ cm}^2 \text{ s}^{-1}$ for S/CC (Figure S8).

To examine whether this electrochemical behavior is accompanied by different polysulfide interaction, Li_2S_6 adsorption and post-exposure X-Ray photoelectron spectroscopy (XPS) measurements were further carried out (Fig. 3d–f). The Li_2S_6 solution treated with NCSe@CC shows the largest decrease in absorbance among the tested

hosts. (Fig. 3d). Quantitative comparison at the characteristic S_6^{2-} absorption around 340 nm [52, 53] showed relative absorbance decreases of 26.4%, 33.6%, and 37.6% for CC, NCPRe@CC, and NCSe@CC, respectively, further supporting the enhanced LiPS uptake of NCSe@CC. The XPS spectra after Li_2S_6 exposure show binding-energy shifts of 0.25–1.85 eV for the Ni and 0.20–2.15 eV for the Co species in NCSe@CC, supporting interfacial interaction between polysulfide species and the NiCo_2Se_4 surface (Fig. 3e, f). These results indicate that the nanowire-coated host provides stronger chemical affinity for LiPS species, helping to immobilize polysulfides during charge and discharge.

Fig. 3 Sulfur-host interaction and redox kinetics of the S/NCSe@CC scaffold. **a** CV curves of S/CC, S/NCPre@CC, and S/NCSe@CC electrodes, where O1, R1, and R2 denote the characteristic anodic and cathodic peaks of Li-S conversion. **b** Scan-rate-dependent CV curves of the S/NCSe@CC electrode. **c** Corresponding O1 peak current plotted as a function of the square root of scan rate for S/CC, S/NCPre@CC, and S/NCSe@CC. **d** UV-vis absorption spectra of Li_2S_6 solutions after adsorption tests with different host materials. **e, f** Ni 2p and Co 2p XPS spectra of NCSe@CC before and after Li_2S_6 exposure



These observations show that the NiCo_2Se_4 nanowire host provides stronger LiPS interaction and more facile sulfur-redox behavior than the control hosts. The electrochemical consequences of these host-property differences were further evaluated in coin cell configurations (Fig. 4a–e).

2.3 Electrochemical performance of the self-supported cathode architecture

The electrochemical performance of the sulfur-loaded electrodes was next examined to determine whether NCSe@CC functions as an effective sulfur host before evaluating its behavior under curved and hollow configurations. Unless otherwise noted, all specific capacities reported below are based on the active sulfur mass in the cathode. The galvanostatic charge-discharge profiles of S/CC, S/NCPre@CC, and S/NCSe@CC are compared (Fig. 4a). Among the three electrodes, S/NCSe@CC exhibits the highest reversible

capacity and the smallest polarization gap. At 0.1 C, S/NCSe@CC delivers 1544 mAh g^{-1} , while the polarization gap is reduced to 0.13 V, compared with 0.28 V for S/NCPre@CC. These trends are consistent with the CV and LiPS-interaction results described above.

Across the tested current densities, S/NCSe@CC maintains higher capacities than S/CC and S/NCPre@CC, indicating improved rate capability in the present system (Fig. 4b). This behavior is consistent with a host architecture in which the conductive carbon-cloth backbone and the redox-active nanowire surface jointly support electron transport and sulfur conversion. Cycling performance was then compared among S/CC, S/NCPre@CC, and S/NCSe@CC, and the longer-term cycling behavior of S/NCSe@CC was further examined (Fig. 4c, d). S/NCSe@CC retains about 735 mAh g^{-1} after 50 cycles at 0.5 C, whereas S/NCPre@CC and S/CC show substantially lower capacities under the same conditions. In the longer-term measurement,

