

Article

Seam and Face Tensile Properties of Hot-Water Bottles: Manufacturing Cohort Effects in Rubber and Plasticised PVC

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Featured Application

This work supports evidence-informed safety assessment of hot-water bottles by comparing the tensile performance of rubber and plasticised PVC body panels and seams across manufacturing years. The findings may inform product testing, user replacement guidance, and future refinement of durability requirements in hot-water bottle safety standards.

Abstract

Hot-water bottles are widely used domestic heat sources, but seam and neck failures can cause scald injuries, and quantitative evidence supporting replacement guidance remains limited. This study compared the tensile behaviour of unused, dry-stored hot-water bottles manufactured in 2022 and 2024, focusing on vulcanised rubber and plasticised PVC constructions. ISO 37 Type 1 dumb-bell specimens were excised from body panels and seam regions and tested in uniaxial tension at 23 ± 2 °C and $50 \pm 5\%$ RH using a grip-separation rate of 500 mm min^{-1} . Stress–strain curves were analysed to determine maximum stress, failure strain, toughness and tangent modulus, with seam and face specimens compared within each material year cohort. PVC specimens were consistently stiffer and stronger than rubber specimens but failed at lower strain. Manufacturing year-associated differences were material-dependent: PVC-2022 generally showed higher maximum stress and toughness than PVC-2024, whereas Rubber-2022 underperformed Rubber-2024 at large strain. Seam–face ordering also depended on material and year, with PVC faces outperforming seams, while rubber showed cohort-specific behaviour. These findings indicate that hot-water bottle durability is influenced by both material system and joint region, supporting the need to consider seam performance alongside bulk material properties in safety assessment and replacement guidance.



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Keywords: hot-water bottles; tensile testing; vulcanised rubber; plasticised PVC; welded seams; manufacturing year; mechanical properties; product safety

1. Introduction

Hot-water bottles are commonplace, low-cost heat sources used across domestic and clinical settings, so even a small failure rate represents a non-trivial population-level risk. Injuries do occur, most often burns and scalds from material failure at the neck or seams,

overfilling, or use with near-boiling water, underscoring the need to understand how material conditions and geometry interact under realistic loading. The product is governed by BS 1970, which specifies construction, permitted materials (vulcanised rubber and plasticised PVC), labelling, and performance requirements, including tensile strength and ageing tests, that set a benchmark for fitness for purpose at manufacture [1]. Most public guidance advises replacement after around two years, yet this recommendation lacks robust quantitative evidence and is not calibrated to real-world duty cycles; with growing attention on hot-water bottle safety, there is a need for data linking standardised ageing protocols to service-life predictions and evidence-based replacement intervals [2–4].

Hot-water bottles are produced in two distinct material–construction systems that set the baseline for performance and failure. Vulcanised rubber bottles are moulded as a single body with an integral neck; their mechanical response is governed by a crosslinked elastomeric network, filler reinforcement, viscoelastic energy dissipation and resistance to tear propagation under large strain [5–7]. In rubber-like materials, fracture is commonly described in terms of tearing energy or strain energy release, rather than simple small-strain strength alone, because crack growth occurs during large deformation [7]. Plasticised PVC bottles are assembled from flexible sheet stock; perimeter and neck seams are heat-welded, introducing anisotropy and geometric stress concentrators. In practice, their tensile response depends on PVC molecular mobility, plasticiser content, physical ageing and thermal/mechanical processing history. Plasticisation reduces stiffness and increases ductility, while changes in plasticiser concentration or mobility can alter modulus, elongation and fracture appearance.

In both material systems, product geometry and joint construction modify the local stress state. Necks, corner radii, and seams act as stress concentrators, while heat-welded PVC seams introduce local anisotropy, thickness variation and a heat-affected interface that may behave differently from the surrounding sheet material [8–10]. Consequently, tensile performance measured from flat face specimens cannot necessarily be assumed to represent seam or neck behaviour. In practice, rubber designs tend to fail at the neck or other high-strain regions, while PVC designs tend to fail at or near welded seams; the present sampling strategy therefore targeted both bulk face material and seam-containing regions. Stress concentrations at necks and perimeter radii further support targeting these regions for sampling [11].

The degradation mechanisms relevant to these materials are also distinct. In vulcanised rubber, thermo-oxidation ageing can involve competing chain scission and post-crosslinking processes, with changes in stiffness, elongation and crack-growth resistance depending on cure system, filler structure, oxygen access and exposure conditions [12–14]. Ozone exposure can further promote surface cracking under strain, while diffusion-limited oxidation and antidegradant depletion may produce spatially heterogeneous ageing through the material thickness [15,16]. In plasticised PVC, changes in plasticiser content or mobility can alter stiffness, ductility and elongation behaviour [17]. Plasticiser migration and loss may also occur through diffusion from the polymer bulk to the surface and subsequent evaporation, although this was not directly measured in the present study [18]. In seam regions, thermal and mechanical processing during heat sealing may introduce additional local heterogeneity because seal integrity is influenced by sealing temperature, pressure, dwell time, interface conditions and local seal geometry [8,9]. Studies of welded PVC-coated fabrics further show that weld configuration, weld width and loading orientation can affect tensile strength, elongation, strain distribution and failure mode, supporting the interpretation that welded regions should not be treated as mechanically equivalent to the surrounding parent material. These mechanisms provide useful context for interpreting commercial product differences, but the present study should be interpreted

as a cross-sectional comparison of manufacturing year cohorts rather than a controlled ageing experiment.

BS 1970:2012 provides the reference frame for hot-water bottles, specifying construction, permissible materials, labelling, and performance tests; it sets minimum tensile and elongation requirements and requires retention of properties after conditioning intended to simulate use. This makes compliance a durability expectation, not just a point-of-sale criterion. A recent BSI review has increased emphasis on clear user guidance and risk reduction measures [19]. The current study objective is to compare the tensile mechanical properties of face and seam specimens from unused, dry-stored rubber and PVC hot-water bottles manufactured in 2022 and 2024 and to determine whether differences are detectable between these manufacturing year cohorts.

2. Materials and Methods

Commercially available hot-water bottles were tested in two material–construction systems: moulded vulcanised rubber and heat-sealed plasticised PVC. These material classes were selected because they are the principal construction types used for hot-water bottles and are the relevant commercial systems for product safety assessment and replacement guidance. For each make and model, the declared material, batch code or daisy-wheel date, country of manufacture, bottle capacity, construction type and sampling region were recorded where available. Each bottle was visually inspected for defects before sampling. Exact compound formulations were not available from product labelling or manufacturer information; therefore, rubber composition, filler loading, cure system, antidegradant package, PVC resin grade, plasticiser type/content and stabiliser package could not be determined. The study should therefore be interpreted as a comparison of commercial product cohorts rather than a controlled comparison of known laboratory formulations.

2.1. Tensile Specimen Preparation

2.1.1. Body Panel (Face) Specimens

Dog-bone specimens were excised from the flat body panel using a DXF sampling template to fix location and orientation (Figure 1). Cutting was performed using a water jet cutter. The gauge length lay entirely within the flat face, avoiding ribs and the corner radius. Specimens conformed to ISO 37 dimensions; no post-cut finishing was applied. Width and thickness were measured at three points within the gauge length; mean values were used for stress calculation.

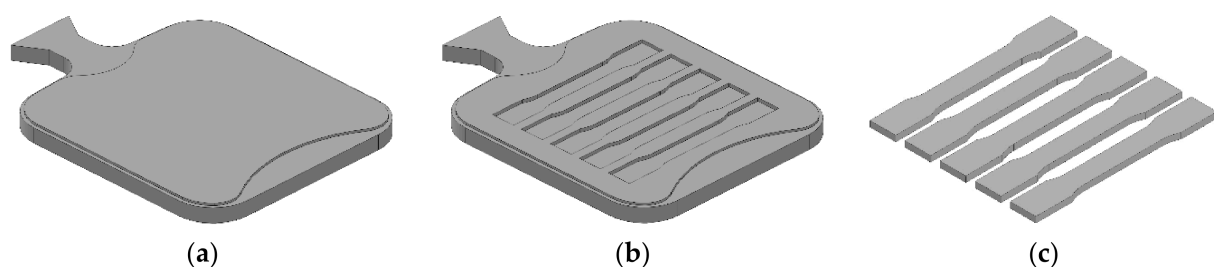


Figure 1. Schematic of face extracted tensile samples with (a) full bottle specimen, (b) excised bottle, and (c) excised samples.

2.1.2. Seam Specimens

Specimens were also excised from the seams of the water bottles in line with findings from a previous study [11]. Linear straightedge samples were excised with the side seam centred within and bisecting the gauge length (Figure 2). The loading axis was perpendicular to the seam line to assess across-seam tensile performance. Specimens followed

ISO 37 dimensions; edges were left as-cut. Width and thickness were measured at three points within the gauge length with a vernier calliper (DuraTool, Taichung City, Taiwan); the mean values defined the cross-sectional area. Seam and face specimens were sampled from different bottles within each cohort and were therefore treated as independent groups.

