

Restoring Thin Cylinder Apparatus for Sustainable Engineering Education

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ABSTRACT

This study documents the successful restoration and modification of an obsolete 2003 TecQuipment SM1007 Thin Cylinder Apparatus to revive its utility for engineering laboratory education. The equipment was originally rendered non-functional by software compatibility issues where the original data acquisition software was restricted to obsolete Windows XP systems and sensor deterioration. It was refurbished by installing six new KR120-5P-23 uniaxial strain gauges (120 Ω resistance, 2.00 gauge factor) and integrating an existing TDS-303 portable data logger. The refurbishment procedure involved surface preparation of the aluminium cylinder using 70% ethanol solution and fine-grade sandpaper, pre-installation gauge resistance verification with a DT-832 digital multimeter, and bonding with a cyanoacrylate adhesive. This targeted physical intervention bypassed the outdated computer-dependent setup at a direct material cost of approximately RM 150, representing an estimated material-cost reduction of over 99% compared to purchasing a new commercial system (estimated at RM 80,000 to RM 90,000 in 2025). A performance evaluation was executed across six pressure levels up to 3.05 MPa for validation, by comparing the experimental hoop, longitudinal, and angular strain values against the original manufacturer's benchmark reference data. The results confirm that the modified apparatus exhibits a highly linear strain pressure response that mirrors the reference standard. Five of the six gauges recorded average Relative Percentage Deviation (D) well under 20% (ranging from 11.66% to 17.16%). A higher D of 48.39% for Gauge 3 was isolated as a mathematical consequence of a tiny reference strain denominator near the zero-strain axis, rather than sensor malfunction. Additionally, a minor physical pressure deviation identified at 2.49 MPa was hypothesized to stem from mechanical aging of the hydraulic system rather than instrumentation error. These findings suggest that in-house upcycling represents a practical circular-economy pathway to facilitate experiential laboratory education in resource-constrained academic settings.

Keywords: Circular Economy; Thin Cylinder Apparatus; Strain Gauge; Engineering Education; Equipment Refurbishment.

INTRODUCTION

Scientific and engineering laboratories are crucial for developing climate change solutions. However, their traditional operations carry a heavy environmental cost. Laboratories consume five to ten times more energy per square meter than standard office spaces and can account for up to 60–65% of an entire university's total energy footprint [3]. To resolve this operational paradox, "Green Lab" initiatives have emerged to promote energy, resource, and waste efficiency without compromising educational or research quality.

A core tenet of this sustainability movement is transitioning away from the linear "take-make-dispose" paradigm toward a regenerative Circular Economy (CE) model [5]. Prioritizing repair, reuse, and refurbishment keeps equipment in active use, thus offering 30% to 70% capital savings while preventing heavy metals and electronic waste from entering municipal landfills [5]. Within mechanical engineering, this approach is optimized through "upcycling" or reusing obsolete machinery to create a new product of higher quality, utility, or value than the original [2]. Upcycled design is highly challenging because experimental equipment demands tight tolerances,

structural integrity, and low measurement noise. However, legacy systems often surpass modern counterparts in structural stiffness and geometric accuracy [2]. Combining these rigid foundations with modern data acquisition (DAQ) systems and sensors can achieve polyfunctional performance while avoiding software obsolescence [2].

Implementing sustainability is highly uneven globally, particularly in resource-constrained regional contexts where engineers encounter tight budgets, outdated machinery, and limited support [6]. Overcoming these barriers requires a proactive organizational culture. Universities can foster this by integrating sustainability and preventive maintenance concepts directly into engineering curricula via hands-on experiential learning modules [4]. While cash-constrained laboratories can leverage free or open-source computer-aided engineering (CAE) software (e.g., Onshape, Octave, and Simscales) to teach complex kinematics and modeling, physical testing remains a pedagogical necessity [1].

In experimental mechanics, physical validation remains the gold standard for verifying theoretical equations and assessing structural integrity. While analytical models provide idealized predictions, manufacturing tolerances, material anisotropy, and boundary condition variations frequently introduce physical discrepancies in real-world systems. Researchers have historically relied on electrical resistance strain gauges to bridge this gap between theory and actual material performance. For instance, Nishma et al. (2017) [15] demonstrated that experimental strain measurements on thin-walled cylinders under internal pressurization yield linear pressure-strain trends that validate classical Hooke's Law and thin-cylinder stress distributions in both open-ended and closed-ended states. To ensure measurement reliability, modern researchers emphasize the necessity of robust physical calibration procedures. Beghini et al. (2023) [8] validated strain gauge installation and wiring configurations on calibration benches, thus demonstrating that precise surface preparation and installation are fundamental to preventing signal drift and misalignment. Similarly, Bogusz et al. (2024) [9] highlighted the continued relevance of strain gauge instrumentation by using digital image correlation (DIC) to validate that discrete foil gauges provide exceptionally high localized strain-mapping accuracy.