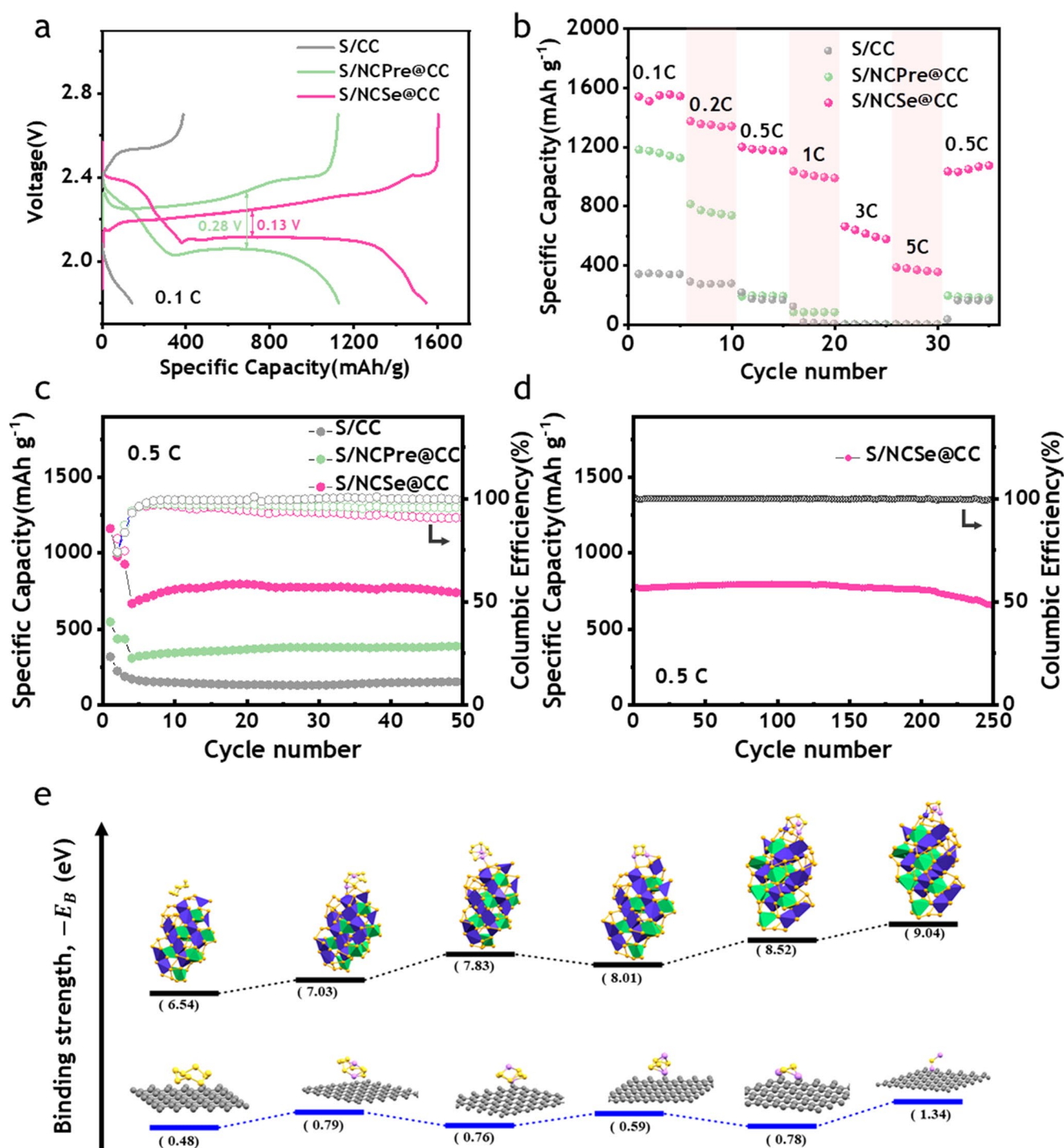


Fig. 4 Electrochemical performance comparison of S/CC, S/NCPRe@CC, and S/NCSe@CC cathodes, with DFT analysis of LiPS binding. **a** Galvanostatic charge-discharge curves of the three electrodes, showing reduced polarization for S/NCSe@CC. **b** Rate capability at various

current densities. **c** Cycling performance comparison between S/CC, S/NCPRe@CC, and S/NCSe@CC. **d** Long-term cycling stability of the S/NCSe@CC cathode. **e** DFT calculated binding strengths, defined as $-E_B$, of LiPS on graphene (blue) and (001) surface of NiCo₂Se₄ (black)

S/NCSe@CC also maintains stable cycling behavior over 250 cycles. NCSe@CC therefore provides more effective sulfur hosting than bare CC and NCPRe@CC in the present system.