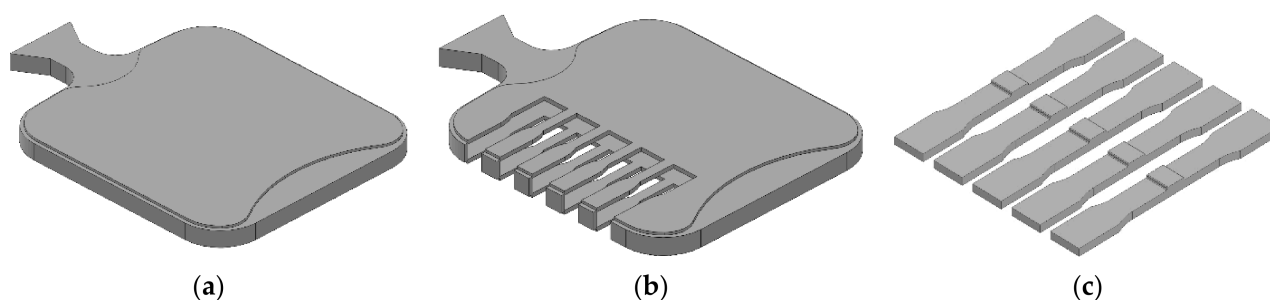


Figure 2. Schematic of seam extracted tensile samples with (a) full bottle specimen, (b) excised bottle, and (c) excised samples.

2.2. Tensile Testing Protocol

Uniaxial tensile tests were performed on an Instron 3369 (Figure 3) fitted with a Class-1 load cell (per BS EN ISO 7500-1:2018 [20]) and self-aligning grips. Specimens conformed to BS EN ISO 37:2017 [21] Type 1 dumb-bell geometry; the initial gauge length (L_0) was the ISO value for that geometry. Tests were conducted at 23 ± 2 °C and $50 \pm 5\%$ RH. Immediately prior to testing, width and thickness were measured at three positions within the gauge length using a DuraTool vernier calliper (± 0.01 mm); the mean values defining the initial cross-sectional area (A_0) thicknesses of each cohort can be seen in Table 1.

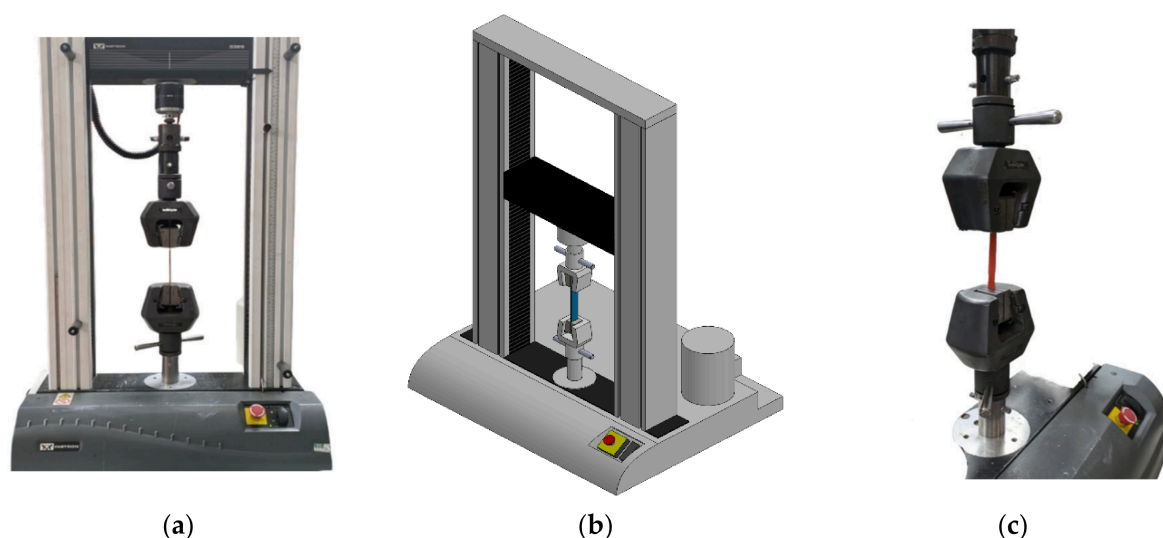


Figure 3. Schematic of Instron 3369 with uniaxial tensile sample in situ, (a) Front view of the machine during a test, (b) CAD representation of the machine components, (c) A tensile sample during a test.

Table 1. Cohort sample thickness.

Cohort	Face Thickness [M $\pm$ SD] (mm)	Seam Thickness [M $\pm$ SD] (mm)
Rubber 2022	2.11 [± 0.01]	2.16 [± 0.01]
Rubber 2024	2.18 [± 0.00]	2.20 [± 0.01]
PVC 2022	1.99 [± 0.01]	2.00 [± 0.01]
PVC 2024	2.08 [± 0.02]	2.10 [± 0.02]

Each specimen was mounted carefully to avoid pre-stress, with the loading axis aligned to the gauge centreline; for PVC seam specimens, the weld bead lay perpendicular to the loading axis and centred within the gauge. The grip separation rate was 500 mm min^{-1} , in accordance with ISO for Type 1 dumb-bells. Force and crosshead displacement were acquired continuously; engineering stress and strain were calculated according to Equations (1) and (2).

$$\sigma_{eng} = F/A_0 \quad (1)$$

$$\epsilon_{eng} = \Delta L/L_0. \quad (2)$$

Ultimate tensile strength (σ_u) was taken as the maximum engineering stress; elongation at break was computed from the crosshead displacement at the first $\geq 10\%$ force drop after the peak or at complete rupture. Pre-defined exclusions were jaw slip, off-axis fracture, or violation of the gauge region.

2.3. Microscopy

Post-failure fracture morphology was assessed qualitatively by digital optical microscopy on representative face and seam tensile specimens obtained from rubber and PVC hot-water bottles manufactured in 2022 and 2024. Imaging was performed using a high-resolution USB digital microscope system with 4K image capture; nominal magnification up to $1000\times$ (Jiusion, China) in a controlled illumination set-up was used to improve the consistency of contrast and reduce reflection artefacts. Figure 4 shows how samples were oriented to expose the fracture edge and through-thickness tear profile, enabling qualitative assessment of fracture path, local deformation features, surface texture, and the presence of any visually apparent discontinuities or defect-like regions. Representative micrographs were used for comparative interpretation only and were not subjected to quantitative image analysis.

2.4. Data Processing and Statistics

Stress–strain curves were analysed up to the first force drop of $\geq 10\%$ after the peak or to complete rupture if no such drop occurred. Maximum stress, failure strain, and toughness were then calculated from this truncated response. Within each cohort, seam and face were compared using non-parametric methods: outcomes were summarised as median [IQR], differences were tested with two-sided Mann–Whitney U tests, and effect sizes were reported as Cliff's δ . Mann–Whitney U tests were performed using asymptotic two-sided p -values.

True stress–strain curves were also derived from the engineering stress–strain data for supplementary presentation. True strain ϵ_{true} was calculated according to Equation (3), and true stress σ_{true} was calculated according to Equation (4). These converted curves assume homogeneous deformation and approximately constant volume.

$$\epsilon_{true} = \ln(1 + \epsilon_{eng}) \quad (3)$$

$$\sigma_{true} = \sigma_{eng}(1 + \epsilon_{eng}) \quad (4)$$

where σ_{eng} is calculated as the applied tensile force divided by the original, unstretched, cross-sectional area of the specimen, as described in Equation (1).

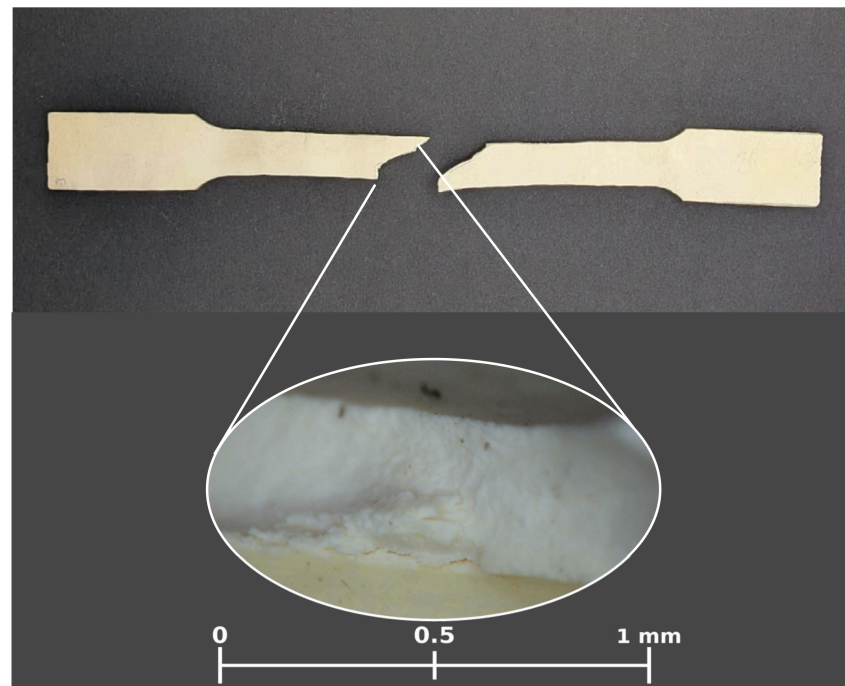


Figure 4. Schematic to demonstrate the location of microscopy on failed specimens.