Evaluating the multi-axial strain field on a cylindrical surface requires an understanding of how directional strain components couple under internal pressure. Under open-ended conditions, the direct axial stress is theoretically zero, yet the cylinder experiences physical axial contraction due to the lateral strain coupling described by the Poisson effect. Schaefer et al. (2020) [16] examined these 3D strain-deflection coupling mechanisms by illustrating how circumferential expansion dictates axial behaviors even in the absence of primary axial loads. To capture these complex multi-axial fields, strain rosettes or multi-angle gauge layouts are conventionally deployed. Farrugia et al. (2023) [11] formulated rosette-based analytical frameworks to resolve compliance matrices and principal strains on curved mechanical structures. Furthermore, Matveenkov et al. (2021) [14] analyzed the reliability of these rosette systems under load, confirming that multi-angle configurations successfully isolate shear strains from primary normal strains, making them ideal for complex integrity monitoring on pressurized cylindrical boundaries.

The upcycling of legacy laboratory hardware aligns with a growing movement toward environmental sustainability and circular-economy practices in higher education. Rather than discarding obsolete equipment, extending the physical lifecycle of robust structural assets offers a high-value pathway for resource-constrained departments. Glisic (2022) [12] provided a historical overview of strain sensor instrumentation, by highlighting the unchanged core physics of foil strain gauges which led to a successful restoration to full analytical capabilities of the retrofitted vintage mechanical hardware with modern, low-cost data loggers. Diah et al. (2025) [10] further supported this upcycling paradigm by showing that integrating modern industrial strain sensors into existing educational hardware can bypass proprietary software lock-ins and provides student-accessible, transparent data acquisition frameworks. This retrofitting model directly supports sustainable engineering pedagogy by teaching students both the physical principles of experimental mechanics and the ecological importance of active asset stewardship.

This study presents a practical, cost-effective model of laboratory upcycling by restoring an obsolete 2003 TecQuipment SM1007 Thin Cylinder Apparatus. Originally disabled by software compatibility limitations where the original DAQ was restricted to Windows XP and sensor decay, the system was refurbished by retaining its structurally robust steel cylinder. This frame was retrofitted with six new KR120-5P-23 strain gauges and a portable TDS-303 data logger. This targeted low-carbon physical intervention was achieved for a material cost

of approximately RM 150 as compared to a capital expenditure of RM 80,000 to RM 90,000 for a new system (as of 2025). By validating the modified apparatus's linear strain-pressure response against original reference values [7], this project demonstrates a replicable method for maintaining high-quality, physical teaching resources while actively practicing ecological stewardship.

METHODOLOGY

This section outlines the systematic procedure used to restore, instrument, and validate the obsolete 2003 TecQuipment SM1007 Thin Cylinder Apparatus. The methodology is structured into three primary phases: (i) hardware and instrumentation integration, (ii) surface preparation and physical sensor installation, and (iii) experimental testing and validation procedures.

Refurbished Instrumentation and Hardware Integration

The core objective of this refurbishment was to bypass the original, non-functional computer-dependent Data Acquisition (DAQ) system which was restricted to obsolete Windows XP software, and replace deteriorated factory sensors using existing laboratory hardware and low-cost components. The primary instruments and materials utilized are as below:

- (1) The 2003 SM1007 Thin Cylinder Apparatus housing a robust aluminum thin-walled cylindrical pressure vessel as shown in Figure 1.
- (2) The TDS-303 Portable Data Logger (built 2002) which can automatically record the electrical resistance changes from the newly installed strain gauges and convert these signals into strain readings in units of microstrain ($\mu\epsilon$), display and store the data digitally at each applied pressure level. Prior to the experiment, the data logger was configured to correctly identify all six gauges channels and was programmed with the appropriate gauge factor of 2.00, corresponding to the KR120-5P-23 strain gauges.
- (3) Six new KR120-5P-23 uniaxial strain gauges with specifications as listed in Table 1.

Pre-installation checks were conducted using a DT-832 digital multimeter, and bonding was secured using high-strength ethyl cyanoacrylate adhesive.