To support the experimental observations, density functional theory (DFT) calculations were carried out for LiPS adsorption on graphene and NiCo₂Se₄(001) surface (Fig. 4e; Figures S9 and S10). The (001) surface was selected as a

representative surface based on the ~ 0.535 nm lattice fringe observed by HRTEM, consistent with the $\text{NiCo}_2\text{Se}_4(001)$ plane, as well as previous Li–S studies in which the (001) surface was explicitly considered for LiPS adsorption together with the (110) surface [48]. The optimized adsorption structures show that LiPS species remain only weakly perturbed on graphene, whereas on $\text{NiCo}_2\text{Se}_4(001)$ they undergo more distinct structural reorientation, with Li atoms approaching electronegative Se sites and S atoms interacting more closely with Co/Ni centers, indicating stronger chemical affinity with the selenide surface (Figure S9). Consistent with this, the calculated binding strengths $-E_B$ are substantially higher on NiCo_2Se_4 (6.54–9.04 eV) than on graphene (0.48–1.34 eV), demonstrating stronger anchoring and stabilization of LiPS intermediates on the selenide host (Fig. 4e). In addition, the calculated free-energy profile for sulfur reduction shows a more favorable stepwise conversion pathway on NiCo_2Se_4 than on graphene (Figure S10). In particular, the thermodynamic penalty for the $\text{Li}_2\text{S}_4 \rightarrow \text{Li}_2\text{S}_2$ conversion decreases from 1.05 eV on graphene to 0.61 eV on NiCo_2Se_4 , indicating that the conversion toward lower-order sulfur species is more thermodynamically accessible on the selenide surface. These computational results are consistent with the experimentally observed trend of stronger LiPS interaction and more facile sulfur-redox behavior on the selenide-coated host. The results establish NCSe@CC as a cathode architecture in which the nanowire host phase is structurally integrated with the carbon-cloth framework while remaining electrochemically functional for sulfur conversion. This validation is important not as an end point by itself, but as the basis for testing whether the same architecture can preserve that function during cavity-constrained curved integration.

2.4 Curvature-conditioned cathode integrity and curved pouch-cell operation

After confirming the electrochemical advantages of S/NCSe@CC in coin cells, we next examined whether the cathode scaffold could retain its structural and electrical operability after repeated curvature conditioning. The S/NCSe@CC electrode was subjected to 1,000 repeated curvature cycles at a bending radius of 2.5 mm (Fig. 5a; Video S1). The different curvature radii used throughout the electrode, pouch cell, and mechanical loading experiments were selected to represent the range of local geometries expected in non-planar structural components (Table S4). This test was designed to evaluate whether the directly integrated nanowire scaffold could preserve host–collector coupling under repeated curvature, rather than simply demonstrate free-standing flexibility.

After curvature conditioning, the electrode morphology was examined at the top, middle, and edge regions of the deformed electrode. SEM images show that the nanowire-integrated surface morphology is largely retained across these regions, without severe active-layer detachment or catastrophic cracking (Fig. 5b–d). To further quantify the electrical stability during repeated curvature deformation, the two terminal in-plane resistance of NCSe@CC was measured at 100 cycle intervals. The resistance remained within approximately $3.1\text{--}5.4\ \Omega$ over 1000 cycles (Figure S11). The absence of a progressive resistance increase indicates no systematic deterioration of the macroscopic electrical conduction pathway. Together with the post-cycling SEM observations, these results support retained nanowire fiber integration after repeated curvature exposure. Consistent with this structural retention, pouch cells assembled using the mechanically conditioned electrode show an initial charge-discharge profile similar to that of cells prepared with the pristine electrode, without severe additional polarization or immediate capacity loss (Fig. 5e). Repeated curvature therefore does not cause severe structural disruption or immediate electrochemical failure in the NCSe@CC host.