3. Results

3.1. Tensile Testing Results

The tensile results are organised to separate the behaviour of the body panel material from that of the seam region. This approach allows the main trends in material type and manufacturing year to be considered first, before assessing whether the seam behaves in the same way as the corresponding face material. This distinction is important because the seam is often the critical region in service and may not be adequately represented by face specimens alone.

3.1.1. Face Specimens Testing Results

Face dumb-bells were available for all four cohorts (Rubber-2022, Rubber-2024, PVC-2022, PVC-2024; number of samples $n = 5$ per cohort). Strain is dimensionless ($\epsilon = \Delta L/L_0$), and tangent modulus is reported in MPa ($d\sigma/d\epsilon$). Figure 5 shows the ensemble engineering stress–strain responses with mean $\pm$ SD bands. Both PVC cohorts exhibit markedly higher stress at matched strain than the rubber cohorts across the full range, consistent with greater stiffness. Within materials, PVC-2022 lies consistently above PVC-2024, while Rubber-2024 lies slightly above Rubber-2022.

Figure 6 summarises tangent modulus as a function of stress (pre-specified stress levels). PVC shows higher E_t than rubber at every level examined. The ordering observed in Figure 5 is preserved: PVC-2022 $>$ PVC-2024 and Rubber-2024 $\geq$ Rubber-2022. These trends hold from the lowest stress level up to the highest common level assessed.

Maximum engineering stress for faces is shown in Figure 7. PVC cohorts achieve substantially higher maxima than rubber (PVC medians were 7.64 MPa–8.34 MPa and rubber 2.92 MPa–3.09 MPa), with PVC-2022 exceeding PVC-2024 and a small separation between Rubber-2024 and Rubber-2022.

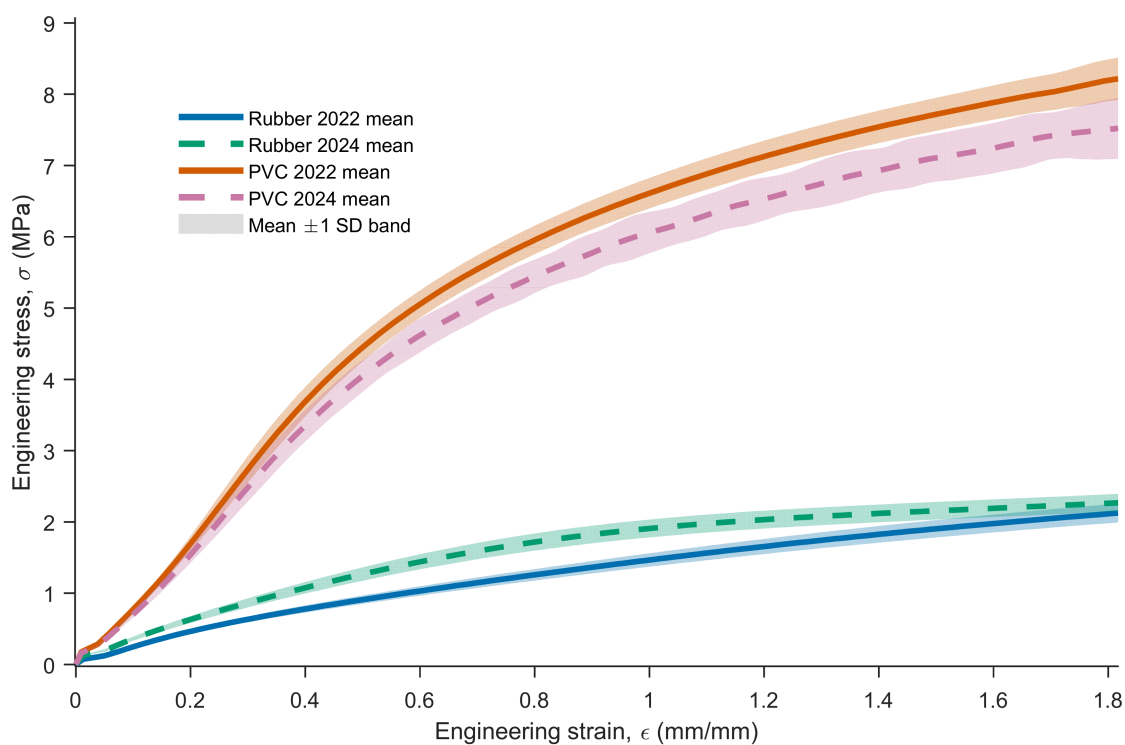


Figure 5. Stress–strain overlays for face samples by group: mean curve with $\pm$ SD shaded band; legend indicates sample group.

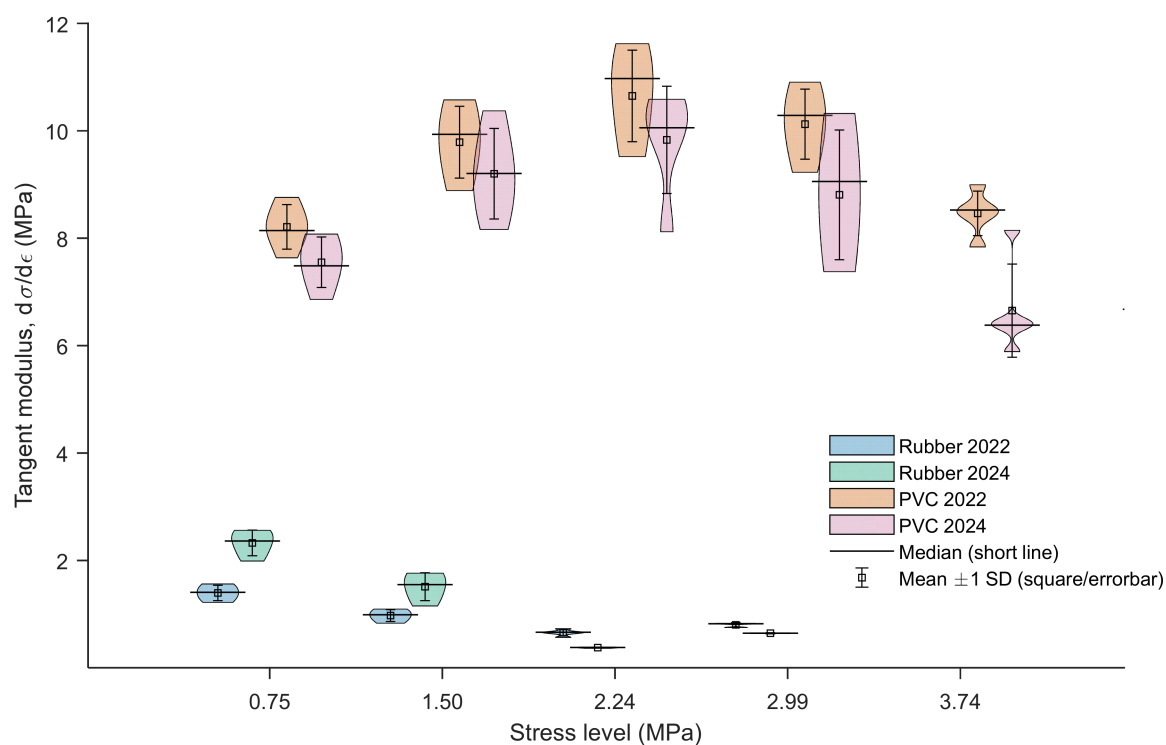


Figure 6. Tangent modulus ($d\sigma/d\epsilon$) at fixed stress levels for face samples: grouped violin plots by cohort; x-axis lists evaluation stresses. Filled shape = distribution; long thick horizontal bar = mean; short thin bar = median; square marker = mean; vertical whisker = ± 1 SD.