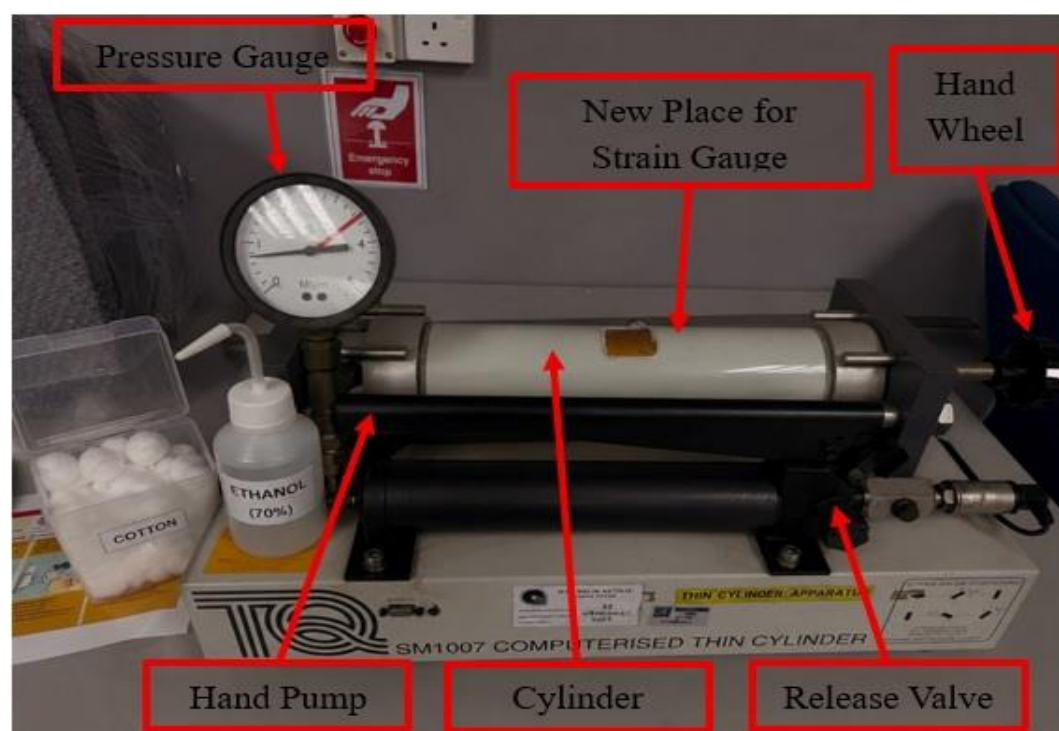


Figure 1: 2003 SM1007 Thin Cylinder Apparatus.

Table 1: Technical Specifications of the KR120-5P-23 Strain Gauges.

Parameter	Technical Specification / Value
Model / Type	KR120-5P-23
Sensor Design	Uniaxial strain measurement
Grid Dimensions	5 mm (Length) x 3 mm (Width)
Base Dimensions	9.4 mm (Length) x 6 mm (Width)
Nominal Resistance	120 Ω
Resistance Tolerance	Within $\pm 0.3\%$ of nominal resistance
Base Material	Polyester
Gauge Factor	2.00 (Nominal)
Measurable Strain Limit	2% to 4% maximum elongation
Operating Temperature	-30°C to +80°C
Thermal Output	$\pm 2 \mu\epsilon$ /(RT to 80°C)
Fatigue Life	$> 1 \times 10^5$ reversals
Thermal Compensation Code	-23 (Aluminum alloy)
Lead Wire Length	1.0 meter

Surface Preparation and Sensor Installation Procedure

A highly systematic six step surface preparation and mounting procedure was executed in an indoor and temperature-controlled laboratory setting to guarantee stable and error free strain transmission from the thin cylinder wall to the strain gauges. The steps are as listed below:

- (1) Chemical cleaning of the aluminum cylinder mounting locations using a 70% ethanol solution to eliminate grease and fingerprint contaminants.
- (2) Mechanical surface abrasion using fine-grade sandpaper to scour away the protective aluminum oxide layer and establish a micro-rough surface profile to maximize adhesive interlocking.
- (3) Precision alignment and position marking relative to a 0° reference line, thus establishing exact spatial orientations for each gauge. Gauge 2 (G2) is at 0° (longitudinal), Gauge 3 (G3) is at -30°, Gauge 4 (G4) is at +45°, Gauge 5 (G5) is at +60°, and Gauges 1 (G1) and 6 (G6) are at 90° (hoop strain).
- (4) Pre-bonding quality control checks using the DT-832 multimeter to confirm each gauge's baseline resistance fell within $120 \pm 0.3 \Omega$.
- (5) Rapid-bonding using cyanoacrylate adhesive by applying uniform pressure for 60 seconds to achieve bubble-free polymerization.
- (6) Wiring the lead lines to the TDS-303 logger in active quarter-bridge Wheatstone circuit configurations.