We next examined whether the pouch-cell configuration remained operational after adaptation to a cylindrical curved geometry. Under the curved configuration, it delivered an average specific capacity of $1117\ \text{mAh g}^{-1}$ at 0.02 C, corresponding to 94.0% of the flat-state capacity of $1,188\ \text{mAh g}^{-1}$. At a sulfur loading of $1\ \text{mg cm}^{-2}$, the flat and curved values correspond to areal capacities of approximately 1.19 and $1.12\ \text{mAh cm}^{-2}$ (Fig. 5f; Table S3). These pouch-cell measurements were conducted under a controlled baseline condition (sulfur loading of $\sim 1\ \text{mg cm}^{-2}$ and E/S ratio of $13\ \mu\text{L mg}^{-1}$) to evaluate the effect of geometric constraint without simultaneously varying practical-cell parameters. Since non-planar structural-battery integration involves coupled electrochemical and mechanical variables, including sulfur loading, electrolyte amount, operating rate, prescribed geometry, and mechanical constraint, the present study first establishes cathode operability under this baseline condition; higher sulfur loading, leaner electrolyte conditions, and higher-rate operation remain necessary for subsequent practical high-energy implementation. These results demonstrate that the S/NCSe@CC cathode scaffold can preserve electrochemical function after repeated curvature conditioning and under cylindrical pouch-cell operation.

2.5 Voltage retention under external loading of cylindrical pouch assemblies

To further evaluate the relevance of the S/NCSe@CC cathode for non-planar structural-battery integration, we examined the