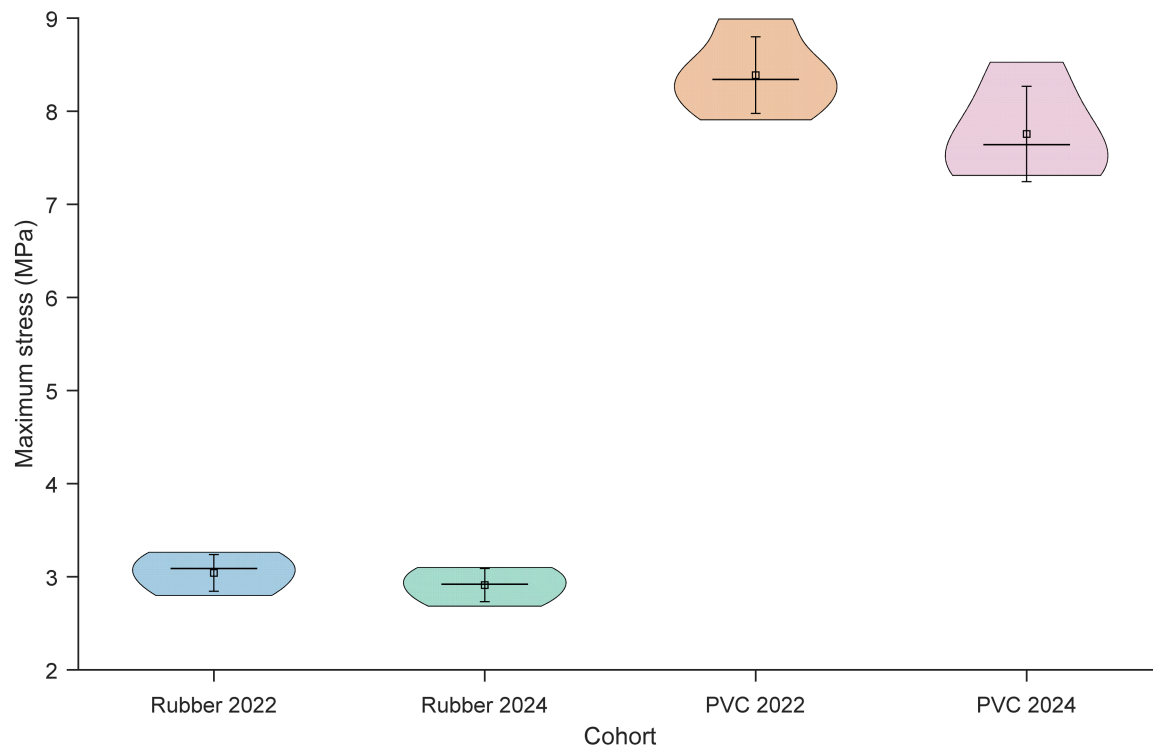


Figure 7. Maximum stress per sample: grouped violin plots for face samples. Filled shape = distribution; long thick horizontal bar = mean; short thin bar = median; square marker = mean; vertical whisker = $\pm$ SD.

3.1.2. Seam Specimens Testing Results

Figure 8 shows the ensemble engineering stress–strain responses (mean $\pm$ SD). PVC seams carry substantially higher stress at matched strain than rubber across the full range. Within materials, Rubber-2024 tracks above Rubber-2022 from mid-strain onwards, while PVC-2022 remains above PVC-2024 throughout, indicating higher ultimate stress for the older PVC cohort. Variability increases with strain for all groups and is most pronounced for Rubber-2024 at high strain.

Figure 9 summarises tangent modulus at pre-specified stress levels. PVC exhibits higher E_t than rubber at every level examined. Within the PVC seam specimens, PVC-2022 and PVC-2024 showed broadly comparable tangent modulus behaviour across the common stress range, with overlapping distributions and no consistent cohort ordering. PVC-2024 showed slightly higher central values at some lower stress levels, whereas PVC-2022 was equal or higher at higher stress levels. This indicates that the manufacturing year-associated difference in PVC seam behaviour was more apparent in load-bearing capacity and maximum stress than in local tangent stiffness at fixed stress. Within rubber, Rubber-2022 tends to have slightly higher E_t than Rubber-2024 at lower stress, with convergence toward the highest common level. Dispersion is wider for PVC than rubber at most levels, especially at low–mid stress.

Figure 10 indicates a clear ordering of central tendency: PVC-2022 shows the highest maximum stress, followed by PVC 2024, then Rubber-2024, with Rubber-2022 lowest. Across materials, the PVC cohorts cluster at higher stresses than the rubber cohorts. Within materials, PVC-2022 exceeds PVC 2024, whereas Rubber-2024 exceeds Rubber-2022. Dispersion is largest for Rubber-2024, moderate for PVC-2024, and tightest for PVC-2022 and Rubber-2022.

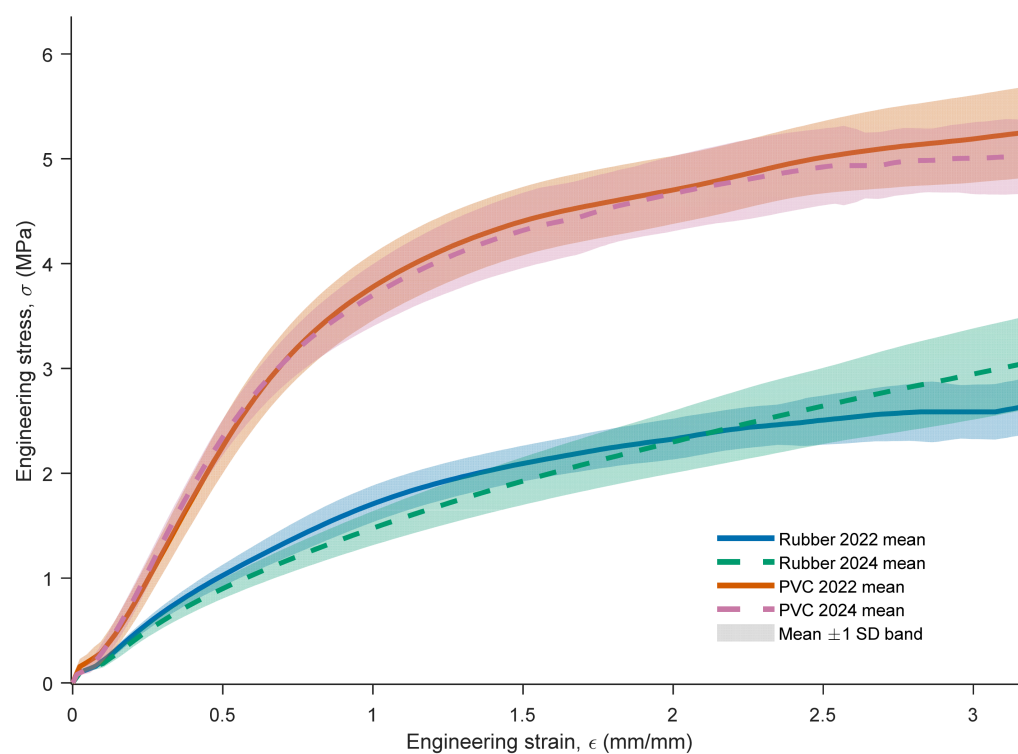


Figure 8. Stress–strain overlays by group for seam samples: mean curve with $\pm$ SD shaded band; legend indicates cohorts.

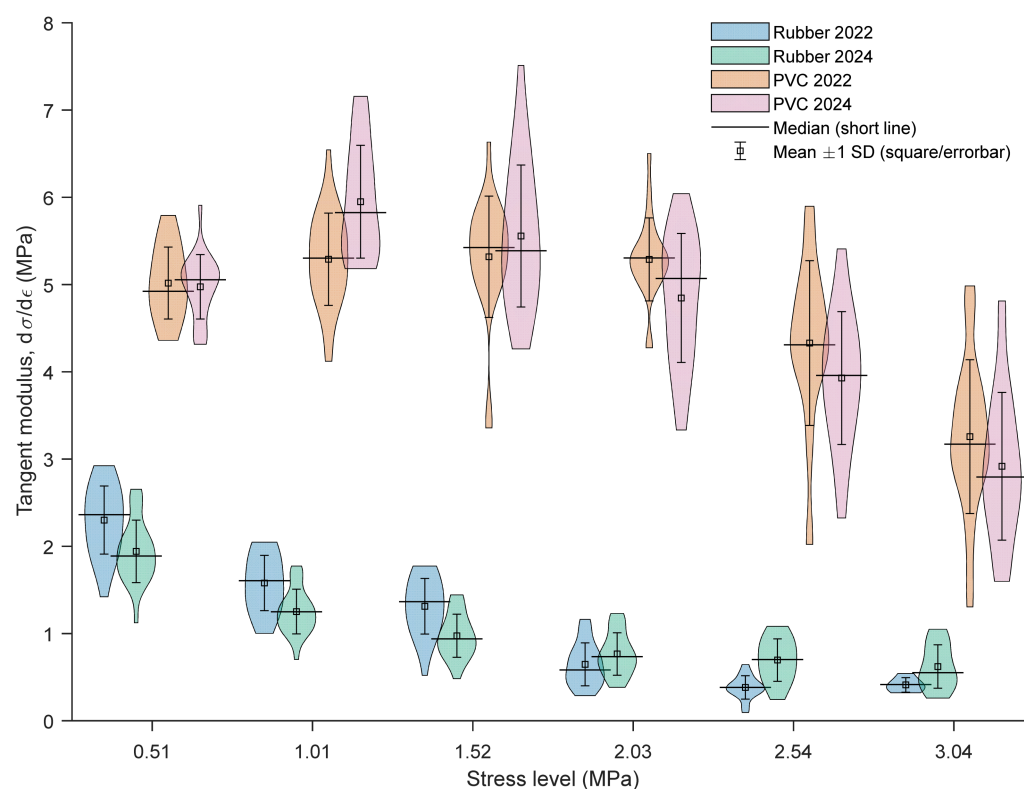


Figure 9. Tangent modulus ($d\sigma/d\epsilon$) at fixed stress levels for seam samples: grouped violin plots by cohort; x-axis lists evaluation stresses. Filled shape = distribution; long thick horizontal bar = mean; short thin bar = median; square marker = mean; vertical whisker = $\pm$ SD.