The complete strain gauge installed 2003 SM1007 Thin Cylinder Apparatus is as shown in Figure 2. All six gauge lead wires were labelled according to the gauge numbering.



Figure 2: 2003 SM1007 Thin Cylinder Apparatus with installed new strain gauges.

Experimental Procedure and Validation Plan

The experimental validation was conducted under open-ended and unconstrained boundary conditions to allow unrestricted axial and circumferential expansion of the cylinder. First, the TDS-303 data logger was powered on and thermally stabilized by mapping channels 1-6 and establishing a zero-strain baseline ($\epsilon_0 = 0 \mu\epsilon$) at atmospheric pressure. Second, the internal hydraulic pressure was systematically raised via a manual pump across six pressure increments (0.58, 1.05, 1.54, 2.02, 2.49, and 3.05 MPa) in a single-run, step-up pressure sweep. A 60-second stabilization hold was observed at each step before recording (the limitations of this single-run approach are discussed in Section 3.7). Third, upon maximum depressurization, zero-return stability was checked. Finally, collected experimental strain data (ϵ_{exp}) were compared against the original TecQuipment SM1007 (2003) Reference Manual benchmarks (ϵ_{ref}) by calculating the sensor-specific Relative Percentage Deviation (D): $D = [(\epsilon_{ref} - \epsilon_{exp}) / \epsilon_{ref}] \times 100\%$.

RESULTS AND DISCUSSION

Comparative Analysis of Experimental and Reference Strain Values

Table 2 compares the experimental strain readings against the manufacturer's original calibrated baseline values [7] across all six pressure load (P) steps up to 3.05 MPa. This is to validate the performance of the modified thin cylinder apparatus.

Table 2: Side-by-Side Comparison of TecQuipment Reference and Modified Apparatus Experimental Strain Values ($\mu\epsilon$).

P (MPa)	G1 (Ref/Exp)	G2 (Ref/Exp)	G3 (Ref/Exp)	G4 (Ref/Exp)	G5 (Ref/Exp)	G6 (Ref/Exp)	Orientation
0.58	111.4 / 90.0	-36.4 / -30.0	1.2 / 0.09	36.4 / 42.0	72.0 / 60.0	112.2 / 95.0	Multi-axial
1.05	201.6 / 170.0	-67.8 / -55.0	1.0 / 0.20	64.8 / 80.0	130.0 / 113.0	203.0 / 175.0	Multi-axial

1.54	295.4 / 263.0	-101.0 / -87.0	0.6 / 0.30	93.8 / 119.0	190.4 / 169.0	297.6 / 265.0	Multi-axial
2.02	388.0 / 358.0	-133.0 / -118.0	0.4 / 0.40	123.2 / 145.0	250.2 / 227.0	391.2 / 356.0	Multi-axial
2.49	477.0 / 365.0	-162.8 / -148.0	0.8 / 0.60	151.8 / 161.0	307.8 / 280.8	481.2 / 356.0	Multi-axial
3.05	584.8 / 526.0	-199.2 / -178.0	1.4 / 0.80	186.6 / 211.8	377.4 / 336.0	589.6 / 533.0	Multi-axial

The experimental strain values exhibit a highly linear relation with internal pressure, matching the fundamental linear elastic trends expected of a thin-walled cylinder [7]. Gauges 1 and 6, oriented at 90° to record circumferential (hoop) strain, correctly measured the largest positive tensile strains of 526.0 $\mu\epsilon$ and 533.0 $\mu\epsilon$ respectively at the maximum test pressure of 3.05 MPa. Conversely, Gauge 2 (oriented at 0° longitudinally) recorded a maximum compressive strain of -178.0 $\mu\epsilon$. This compressive response is a physical consequence of the Poisson effect [7], wherein the unconstrained axial contraction of the cylinder wall counters longitudinal expansion under hydraulic load. Figure 3 shows the comparison between the modified apparatus experimental results and the TecQuipment reference values [7].