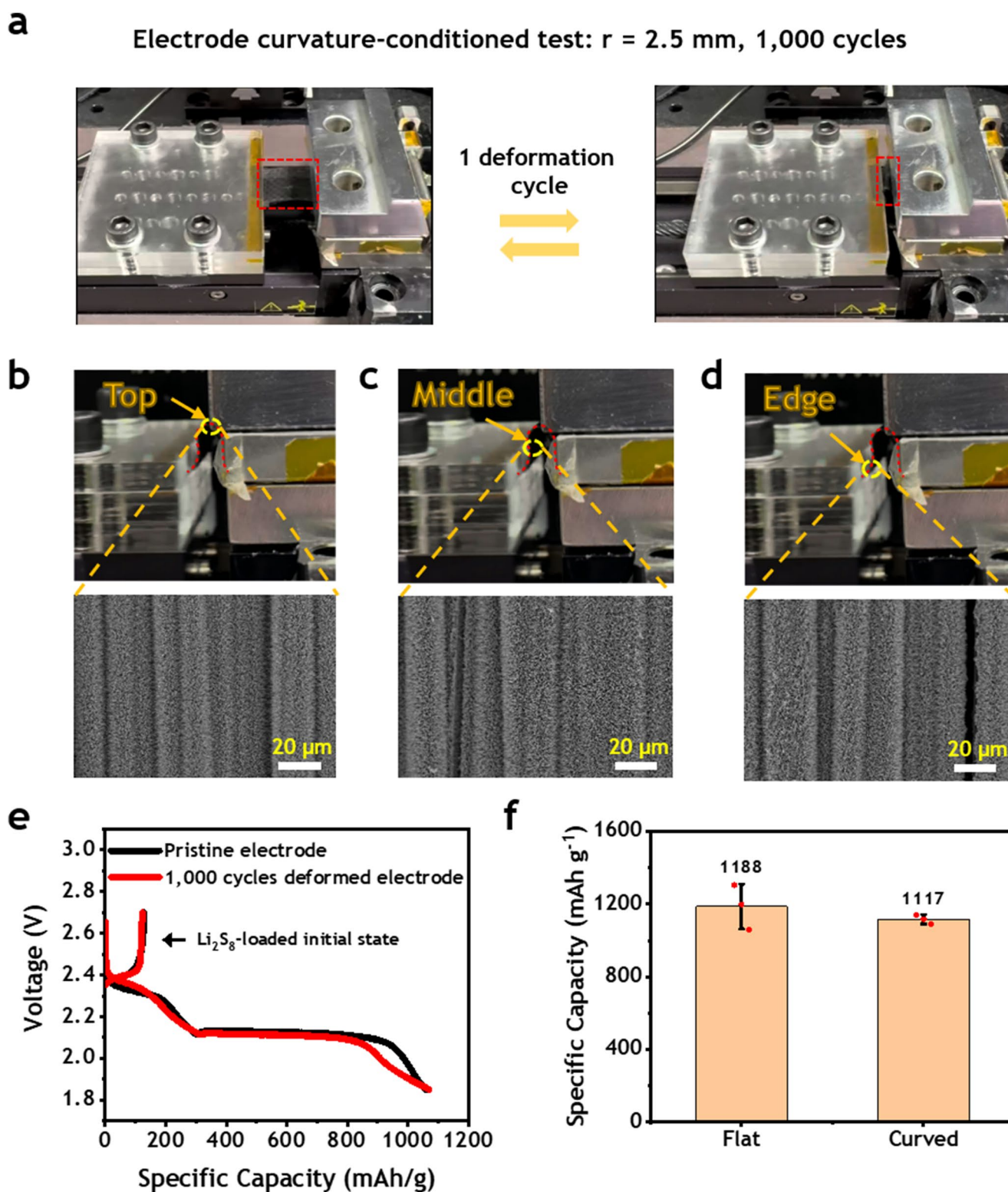


Fig. 5 Retention of nanowire–fiber integration and pouch-level electrochemical accessibility after curvature conditioning. **a** Curvature-conditioning test setup using a bending radius of 2.5 mm for 1,000 bending-release cycles. **b–d** SEM images collected from the top, middle, and edge regions of the curvature-conditioning NCS@CC electrode.

e Initial charge-discharge profiles of Li–S pouch cells assembled with pristine and curvature-conditioning S/NCS@CC cathodes. **f** Comparison of the initial discharge capacities of pouch cells under flat and curved configurations

voltage response of a cylindrical pouch-cell assembly under external loading. The pouch cell was placed within a cylindrical structural frame and supported by compliant silicone pads to reduce localized stress concentration during loading (Fig. 6a and Figure S12). Force–stroke responses measured with different silicone-pad configurations showed comparable global loading behavior, confirming that the compliant support did not substantially change the imposed external-loading condition (Figure S13). This configuration was designed to represent a cavity-constrained integration condition in which the cell is not freely bent, but fixed within a predefined curved geometry and subjected to external mechanical constraint.

A stroke-controlled loading test was then conducted while monitoring the cell voltage under a 44 k Ω resistor load (Fig. 6b, c). The force–stroke response confirmed that the pouch assembly experienced progressively increasing mechanical constraint during loading (Fig. 6b). Comparison with the corresponding pouch-free PLA/two-pad control in Figure S13 showed that the measured force at a stroke of 15 mm increased from approximately 260 to 275 N after pouch-cell incorporation. This 15 N increase represents the pouch-associated change in the global mechanical response, confirming mechanical engagement of the pouch cell within the constrained assembly. Despite this increasing constraint and subsequent polylactide (PLA)-frame fracture during loading, the voltage remained stable without abrupt voltage collapse, changing only from 2.457 to 2.452 V, corresponding to a decrease of approximately 5 mV (Fig. 6c, d). The voltage retention, calculated from the average voltage during the 10 s hold at each loading step, was 99.96%, 99.835%, and 99.828% at the 5, 10, and 15 mm loading steps, respectively (Fig. 6e and Table S5). Continuous electrical output under mechanical loading is essential for maintaining electrochemical operation. Disruption of the electrical pathway would lead to abrupt voltage loss. The nearly unchanged voltage during stepwise loading therefore indicates that the integrated pouch cell retained electrical continuity and remained electrically operable throughout the applied deformation. Additionally, a complementary qualitative demonstration using a thermoplastic polyurethane (TPU) cylindrical pouch-cell assembly shows continuous LED illumination without visible flickering under external mechanical loading (Video S2). These results indicate that the S/NCSe@CC-based pouch assembly preserves electrical operability under external loading in a retained cylindrical configuration, supporting the role of the directly integrated nanowire–carbon cloth cathode scaffold in maintaining host–collector coupling and electron-transport continuity under mechanically constrained curvature.