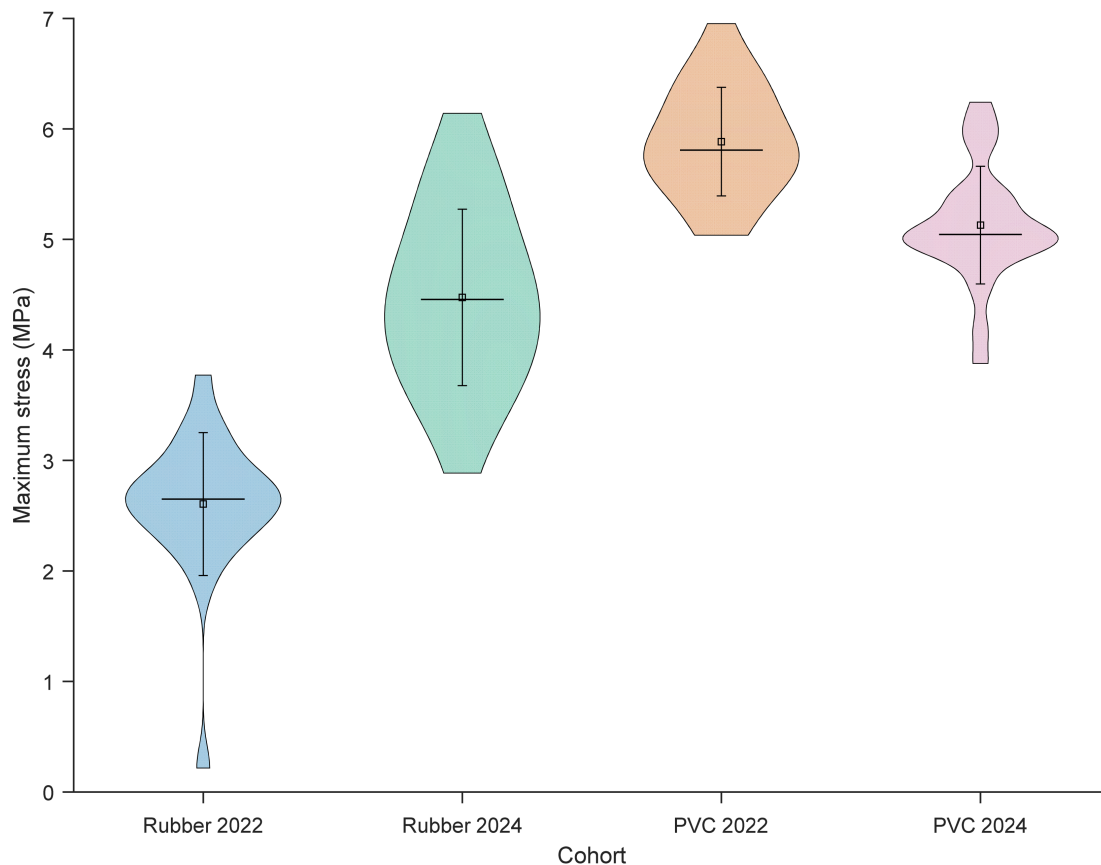


Figure 10. Maximum stress per sample: grouped violin plots for seam samples. Filled shape = distribution; long thick horizontal bar = mean; short thin bar = median; square marker = mean; vertical whisker = $\pm$ SD.

3.1.3. Seam vs. Face Specimens

Figures 11–13 compare seams and faces within each cohort. For Rubber-2022 (panels a), seam and face stress–strain curves are similar up to ~ 1 mm/mm strain, after which the face response remains slightly above the seam. Faces achieve the higher maximum stress, while seams show marginally higher tangent modulus at the lowest stress levels with convergence by ~ 2.1 – 3.1 MPa. For Rubber-2024 (panels b), seams exceed faces across most of the strain range and attain clearly higher maxima; the tangent modulus is consistently higher for seams at all examined stress levels. For PVC-2022 (panels c), faces carry substantially higher stress at matched strain than seams and show markedly higher maxima; face tangent modulus is higher than seam tangent modulus at every stress level. PVC-2024 (panels d) mirrors this pattern: faces outperform seams throughout the strain range, with higher maxima and higher tangent modulus at all stress levels. Converted true stress–strain plots are provided in the Supplementary Materials to support comparison with numerical modelling workflows (Figures S1–S3).

Across cohorts, the material effect dominates: PVC faces outperformed PVC seams, Rubber-2024 seams outperformed Rubber-2024 faces, and Rubber-2022 showed near-parity except for a modest face advantage in maximum stress with little stiffness difference at mid–high stress. Dispersion is larger for seams than faces in rubber (notably Rubber-2024), consistent with geometric/structural heterogeneity at the joint; PVC comparisons show narrower and higher face distributions. As summarised in Table 2, seam–face comparisons were performed within each cohort using two-sided Mann–Whitney tests with Cliff’s δ . Tangent modulus (E_t) was evaluated at a common mid-stress of 2.59 MPa. Results are reported as medians with associated p -values and effect sizes.

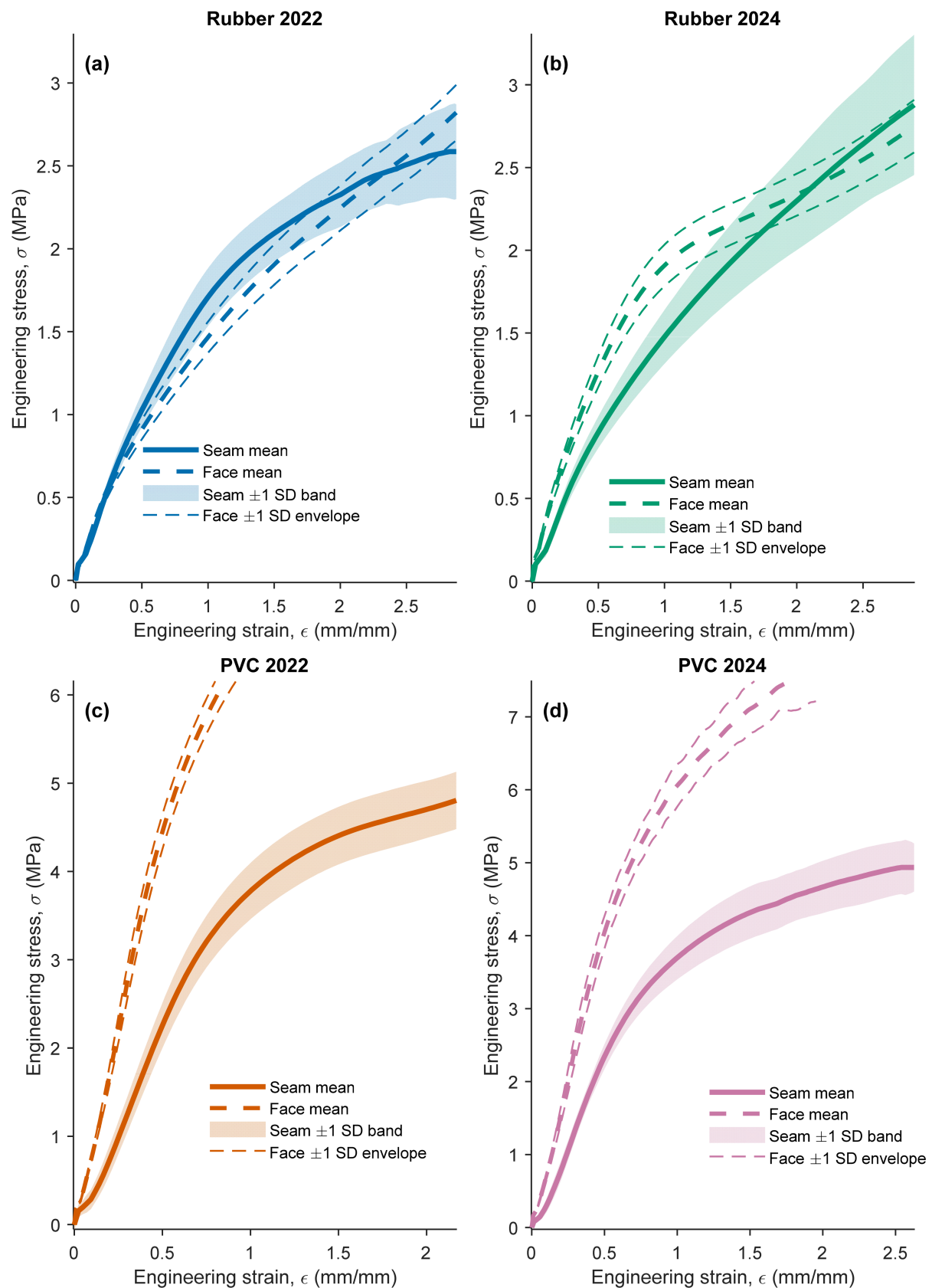


Figure 11. Comparative stress–strain responses for seam and face specimens by cohort: (a) Rubber-2022, (b) Rubber-2024, (c) PVC-2022, (d) PVC-2024 (mean $\pm$ SD).

