

Article

Full-Scale Tests of a Styrene–Olefin Thermoplastic Viscoelastic Damper for Large-Deformation Vibration Control

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Abstract

Viscoelastic (VE) dampers are widely used for structural response control, but broader engineering adoption is often constrained by temperature- and amplitude-dependent properties and limited full-scale evidence on reliable performance when deformation demands exceed the conventional 300% shear-strain design domain. This study experimentally characterizes a full-scale TRCS-type VE damper (TRCS500T-10) employing a styrene–olefin thermoplastic elastomer, with an emphasis on large-deformation and beyond-design behavior. Four nominally identical specimens were tested in a temperature-controlled chamber using sinusoidal, displacement-controlled loading at target shear strains of 300% (≈ 30 mm) and 450% (≈ 45 mm). Effective engineering parameters were obtained from stable hysteresis loops using a Kelvin–Voigt-based reduction, including effective stiffness K_{eff} , effective damping coefficient C_{eff} , effective damping ratio ζ_{eff} , and dissipated energy per cycle W_d . At 300% shear strain, the dampers exhibited stable hysteresis with acceptable specimen-to-specimen variability and only modest changes in K_{eff} , C_{eff} , and W_d over an ambient-temperature interval of approximately 20–33 °C, while ζ_{eff} remained around 0.40–0.42. Beyond-design tests at 450% shear strain maintained stable force–displacement loops with substantial load capacity (peak forces ≈ 435 –492 kN) and increased per-cycle energy dissipation (approximately 4.0×10^4 kN·mm). Manufacturer-provided polynomial relations were used to standardize the measured properties to a reference condition and to compile a parameter-estimation table for preliminary engineering application. A monotonic ultimate test on specimen TRC500T-05 indicated an ultimate shear deformation capacity of approximately 850% without interface debonding. Collectively, the results provide full-scale evidence of a widened usable deformation range and a practical, design-oriented parameterization for thermoplastic VE dampers under large deformation demands.



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Keywords: viscoelastic damper; shear deformation; elastomer

1. Introduction

Viscoelastic (VE) dampers are widely adopted as passive response-control devices because they can provide both supplemental stiffness and energy dissipation to structural systems. A typical VE damper consists of multiple steel plates with VE material layers sandwiched between adjacent plates, where relative motion produces shear deformation in the VE layers [1–5]. In structural applications, VE dampers are often categorized as velocity-dependent devices, and the peak damper force generally exhibits a phase lag

relative to the peak deformation [6,7]. This characteristic makes VE dampers attractive for high-rise buildings that must simultaneously satisfy wind- and earthquake-induced performance requirements [8].

The performance of VE dampers is governed primarily by the constitutive behavior of polymer-based materials, whose stiffness and energy dissipation can vary with temperature. For civil engineering applications, it is desirable that the effective damping characteristics remain sufficiently stable within seasonal ambient conditions. As schematically illustrated in Figure 1, elastomeric materials may transition across different mechanical phases as temperature varies, and the damping window is commonly discussed in relation to the interval between the glass transition temperature T_g and a higher critical temperature T_c . In this study, temperature effects are therefore explicitly monitored and reported for all test items, and the regression-based standardization is presented as an engineering convenience rather than a temperature-invariant material law.

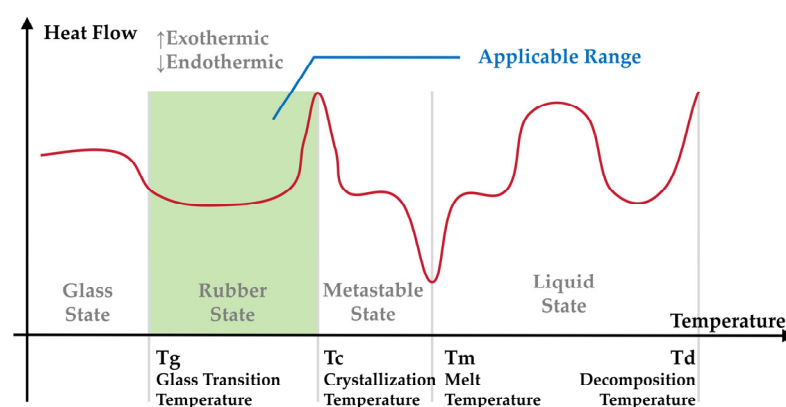


Figure 1. Different phases of elastomers.