Fig. 6 Electrical response of the cylindrical PLA/pouch assembly under external loading. **a** Schematic illustration of the PLA/pouch assembly connected to a 44 k Ω external resistor for voltage monitoring. **b** Force–stroke response of the PLA/pouch assembly during stepwise stroke-controlled loading with 10 s hold periods. **c** Voltage response of the pouch demonstrator during OCV, resistor-loaded, external-loading, and post-PLA-fracture states. **d** Enlarged voltage profile during external loading. **e** Voltage retention calculated from the mean resistor-loaded voltage during each 10 s hold period using the pre-loading resistor-loaded voltage as the reference

2.6 Non-cylindrical hollow-structure integration and drone-leg demonstration

To further demonstrate the applicability of the S/NCSe@CC cathode beyond a simple cylindrical configuration, pouch cells were integrated into non-cylindrical hollow geometries. Figure 7a illustrates the integration concept, in which the S/NCSe@CC pouch cell is positioned within a hollow structural component while maintaining the layered cell configuration. Oval and square cavity geometries were selected as representative non-cylindrical structural forms to evaluate whether the pouch cell could retain electrical operability after geometric insertion and fixation (Fig. 7b).

The open-circuit voltage (OCV) values of the pouch cells were measured before and after integration into the oval and square cavities, while EIS measurements were additionally performed using the same pouch cell in the flat, oval, square, and drone-leg configurations. As shown in Fig. 7c and Figure S14, the OCV values remained stable after integration into the oval and square cavities, while the Nyquist plots remained closely comparable among the flat, oval, square, and drone-leg configurations. These results indicate that geometric insertion and fixation did not induce substantial electrical failure or additional cell impedance. This demonstration shows that the non-planar pouch-cell architecture can be inserted and fixed within predefined structural cavities, rather than remaining limited to a planar or freely bendable format.

Finally, component-level applicability was demonstrated using a drone-leg configuration, where the integrated pouch-cell maintained LED operation after fixation (Fig. 7d–e, Figures S15 and S16, and Video S3). This demonstration verifies that the S/NCSe@CC-based pouch cell can maintain device-level electrical output after insertion, fixation, and operation within a non-planar structural component. These results demonstrate the feasibility of using directly integrated S/NCSe@CC cathode scaffolds for non-planar Li–S structural-battery integration in lightweight autonomous platforms.