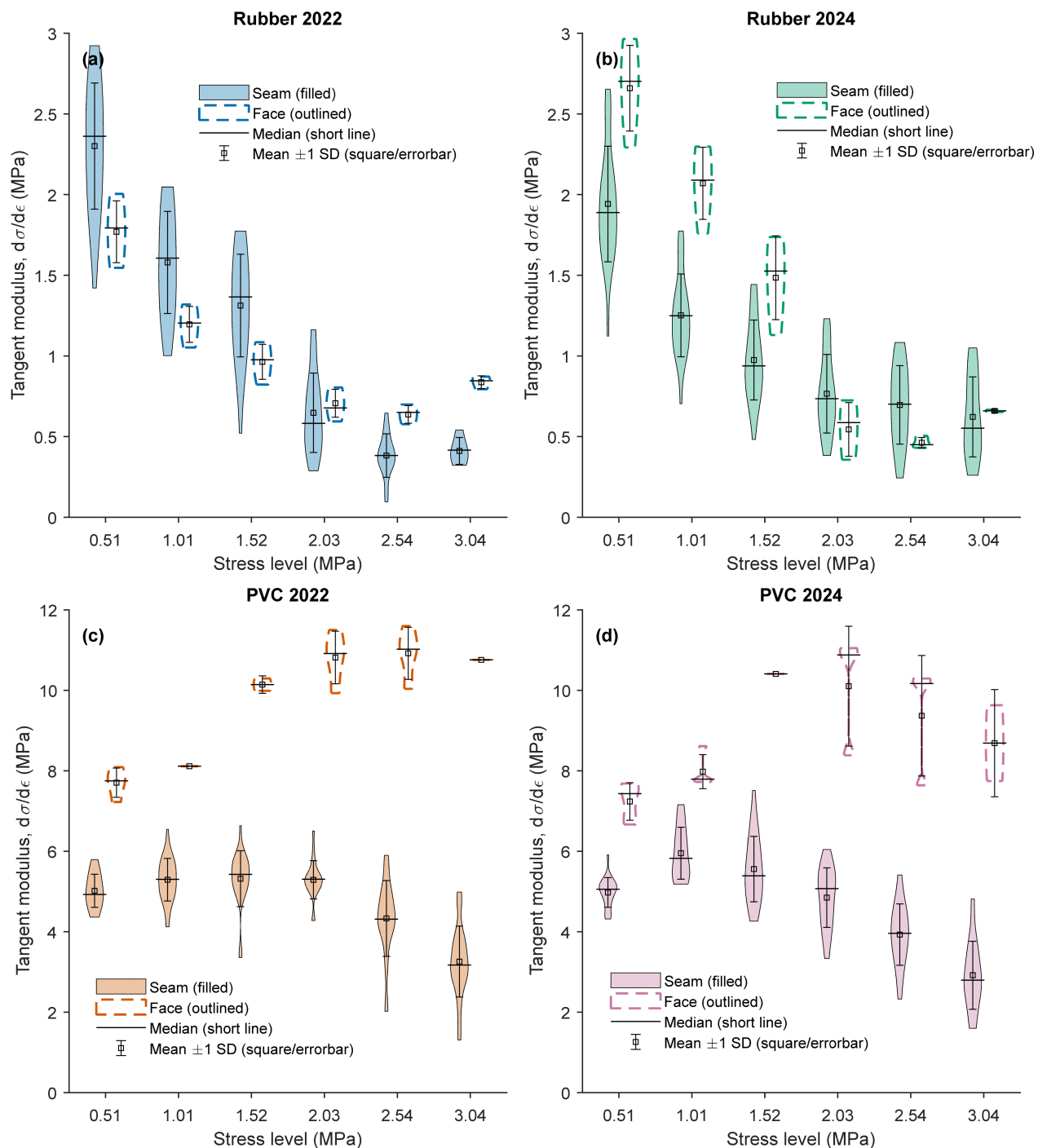


Figure 12. Tangent modulus $d\sigma/d\epsilon$ (MPa) at fixed stress levels for seam and face specimens by cohort: (a) Rubber-2022, (b) Rubber-2024, (c) PVC-2022, and (d) PVC-2024. For each stress level, the violin shows the distribution of per-sample local slopes (windowed weighted least squares), with median, mean and $\pm$ SD whiskers; stress levels are aligned across panels.

In Rubber-2022, face specimens had higher maximum stress than seam specimens (3.09 vs. 2.67 MPa; $p = 0.045$; $\delta = +0.58$). Face specimens also had higher Et at 2.59 MPa (0.659 vs. 0.334 MPa; $p = 0.002$; $\delta = +0.95$). In Rubber-2024, seam specimens had higher maximum stress than face specimens (4.54 vs. 2.92 MPa; $p = 0.001$; $\delta = -0.95$). Et at 2.59 MPa was also higher in seam specimens (0.708 vs. 0.482 MPa), although this comparison did not reach statistical significance ($p = 0.066$; $\delta = -0.54$).

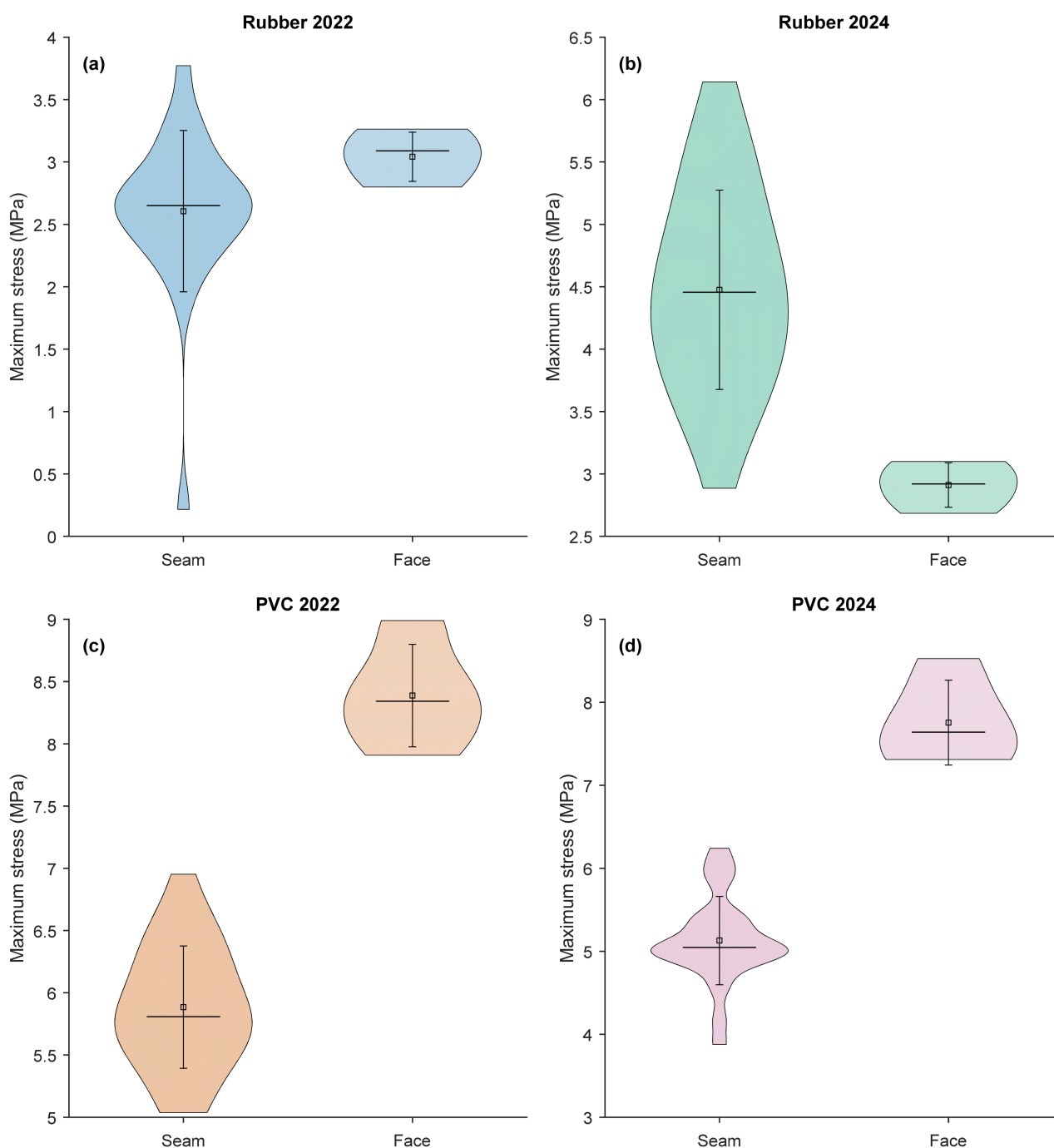


Figure 13. Maximum stress (MPa) for seam versus face specimens by cohort: (a) Rubber-2022, (b) Rubber-2024, (c) PVC-2022, and (d) PVC-2024. Violin density with mean (thick bar), median (thin bar), and $\pm$ SD whiskers; seam and face are shown side by side for each panel.

In PVC-2022, face specimens had higher maximum stress than seam specimens (8.34 vs. 5.81 MPa; $p < 0.001$; $\delta = +1.00$) and higher Et at 2.59 MPa (11.0 vs. 4.23 MPa; $p = 0.002$; $\delta = +1.00$). In PVC 2024, face specimens likewise had higher maximum stress than seam specimens (7.64 vs. 5.05 MPa; $p < 0.001$; $\delta = +1.00$) and higher Et at 2.59 MPa (10.2 vs. 3.90 MPa; $p = 0.006$; $\delta = +1.00$).

Converted true stress–strain curves are provided in the Supplementary Materials to support comparison with numerical modelling workflows (Figures S1–S3).