High-damping rubber is one of the most commonly used and extensively investigated VE materials for dampers [9]. Nevertheless, rubber-based VE dampers may face limitations when large shear deformation is required. First, rubber generally requires vulcanization to develop its final properties and to achieve reliable bonding to steel plates, which may increase manufacturing complexity and introduce quality-control sensitivity [10]. Second, under substantial deformation, rubber layers may detach from steel plates, and the applicable shear deformation of rubber-based VE dampers is often limited to approximately 250–300%, beyond which unexpected failure modes may occur. The typical hysteretic behavior of rubber-based VE dampers is often represented using formulations such as the Bouc–Wen model [11]. In such cases, the phase lag between the peak damper force and the structural deformation response may be less pronounced, potentially introducing additional internal forces to adjacent beams and columns during seismic events.

Thermoplastic elastomers (TPEs) provide an alternative material platform because they can exhibit rubber-like elasticity at ambient temperatures while remaining processable by means of heating and molding, thereby combining features of conventional thermoplastics and vulcanized rubbers. The essential structural feature of TPEs is the coexistence of hard and soft segments within the polymer chain; interactions among hard segments form microdomains that act as physical cross-links, while soft segments provide flexibility and large deformability. Figure 2 summarizes common TPE families, including styrene-based block copolymers. In addition, elastomeric materials can be broadly classified by synthesis method into copolymerization and blending, as illustrated in Figure 3. In the context of structural dampers, standardized physical indices such as Shore hardness are often used for preliminary material specification; the damper material considered in this study typically falls within a Shore hardness range of 30–60 degrees [12–15].

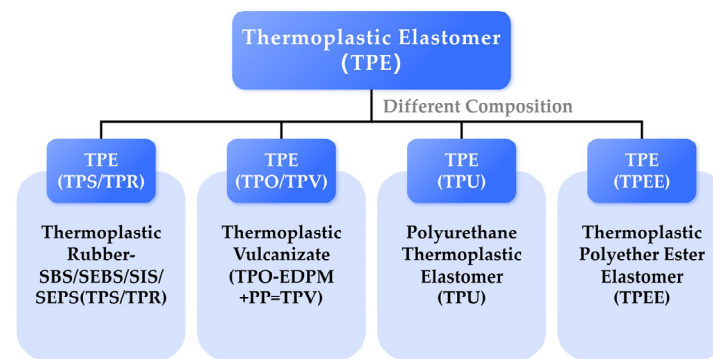


Figure 2. TPE family and category.

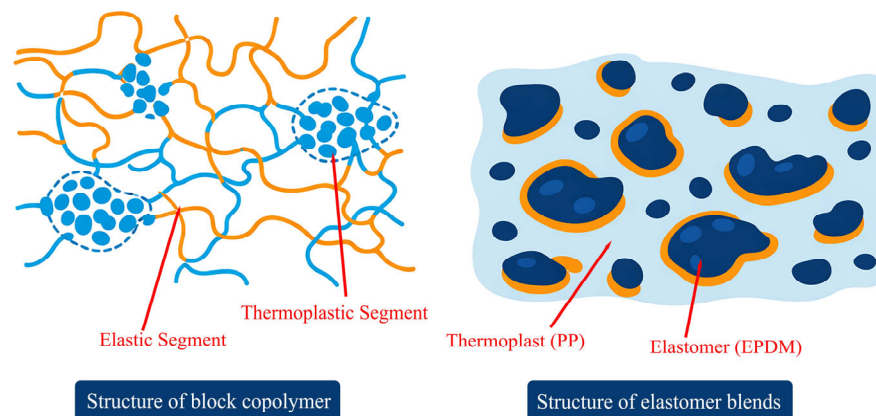


Figure 3. Typical copolymerization and blending polymer.

In the most recent literature (2023–2025), research on viscoelastic dampers (VEDs) for building vibration control has continued to expand from traditional “design-domain” characterization toward large-deformation and performance-based applications. On the component side, several studies have emphasized that VED properties remain strongly dependent on loading frequency and displacement amplitude and have proposed advanced constitutive representations (e.g., higher-order fractional-derivative formulations and internal-variable enhancements) to capture amplitude/frequency/temperature effects over broad testing domains [16]. Complementary efforts have explored new device concepts and layouts intended to improve constructability or deformation accommodation in retrofits, including rotational VED configurations and rubber-based bracing-type implementations that are evaluated through cyclic tests and structural analyses [17]. In parallel, design-oriented studies have proposed performance-driven sizing/placement procedures for VEDs, for example, multi-performance retrofitting frameworks that explicitly consider changes in deformation demand and energy dissipation capacity after damper installation [18].