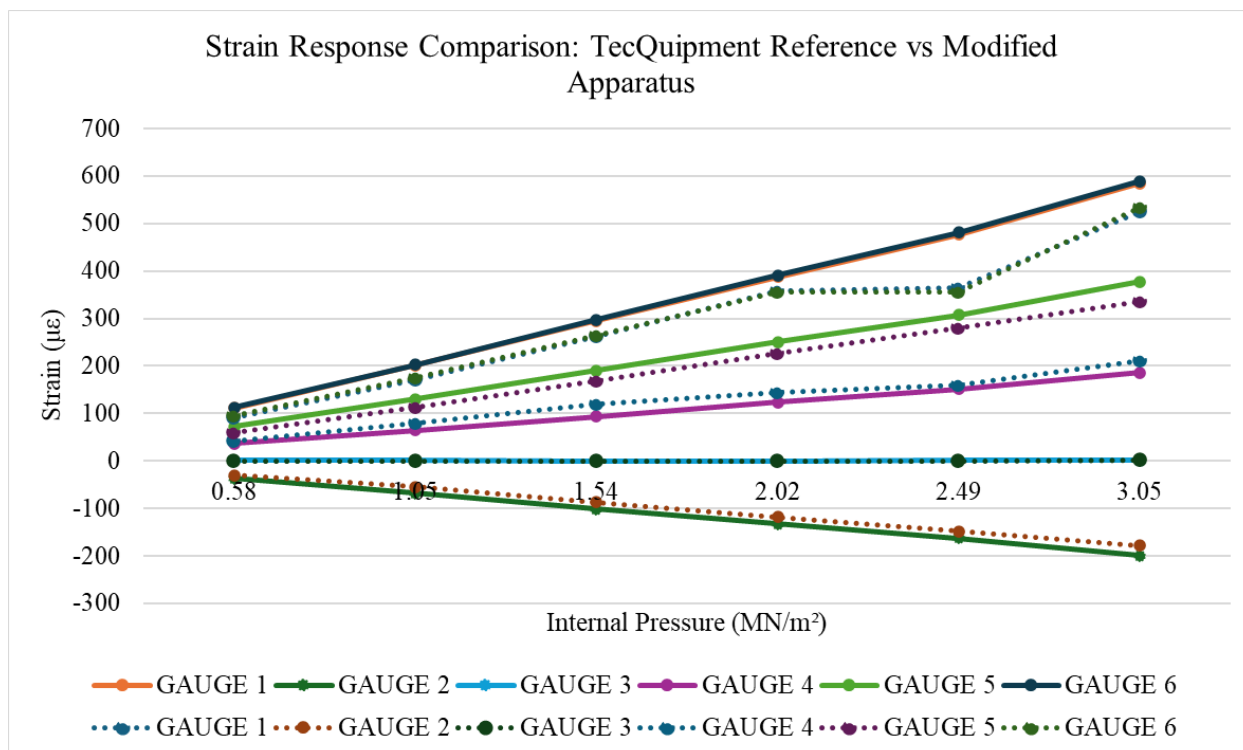


Figure 3: Strain result comparison; Solid Line for TecQuipment Reference data vs. Dotted Line for Modified Apparatus Data.

To validate the experimental results, a classical thin-walled cylinder stress-strain framework was established. For an open-ended cylinder configuration, the internal pressure acts solely on the cylindrical wall surface without loading the end caps [15]. Under these conditions, the theoretical longitudinal stress is zero ($\sigma_L = 0$), while the circumferential (hoop) stress (σ_h) is given by:

$$\sigma_h = \frac{P \cdot r}{t}$$

where P is the internal gauge pressure (MPa), $r = 40$ mm is the internal radius of the cylinder, and $t = 3$ mm is the wall thickness.

By applying the generalized Hooke's Law for a biaxial strain state, the expected strains in the principal hoop (ε_h) and longitudinal (ε_L) directions are expressed as:

$$\varepsilon_h = \frac{\sigma_h}{E}$$

$$\varepsilon_L = \frac{-\nu \sigma_h}{E}$$

where $E = 69$ GPa represents the Young's Modulus and $\nu = 0.33$ represents the Poisson's ratio for the Aluminum Alloy 6063 material of the apparatus [7].

This formulation mathematically demonstrates that while the longitudinal stress is theoretically zero under open-ended boundary conditions, a negative (compressive) longitudinal strain (ε_L) is physically expected. This compressive response, measured experimentally by Gauge 2 (oriented at 0° axial), is a direct result of the lateral contraction coupled to the hoop expansion via the Poisson effect. At the maximum tested pressure of 3.05 MPa, the theoretical hoop stress of 40.67 MN/m² yields an expected longitudinal compressive strain of -194.49 $\mu\epsilon$, which closely mirrors the experimentally recorded value of -178.00 $\mu\epsilon$.