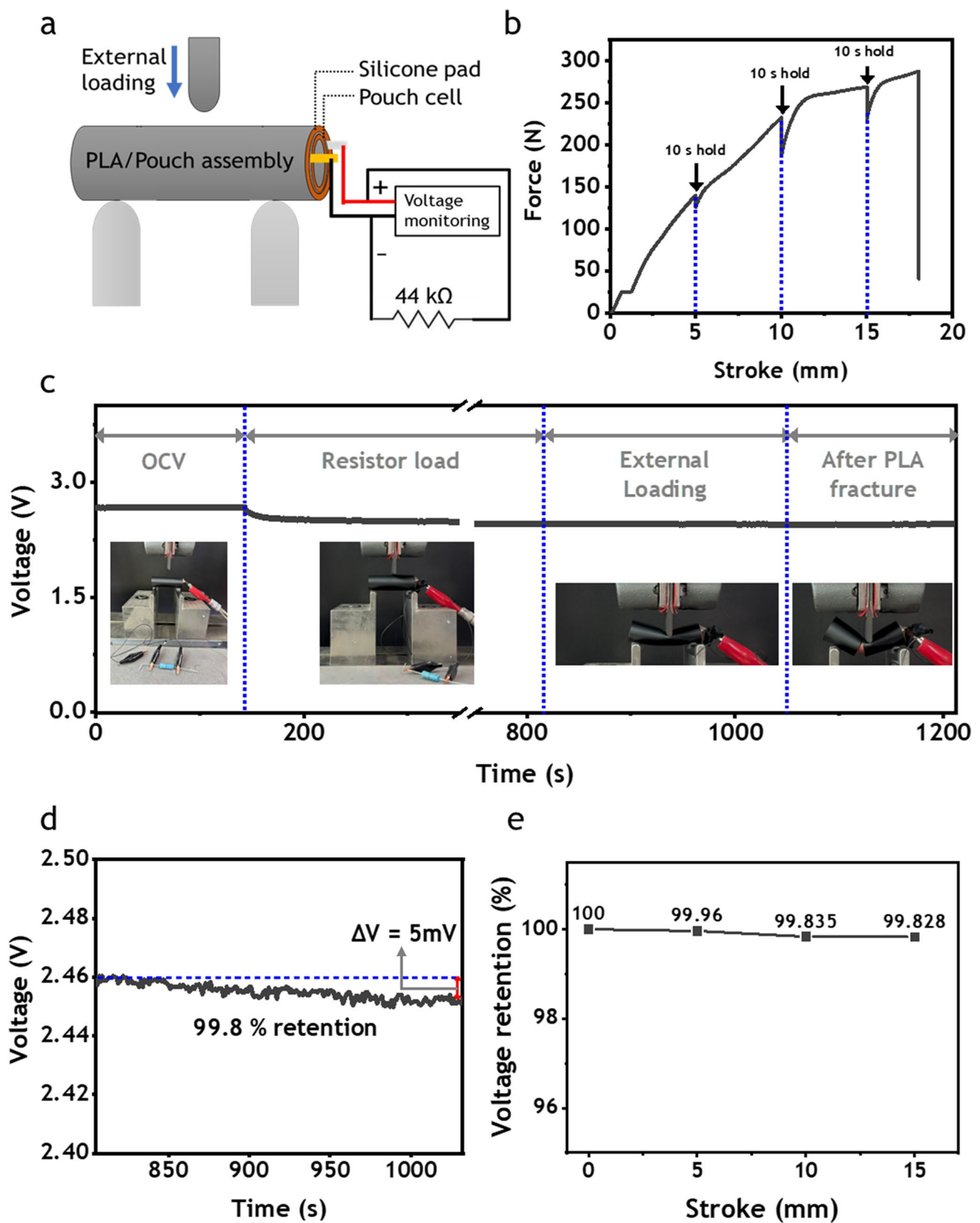
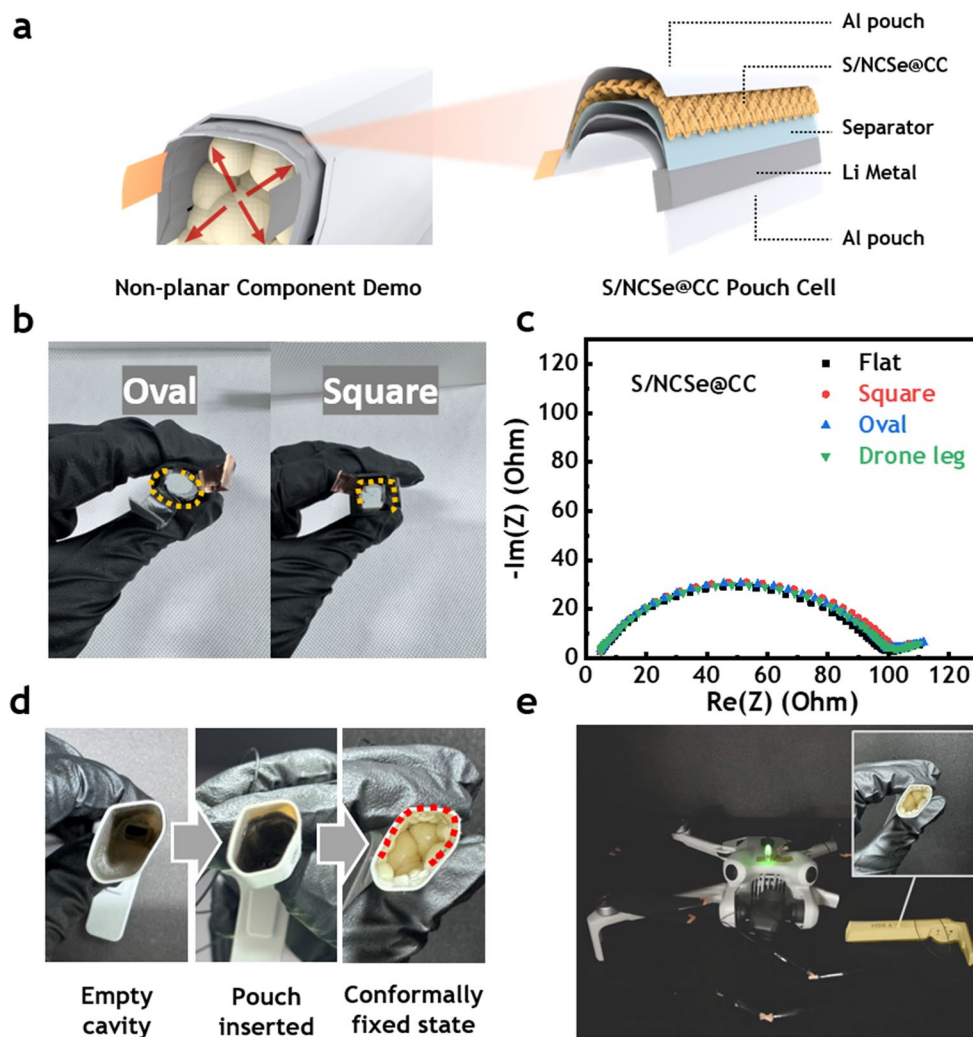