Despite these advances, two practical gaps remain evident for beyond-design seismic demands. First, while recent experiments commonly address amplitude dependence and, in some cases, fatigue-type softening under repeated loading [19], there are still relatively limited public datasets on full-scale, commercially relevant VED components tested under very large cyclic shear deformations representative of “over-design” drift demands in buildings. Second, structural-scale validations and monitoring studies have highlighted amplitude-dependent behavior and the importance of linking global response to local damper deformation, yet they also reinforce the need for component-level evidence to support reliable parameterization at large deformation levels [20]. Motivated by these needs, the present study provides a full-scale experimental characterization of a TRCS-type

VE damper employing a styrene–olefin thermoplastic elastomer, with explicit emphasis on large-deformation (300%) and beyond-design (450%) cyclic behavior under controlled temperature conditions, together with an ultimate monotonic deformation benchmark.

Motivated by the need for VE dampers capable of sustaining large shear deformation while maintaining stable hysteretic energy dissipation, this study investigates a VE damper employing a styrene–olefin-based elastomer compound. The material is intended to provide effective damping performance under ambient conditions while exhibiting reduced sensitivity to temperature variation within a broad service temperature range. From an engineering standpoint, a shear strain of 300% is commonly treated as a practical design limit for VE dampers; therefore, it is necessary to clarify whether stable hysteretic behavior can be maintained beyond this threshold and to quantify the key mechanical properties required for structural design. Accordingly, the objectives of this study are as follows: (i) to summarize the material platform and its applicability to structural VE dampers, supported by the material classification and temperature-related considerations; and (ii) to establish an experimental basis for evaluating the large-deformation performance and engineering usability of the styrene–olefin-based VE damper system.

2. Materials and Methods

2.1. VE Material and Targeted Temperature Range

The viscoelastic (VE) material investigated in this study is a high-damping compound formulated as a styrene–olefin-based thermoplastic elastomer. The manufacturer reports a broad service temperature range of $-5\text{ }^{\circ}\text{C}$ to $50\text{ }^{\circ}\text{C}$, which was adopted to represent typical ambient conditions relevant to building applications.

For practical specification, Shore hardness is commonly used as a standardized index for thermoplastic elastomers; the VE compound considered here typically falls within a Shore A hardness range of 30–60. The compound is reported to contain approximately 42–52% elastomer by weight together with approximately 42–52% damping material by weight, and it is intended to provide reduced temperature sensitivity and large elongation capacity for large-deformation damper applications. For qualitative reference only, Figure 4 illustrates a schematic comparison between a conventional high-damping rubber concept and an idealized styrene–olefin-based thermoplastic elastomer morphology.

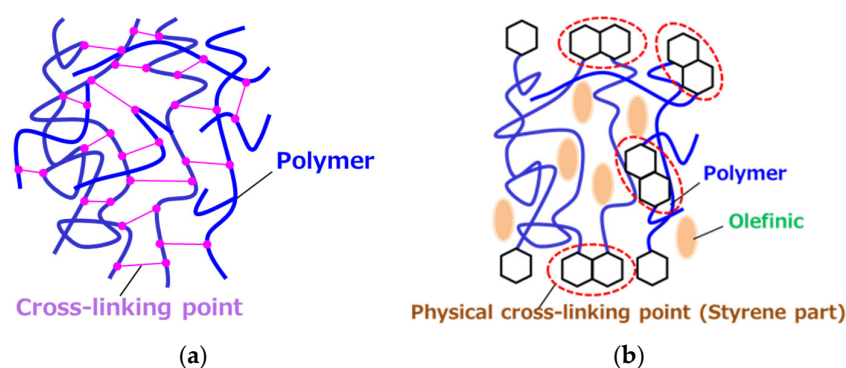


Figure 4. Molecular configurations of VE materials: (a) High-damping rubber; (b) Styrene–olefin-based elastomer.

2.2. Damper Configuration and Specimens (TRCS Type)

The investigated VE damper adopts a TRCS-type configuration, for which the physical dimensions and detailed design drawings are provided in Figure 5. The damper is described as compact in appearance, facilitating transportation and integration into structural systems.