Linearity Validation

As shown in previous Figure 3, the experimental strain values exhibit a highly linear relation with internal pressure. In this section, the statistical parameters are discussed objectively. Table 3 shows Linear Regression Parameters for Strain Gauges.

Table 3: Linear Regression Parameters for Strain Gauges.

Strain Gauge	Primary Measurement Orientation	Linear Regression Equation	Coefficient of Determination (R^2)	Adjusted R^2 (Excluding 2.49 MPa Anomaly)
Gauge 1	Hoop (90°)	$\varepsilon = 167.22 P - 3.71$	0.9724	0.9986
Gauge 2	Axial (0°)	$\varepsilon = -61.19 P + 6.77$	0.9988	0.9992
Gauge 3	Shear (-30°)	$\varepsilon = 0.28 P - 0.11$	0.9766	0.9727
Gauge 4	Shear (45°)	$\varepsilon = 65.26 P + 9.75$	0.9858	0.9951
Gauge 5	Shear (60°)	$\varepsilon = 113.12 P - 4.66$	0.9992	0.9994
Gauge 6	Hoop (90°)	$\varepsilon = 165.27 P + 1.10$	0.9622	0.9997

To mathematically validate the structural response of the upcycled apparatus, a first-order ordinary least-squares (OLS) linear regression analysis was conducted for all six strain gauges across the operational pressure range (0 to 3.05 MPa). The resulting linear regression equations, slopes, intercepts, and coefficients of determination (R^2) are compiled in Table 3.

The baseline statistical analysis demonstrates strong linear agreement, with five out of six gauges exhibiting R^2 values above 0.97. The Gauge 5 (shear 60°) achieved a near-perfect R^2 of 0.9992 across the full testing sweep.

Notably, the primary hoop sensors, Gauge 1 and Gauge 6, exhibited slightly lower baseline R^2 values of 0.9724 and 0.9622 respectively. This mild deviation is entirely attributable to the isolated, localized pressure-bypass anomaly observed at the 2.49 MPa interval.

To test the validity of the hydraulic-bypass anomaly hypothesis, an adjusted regression model was evaluated by omitting the single 2.49 MPa data point. Upon adjusting for this temporary system fluctuation, the R^2 values for the hoop-oriented Gauge 1 and Gauge 6 sensors dramatically improved to 0.9986 and 0.9997 respectively. This remarkable statistical improvement mathematically demonstrates that the sensor response is inherently highly linear, validating both the precision of the new sensor installations and the integrity of the vintage SM1007 structural hardware.

Systematic Underestimation and Sensor Calibration Factors

Again, as displayed in previous Figure 3, the modified apparatus consistently records lower strain magnitudes than the TecQuipment reference values for Gauges 1, 2, 5, and 6. At the maximum load step of 3.05 MPa, the experimental underestimations are 58.8 $\mu\epsilon$ for Gauge 1, 56.6 $\mu\epsilon$ for Gauge 6, 21.2 $\mu\epsilon$ for Gauge 2, and 41.4 $\mu\epsilon$ for Gauge 5. This uniform downward shift points to a minor systematic offset rather than random sensor drift. This systematic discrepancy is hypothesized to stem from three primary factors:

- (1) Differences in signal conditioning, filtering algorithms, and resistance-to-strain conversion scaling between the integrated 2002 TDS-303 data logger and the original 2003 computer-based system.
- (2) Tiny, non-homogenous variations in the thickness of the cyanoacrylate adhesive bond which slightly dampens the shear strain transfer.
- (3) Unavoidable manual alignment errors where a subtle angular deviation of 1° to 2° from the exact theoretical axis scales down the recorded strain component.

Hydraulic System Anomaly at 2.49 MPa due to Leakage Phenomenon

A distinct physical anomaly appears at the 2.49 MPa pressure interval, where the hoop-oriented Gauges 1 and 6 recorded strain levels of 365.0 $\mu\epsilon$ and 356.0 $\mu\epsilon$ respectively. These values represent a localized flattening of the strain response relative to the previous 2.02 MPa step, skipping the expected linear step increase of approximately 90 $\mu\epsilon$.

It is hypothesized that this anomaly may be associated with a minor, momentary pressure drop or seal-bypass event within the aging 2003 thin cylinder's hydraulic valves. Because Gauges 1 and 6 are oriented in the hoop direction, they exhibit the highest sensitivity to localized fluid pressure variations, which would explain why their strain curves flattened while other intermediate-angle gauges were less affected.