Table 2. Seam-versus-face tensile properties by manufacturing cohort. Values are median [IQR]. Seam $n = 25$; face $n = 5$ per cohort unless noted. p : exact two-sided Wilcoxon rank-sum test; * survives Bonferroni correction (16 comparisons; $\alpha = 0.003$); $^{\dagger} p < 0.05$ uncorrected (exploratory). δ : Cliff's effect size (positive = face > seam).

Cohort	Metric	Seam Median [IQR]	Face Median [IQR]	U	p	δ
Rubber-2022	Maximum stress (MPa)	2.67 [2.43–2.97]	3.09 [2.86–3.20]	23	0.027 †	0.63
	E_t at 2.59 MPa	0.334 [0.307–0.445] ^a	0.659 [0.608–0.667]	1	<0.001 *	0.97
	Failure strain (mm/mm)	2.84 [2.47–3.76]	3.17 [3.17–3.17] ^b	45	0.350	0.28
	Toughness (MPa)	5.15 [4.23–8.31]	5.87 [5.54–6.11]	47	0.416	0.25
Rubber-2024	Maximum stress (MPa)	4.54 [3.86–5.42]	2.92 [2.76–3.07]	122	<0.001 *	−0.95
	E_t at 2.59 MPa	0.708 [0.504–0.895]	0.482 [0.460–0.507]	96	0.065	−0.54
	Failure strain (mm/mm)	6.28 [6.28–6.28] ^b	3.17 [3.17–3.17] ^b	125	<0.001 *	−1.00
	Toughness (MPa)	17.2 [14.8–19.4]	6.47 [6.05–6.68]	125	<0.001 *	−1.00
PVC-2022	Maximum stress (MPa)	5.81 [5.57–6.24]	8.34 [8.09–8.66]	0	<0.001 *	1.00
	E_t 2.59 MPa	4.23 [4.02–4.81]	11.0 [10.5–11.3] ^c	0	<0.001 *	1.00
	Failure strain (mm/mm)	5.22 [3.92–5.64]	2.10 [1.91–2.28]	125	<0.001 *	−1.00
	Toughness (MPa)	23.3 [17.4–26.5]	12.4 [11.1–14.1]	125	0.002 *	−0.84
PVC-2024	Maximum stress (MPa)	5.05 [4.93–5.37]	7.64 [7.32–8.12]	0	<0.001 *	1.00
	E_t at 2.59 MPa	3.90 [3.40–4.40]	10.2 [8.21–10.8]	0	<0.001 *	1.00
	Failure strain (mm/mm)	2.99 [2.60–3.40]	2.10 [1.91–2.28]	105	0.016 †	−0.68
	Toughness (MPa)	11.3 [10.3–13.0]	11.0 [10.3–13.1]	63	1.000	0.00

^a Rubber-2022 seam: $n = 15/25$ specimens reached 2.59 MPa; remaining 10 excluded from E_t comparison. ^b Zero IQR indicates all specimens reached test-end displacement; values reflect maximum recorded strain rather than catastrophic failure strain. ^c PVC 2024 face: $n = 4/5$ specimens reached 2.59 MPa.

3.2. Qualitative Post-Failure Analysis

Representative post-failure digital optical micrographs are shown in Figure 14. These images were used to document visible fracture morphology and fracture location after tensile testing. The analysis was qualitative and was not intended to provide quantitative fracture path measurement or direct evidence of a specific degradation mechanism.

For seam specimens, post-failure inspection confirmed that rupture occurred within the gauge length and within the seam-containing region, rather than at the grips or outside the intended test region. In the seam samples, the fracture path ran along the seam direction. In the PVC seam specimens, failure was located at or adjacent to the welded/heat-affected seam region, consistent with the seam acting as the mechanically relevant region under transverse loading. In the rubber seam specimens, rupture also occurred within the seam-containing gauge region, although the tear path appeared less sharply localised than in the PVC specimens.

In the PVC specimens, the 2022 face and seam samples both exhibited predominantly textured fracture regions with broad, diffuse through-thickness shear features. By contrast, the 2024 PVC specimens showed repeated, sharply defined V-shaped markings extending across the section in both face and seam samples, giving a more regular and segmented tear profile. Within PVC, the visual difference between manufacturing years was more

pronounced than the difference between face and seam location, as the face and seam specimens from a given year showed closely related fracture patterns.

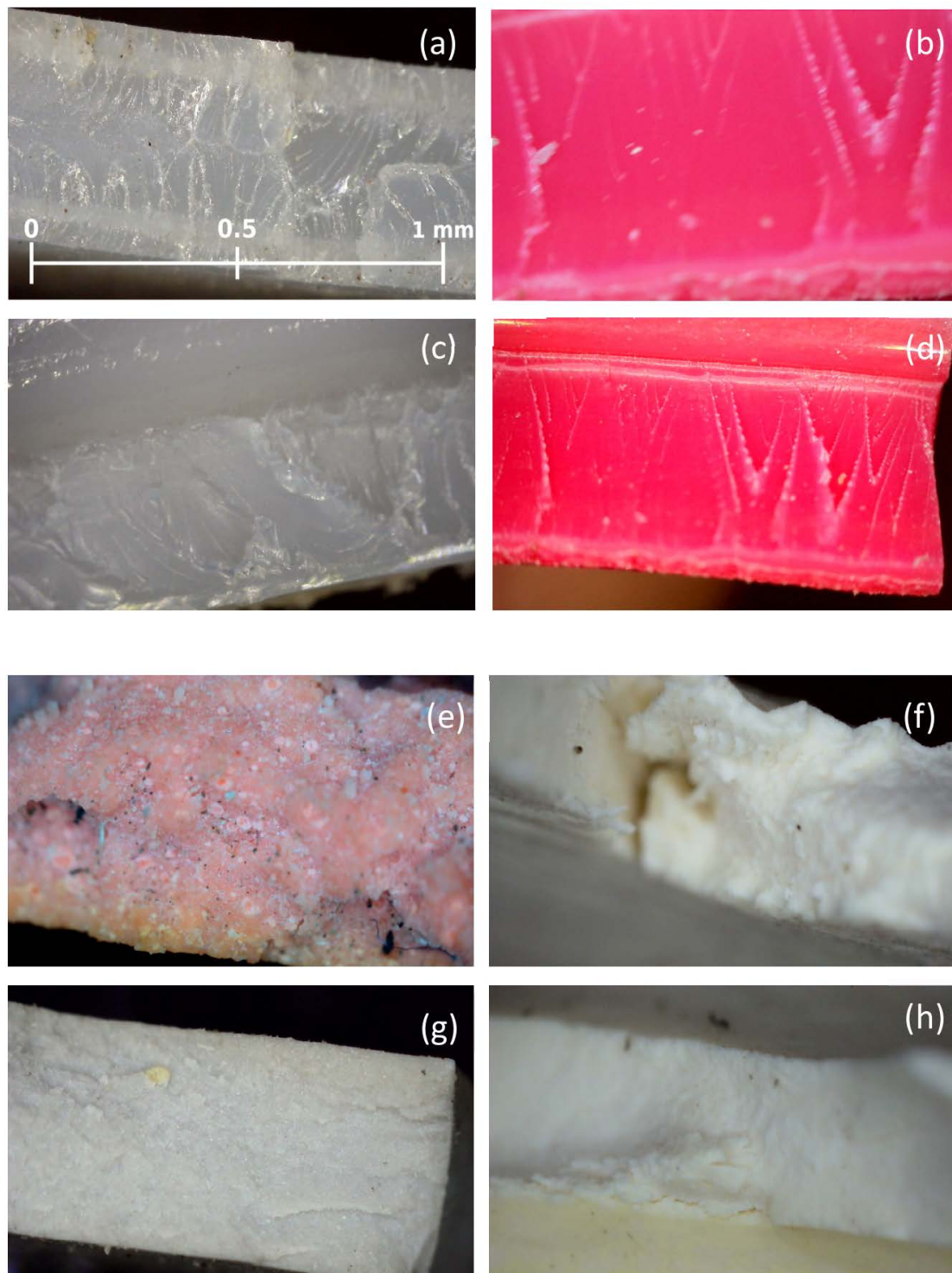


Figure 14. Representative digital optical micrographs of failed tensile specimens: (a) PVC face, 2022; (b) PVC face, 2024; (c) PVC seam, 2022; (d) PVC seam, 2024; (e) rubber face, 2022; (f) rubber face, 2024; (g) rubber seam, 2022; and (h) rubber seam, 2024.

In the vulcanised rubber specimens, the 2022 face sample displayed a coarse, granular fracture surface, whereas the 2022 seam sample appeared comparatively blunt, matte, and relatively planar. The 2024 rubber face specimen exhibited a more irregular topography with local cavities and step-like relief, while the 2024 seam specimen showed a more

heterogeneous tear surface with greater local relief and a less uniformly planar profile than the 2022 seam specimen. Overall, the rubber specimens showed marked year-to-year differences in surface texture, with the older samples appearing rougher and more chalky and the newer samples retaining more localised relief associated with tearing.