Fig. 7 Proof-of-concept geometry-constrained fixation in diverse hollow structural components with different geometries. **a** Schematic illustration of foam-assisted conformal fixation of an S/NCSe@CC-based pouch demonstrator in a hollow structural component. **b** Photographs of oval and square hollow-component configurations. **c** Nyquist plots of the same S/NCSe@CC pouch cell measured in flat, oval, square, and drone-leg configurations. **d** Sequential photographs showing the empty cylindrical component, pouch insertion, and foam-assisted fixation. **e** Drone-leg demonstrator with an integrated S/NCSe@CC-based Li-S pouch cell



3 Conclusion

In this work, we present a directly integrated NiCo_2Se_4 nanowire-carbon cloth cathode scaffold for non-planar Li-S structural battery integration. While the NiCo_2Se_4 phase contributes to enhanced polysulfide regulation and accelerated sulfur-redox kinetics, the central advance lies in the architectural integration achieved through direct nanowire growth, which ensures robust interfacial coupling and continuous electron transport within a mechanically robust fibrous framework. This design enables the preservation of electrical operability under external loading in cavity-constrained, non-planar geometries, addressing a key limitation in extending energy-storage systems beyond planar configurations. The directly grown scaffold maintains structural integrity and electrochemical operability after repeated curvature conditioning and during fixation within diverse hollow geometries, including cylindrical, oval, and square configurations. The successful integration of the pouch cell into a drone-leg component further demonstrates that

the internal volume of lightweight structural elements can be actively utilized for distributed energy storage without compromising device functionality. More broadly, this work presents a material-to-architecture design strategy for non-planar Li-S structural battery integration, in which active materials are directly integrated with conductive scaffolds to ensure functional stability under geometric constraints. This approach provides a viable pathway toward structurally integrated energy storage by enabling the utilization of otherwise inactive structural volume in lightweight autonomous systems.

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Authors' contributions J.H. designed the overall experiment plan. M.G. assisted with material synthesis. M.G., R.E.A.A., C.K., and A.K. assisted with the demonstration experiments. M.G., M.M., R.E.A.A., and L.A. discussed the data and revised the manuscript. Z.U. and H.Y.K performed the DFT simulations. L.A supervised the research. I-K.O. supervised the research at all stages, led all groups, and wrote the paper. All authors discussed the results and commented on the paper.

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Data availability The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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