Although physical limitations in the vintage laboratory apparatus prevented the execution of direct leakage measurements or in-line pressure-decay tests to confirm seal leakage, this hydraulic bypass hypothesis is strongly supported by two observations: first, the physical occurrence of this localized pressure drop was cross-verified using a separate, non-reported diagnostic pressure sweep monitored by an independent secondary data logger, which duplicated the same flattening behavior and thereby ruled out primary instrumentation error or localized electrical transients; and second, the system fully recovered normal linear behavior at the subsequent 3.05 MPa step once the pressure stabilized. The flattening at 2.49 MPa is therefore presented as a localized experimental limitation rather than sensor malfunction or structural failure.

Quantitative Degradation and Sensor Integrity Analysis

To evaluate the measurement accuracy of the refurbished apparatus, the Relative Percentage Deviation (D) was calculated relative to the manufacturer's historical reference data. As shown in Table 4, five of the six strain gauges exhibited an average relative deviation of less than 20% across all pressure steps. While a 20% deviation threshold is broader than commercial metrological tolerances, it is adopted here as a practical pedagogical baseline for undergraduate laboratory demonstrations. In an educational setting, where student experiments

prioritize the qualitative observation of mechanical phenomena (such as multi-axial strain coupling, the Poisson effect, and linear elastic load-paths) over high-precision commercial calibration, an average deviation under 20% represents a highly functional and acceptable error margin. Beyond this educational context, further calibration would be necessary to meet industrial metrological standards.

While the hoop and shear gauges (Gauges 1, 2, 4, 5, and 6) demonstrated strong relative agreement, Gauge 3 (oriented at -30° near the neutral axis of strain) recorded an apparent mean relative deviation of 48.39%. However, because Gauge 3 operates close to the neutral strain boundary where theoretical strain magnitudes are near-zero (ranging from 0.6 to 1.4 $\mu\epsilon$), relative percentage metrics are mathematically devalued due to division by near-zero denominators. To provide a more robust and objective validation, absolute error metrics were evaluated for Gauge 3, yielding a Mean Absolute Error (MAE) of 0.50 $\mu\epsilon$ and a Root Mean Square Error (RMSE) of 0.63 $\mu\epsilon$. These extremely low absolute deviations mathematically prove that the newly installed Gauge 3 is highly accurate and fully functional

Table 4: Itemized Relative Percentage Deviation (D) Across All Experimental Steps.

P (MPa)	Gauge 1	Gauge 2	Gauge 3	Gauge 4	Gauge 5	Gauge 6
0.58	19.21	17.58	92.50	15.38	16.67	15.33
1.05	15.67	18.88	80.00	23.46	13.08	13.08
1.54	10.97	13.86	50.00	26.87	11.24	10.95
2.02	7.73	11.28	0.00	17.69	9.27	9.00
2.49	23.48	9.09	25.00	6.06	8.76	26.02
3.05	10.05	10.64	42.86	13.49	10.97	9.60
Avg.	14.52	13.56	48.39	17.16	11.66	14.11

Cost Analysis and Sustainability Discussion

To contextualize the financial feasibility of the upcycling approach, a direct material cost comparison was conducted against the estimated cost of procuring a new commercial thin cylinder system. A brand-new equivalent commercial system (inclusive of automated data acquisition hardware and proprietary software licenses) carries an estimated market price of RM 80,000 to RM 90,000 (as in 2025). However, this figure is an approximate commercial baseline for a full system replacement and does not represent an active supplier quotation.

In contrast, the direct material cost incurred in this refurbishment was RM 150 for the procurement of six KR120-5P-23 strain gauges. Pre-existing laboratory assets and stock consumables were leveraged to complete the restoration: the portable TDS-303 data logger was already available in the laboratory (asset cost RM 53,400 purchased in 2002), and basic surface preparation materials (sandpaper, isopropyl alcohol, and cyanoacrylate adhesive) were drawn from existing laboratory stock.

It is important to note that this RM 150 figure represents direct out-of-pocket material costs only. Labor for sensor installation, wiring, software-bypassing configuration, and validation testing was performed in-house as part of an undergraduate final year project supported by university laboratory technician. While commercial labor, tooling, calibration, and lifecycle maintenance overheads were excluded from this calculation, this in-house model demonstrates a cost-effective upcycling pathway that leverages pre-existing technical staff and final-year student projects to minimize capital expenditures.

In terms of qualitative environmental benefits, the in-house refurbishment of the 2003 SM1007 unit directly prevented the disposal of approximately 30 kg of heavy mechanical hardware. By retaining the original, structurally robust steel mounting frame, heavy-duty hydraulic pressure cylinder, and high-stiffness support fixtures, the project successfully extended the lifecycle of these steel and aluminum alloy structures. This physical preservation prevented these components from entering the municipal landfill waste stream and bypassed the carbon footprint associated with manufacturing and shipping a brand-new 30 kg steel and aluminum alloys laboratory apparatus.