4. Discussion

Seam specimens from unused, dry-stored bottles show clear material-dependent differences between manufacturing year cohorts. PVC seams are consistently stiffer than rubber at a given strain and have a higher tangent modulus at the same stress. Within PVC, the 2022 bottles generally reach higher maximum stresses than the 2024 bottles, while differences in low-strain stiffness at fixed stress are comparatively small. Taken together, this is consistent with time-dependent plasticiser redistribution and/or limited volatilisation local to the heat-seal, processes that increase stiffness and reduce energy dissipation, in line with evidence that plasticiser loss is a principal driver of embrittlement in plasticised PVC systems [18,22,23]. Post-weld relaxation and microstructural stabilisation may also contribute, because seal performance is highly sensitive to heat-sealing conditions (temperature, pressure, dwell time, and cooling rate), and variations in weld integrity are a dominant source of scatter in the mechanical response [9,24]. Under benign storage conditions (dark, dry, room temperature), photo-oxidation and dehydrochlorination should progress slowly compared with plasticiser transport. By contrast, UV exposure can rapidly accelerate both additive loss and chemical degradation; for example, photo-aged PVC has been shown to leach phthalates substantially faster than unaged material [9,25,26]. The higher stiffness in PVC-2022 relative to PVC-2024 is most plausibly explained by time-dependent plasticiser loss and weld-quality effects, rather than substantial chain scission or dehydrochlorination under benign storage [27–30].

The PVC seam results should be interpreted with particular caution because seam specimens interrogate both sheet material behaviour and weld-region integrity. Unlike face specimens, seam specimens include a heat-affected and geometrically non-uniform region produced during sealing. Heat-seal integrity is known to depend on process and design variables, including sealing temperature, pressure, dwell time, interface conditions and local seal geometry [8,9]. Studies of welded PVC-coated fabrics also show that welded seam configuration, weld width, and loading orientation can affect tensile strength, elongation at break, strain distribution and failure mode, supporting the interpretation that the welded region should not be treated as mechanically equivalent to the surrounding parent material [10]. Local weld morphology, residual stress, cooling history, thickness variation and plasticiser redistribution may therefore influence the tensile response, potentially masking or exceeding any manufacturing year-associated difference in the surrounding sheet material [8,9,17]. This interpretation is consistent with the greater scatter observed in PVC seam specimens and with the lower performance of PVC seams relative to PVC faces. The PVC seam data therefore should not be interpreted as showing a simple manufacturing year effect.

Rubber seams show the opposite trend by year. The newer 2024 cohort sustains higher large-strain stress, greater failure strain, and higher toughness than 2022. Thermo-oxidative reactions proceed at ambient conditions as antidegradants are consumed [31]; the balance shifts toward main-chain scission relative to any late crosslink formation, extensibility falls, and strain localises earlier at geometric stress raisers within the seam [32]. Contemporary reviews and mechanistic studies document this crosslink-versus-scission competition and the role of cure system and oxygen access; ozone cracking at low parts per billion further accelerates surface damage under strain, aligning with earlier neck and edge hot-spot observations [11,14–16]. Any small increases in low-strain modulus with storage are

outweighed by scission-driven ductility loss as failure is approached, yielding inferior ultimate performance for the older rubber cohort [13].

Face dumb-bells primarily report bulk material capacity, whereas seam coupons interrogate joint performance and are therefore more sensitive. Consistently higher stresses and lower scatter in PVC face specimens versus lower and more variable seam results align with weld parameter sensitivity and local plasticiser depletion at seals [9,18,27,33]. In rubber, seam behaviour reflects geometry-driven strain concentrations and diffusion-limited oxidation near edges, explaining cohort-dependent inversion of face–seam ordering [11,13,16]. Practically, face tests benchmark material condition; seam tests capture the safety-critical limit state, and both are required for risk-relevant assessment.

Taken together, fixed-strain stress, maximum stress, toughness, and tangent modulus analyses support a stable cross-material hierarchy in which PVC is stiffer than rubber at the seam, and a bidirectional ageing trajectory in which older PVC retains or slightly enhances load capacity while older rubber loses extensibility and ultimate strength. For BS 1970 performance retention and shelf-life policy under dry storage, this implies that the 2022 rubber seam cohort showed lower ultimate performance than the 2024 rubber seam cohort in the present cross-sectional comparison, whereas PVC seam performance appeared more strongly influenced by weld region behaviour and cohort-specific material differences. Welded seam mechanics studies and seal integrity reviews reinforce that process-driven weld heterogeneity is the dominant source of scatter and early weakness in PVC seams [9,33].

For face specimens, stress at fixed strains followed the same pattern, with PVC-2022 generally carrying greater stress at each evaluated strain than either rubber cohort, while rubber extended further before failure. These observations are consistent with the known effects of plasticisation on PVC (plasticiser content lowers modulus and raises elongation; depletion reverses this) and with thermo-oxidative ductility loss in rubber [13].

The microscopy findings should be interpreted as qualitative observations of post-failure fracture appearance rather than direct evidence of a specific degradation mechanism. Differences in fracture surface texture and tear morphology were visible between cohorts, but these appearances cannot distinguish between formulation, processing history, storage conditions, local geometry, weld quality or true material degradation. Accordingly, the micrographs provide useful visual context for the tensile failure modes but should not be overinterpreted without quantitative fracture analysis and complementary chemical or thermal characterisation.

In plasticised PVC, fracture behaviour is strongly influenced by formulation and plasticiser retention, with loss of plasticiser generally associated with reduced flexibility and greater brittleness. The more regular tearing pattern observed in the 2024 PVC specimens is therefore consistent with a less degraded and potentially less embrittled material state, although microscopy alone cannot distinguish shelf-ageing effects from formulation or processing differences [18,34].

In vulcanised rubber, the 2022 specimens exhibited a rougher, blunter and less drawn fracture appearance than the corresponding 2024 specimens, consistent with a less ductile failure response. This agrees qualitatively with the known effects of thermo-oxidative ageing in vulcanised elastomers, which commonly include reduced extensibility and altered fracture mode. However, as with PVC, these observations should be interpreted cautiously, since microscopy provides qualitative support only and cannot on its own separate ageing from differences in formulation, cure state or manufacture [35].

As part of BS 1970:2012 standards, there are set construction and performance expectations for rubber and plasticised-PVC hot-water bottles, and BSI has reconvened a national committee to review and update the specification [1,19]. Public guidance commonly com-

municates a practical two-year replacement window and use of the daisy-wheel date code. Our 2022–2024 comparison therefore spans the interval UK users are told matters; within this window, we observed material-specific drift, rubber seams trending to lower extensibility and ultimate performance, and PVC seams presenting as stiffer at matched strain with greater weld-driven variability, consistent with UK product-safety actions highlighting weak top seams as a burn hazard. Accordingly, UK-focused messaging should pair the two-year heuristic with explicit seam and neck checks and tighter stock rotation for rubber.

This study has several limitations. The comparison was based on unused, dry-stored bottles from two manufacturing years, so calendar ageing cannot be fully separated from differences in formulation, batch, processing conditions, or weld quality. The sample size was limited, and seam and face specimens were obtained from different bottles within each cohort. This introduces possible bottle-to-bottle variability, so seam–face comparisons should be interpreted as group-level rather than paired within-bottle comparisons. The study did not include hot-water cycling, burst testing, neck region testing, chemical quantification of plasticiser loss, hardness testing, or thermal analysis. Accordingly, the results should be interpreted as manufacturing year-associated mechanical differences under controlled dry-storage conditions, rather than as a direct prediction of in-service lifetime. A further limitation is that strain was derived from crosshead displacement rather than a local extensometer. At large deformation, this may introduce uncertainty due to system compliance, possible grip effects and non-uniform strain localisation within the gauge region. Future work should therefore use video extensometer or digital image correlation to quantify local strain fields, particularly near seams and welded regions.

5. Conclusions

The principal contribution of this study is the demonstration that hot-water bottle seam behaviour cannot be assumed from bulk face material behaviour alone and that this relationship is dependent on both material system and product cohort. This extends existing safety knowledge by providing quantitative evidence that safety-critical regions such as seams and welded interfaces should be assessed directly, rather than relying only on general material properties or face specimen tensile performance. The findings suggest that durability assessment and replacement guidance should consider construction-specific behaviour, particularly the lower and more variable performance of PVC seams relative to PVC faces and the cohort-dependent response of rubber seams. Future work should build on these findings using controlled service simulation protocols—including repeated hot-water filling and cooling cycles, wet thermal exposure, internal pressure testing, and accelerated ageing—combined with local strain measurement and material characterisation methods such as DMA, hardness testing, FTIR, DSC/TGA, and plasticiser assessment for PVC.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/app16136451/s1>, Figure S1: True stress–strain overlays for face samples by group, calculated from engineering stress–strain data using $\sigma_{true} = \sigma_{eng}(1 + \epsilon_{eng})$ and $\epsilon_{true} = \ln(1 + \epsilon_{eng})$. Curves are shown as mean $\pm$ SD. Figure S2: True stress–strain overlays for seam samples by group, calculated from engineering stress–strain data using $\sigma_{true} = \sigma_{eng}(1 + \epsilon_{eng})$ and $\epsilon_{true} = \ln(1 + \epsilon_{eng})$. Curves are shown as mean $\pm$ SD. Figure S3: True stress–strain comparison of seam and face specimens by cohort. Converted true stress–strain curves are shown as mean $\pm$ SD.

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Abbreviations

The following abbreviations are used in this manuscript:

BS	British Standard
PVC	Polyvinyl chloride
RH	Relative humidity
SD	Standard deviation

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