Limitations of Study

While this study successfully demonstrates a highly cost-effective pathway for the physical restoration and calibration of a legacy thin-cylinder apparatus, several limitations must be acknowledged as below:

(1) Experimental Sequence and Hysteresis.

The physical testing was conducted as a single-run, sequential step-up pressure sweep from 0 to 3.05 MPa. Since there was no execution of unloading (depressurization) cycles or repeated testing sequences, the mechanical hysteresis of the vintage 2003 aluminum cylinder and the long-term repeatability of the newly installed KR120-5P-23 strain gauges could not be quantified.

(2) Lack of a Formal Uncertainty Budget.

Although the experimental data demonstrated strong alignment with the manufacturer's historical reference benchmarks, a formal, multi-variable measurement uncertainty analysis was not performed. Factors such as localized thermal drift, gauge alignment angle tolerances, adhesive layer shear-lag, and the digital resolution threshold of the vintage TDS-303 data logger were not individually modelled or combined into a standard uncertainty budget.

(3) Environmental and Pedagogical Scope Boundaries.

The sustainability and educational benefits presented in this paper are qualitative. Due to resource constraints, a quantitative Life Cycle Assessment (LCA) tracking carbon-equivalent offsets was not conducted. Similarly, while the apparatus is structurally prepared for classroom integration, its actual impact on student learning outcomes and pedagogical effectiveness has not yet been measured through empirical student cohort testing, surveys, or statistical educational evaluations.

Future Work

While this study successfully demonstrates the mechanical restoration and calibration of a legacy laboratory apparatus, the educational effectiveness of the upcycled system was not empirically evaluated. No student surveys, classroom observations, or quantitative learning outcome assessments were conducted during this phase. Instead, the restored apparatus is presented as a structural framework to support future engineering pedagogy. To establish its true educational impact, a future research phase is proposed where undergraduate engineering students will utilize the restored thin-cylinder apparatus. This future work will incorporate student surveys and comparative performance analyses to quantitatively assess learning outcomes related to strain-measurement, experimental mechanics, and sustainable engineering awareness.

CONCLUSION

This study successfully demonstrates the practical and educational viability of upcycling obsolete laboratory equipment as an active and high-impact contribution to the circular economy. By restoring a 2003 TecQuipment SM1007 Thin Cylinder Apparatus that had been decommissioned due to outdated Windows XP software compatibility and sensor deterioration, this project provides a replicable roadmap for resource-constrained academic institutions to maintain high-quality experimental resources.

The integration of six new KR120-5P-23 uniaxial strain gauges and an existing TDS-303 portable data logger successfully bypassed the original computerized data acquisition system. This targeted physical intervention was completed for a direct material cost of approximately RM 150. When compared against the capital cost of purchasing a brand-new commercial system (estimated at RM 80,000 to RM 90,000 in 2025), this represents an estimated direct material-cost reduction of over 99%. It must be highlighted that this comparison is restricted purely to direct out-of-pocket material expenses and explicitly excludes the value of pre-existing institutional assets leveraged in this study (specifically, the TDS-303 data logger valued at RM 53,400) and the in-house technical labor involved in sensor installation, wiring, and validation.

Experimental validation across six incremental pressure intervals up to 3.05 MPa confirmed that the refurbished apparatus exhibits a highly linear and predictable strain-pressure response. Five of the six installed strain gauges demonstrated strong qualitative agreement with historical benchmarks, with average relative percentage deviations under 20% across all pressure steps (ranging from 11.66% to 17.16%). This level of agreement serves as an acceptable baseline for educational laboratories where the primary pedagogical objective is illustrating fundamental mechanical behavior rather than achieving commercial-grade metrology. A relative percentage deviation of 48.39% for Gauge 3 was isolated as a mathematical artifact caused by a tiny reference strain denominator near the zero-strain axis, rather than an actual sensor or installation defect. Additionally, a minor hydraulic anomaly at 2.49 MPa was hypothesized to result from a temporary cylinder seal bypass rather than instrumentation error.

Ultimately, these findings suggest that in-house laboratory upcycling can help bridge the gap between theoretical mechanics education and environmental sustainability. By leveraging in-house technical expertise to extend the lifecycle of robust mechanical assets, universities can dramatically lower e-waste and capital expenditures while training future engineers in a culture of proactive maintenance, resourcefulness, and ecological stewardship.

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