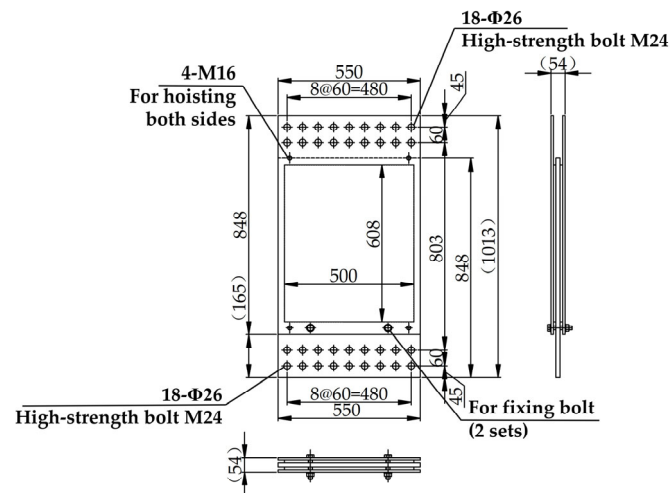


Figure 5. Design drawings of the VE damper.

A key geometric parameter for large-deformation applications is the VE layer thickness, which is 10 mm for the cyclic-test specimens (TRCS500T-10) considered herein. This thickness directly defines the displacement demand associated with a target shear strain. Using the standard relation $\gamma = u/t$ (where u is the shear displacement and t is the VE layer thickness), a 10 mm layer corresponds to maximum displacements of approximately 30 mm and 45 mm for 300% and 450% shear strain, respectively. This is consistent with the test programs (Table 1) and the measured maximum displacements reported in Table 2 (approximately 30 mm for 300% tests and 45 mm for 450% tests). In the present experimental program, temperature-conditioned tests were conducted within the capability of the temperature-controlled chamber (nominal range 5–50 °C), and the achieved ambient and internal material temperatures were monitored and reported for each test item (Section 2.3 and Table 2).

Table 1. Test programs for four VE damper specimens.

Test Specimen	Test Item	Excitation Frequency (Hz)	Ambient Temperature (°C)	Maximum Shear Strain (%)
I	1	0.5	20	300
	2	0.5 Hz	30	300
II	3	0.5 Hz	20	300
	4	0.5 Hz	30	300
III	5	1.0 Hz	10	450
IV	6	1.0 Hz	20	450

Table 2. Experimental measurements.

Specimen	Test Item	T_{amb} (°C)	$u_{d,max}$ (mm)	P_{max} (kN)	$P_{u,max}$ (kN)
I	1	20.2	29.91	309.9	258.6
	2	33.1	28.89	320.8	265.2
II	3	22.7	29.79	289.9	237.8
	4	32.4	29.75	303.8	247.1
III	5	12.6	44.72	492.0	410.5
IV	6	24.4	45.26	434.8	357.5

The damper specimens used in the experiments were manufactured by Sumitomo Riko Company Limited (Nagoya, Japan) with the designation TRCS500T-10. Each VE material layer has an area of 3040 cm^2 , and the damper is reported to provide a nominal maximum force capacity of 500 kN, together with “sufficient displacement capacity” for the targeted seismic demands (Figure 5). For engineering interpretation, the nominal force level and layer area imply an average nominal shear stress on the order of $500 \text{ kN}/3040 \text{ cm}^2 \approx 1.6 \text{ MPa}$, which is consistent with a high-force, large-area VE damper intended for building-scale applications (this value is a derived estimate based on the reported nominal parameters).

For the monotonic ultimate shear deformation test (Section 3.5), a separate specimen TRC(S)500T-05 with two 5 mm thick VE layers and a shear area of 4030 cm^2 was used; the shear strain in that test is calculated based on $t = 5 \text{ mm}$ (per VE layer).

Regarding fabrication and interface reliability, the paper notes that—unlike conventional rubber materials—the adopted VE compound does not require vulcanization; instead, it is heated and applied to steel plates, and after several minutes, the bond is sufficiently strong such that, under large deformation, failure tends to occur within the compound rather than by interface debonding. This processing route is consistent with the intended use case of repeated large shear deformation, where stable composite action between steel plates and VE layers is essential.

A total of four geometrically and mechanically identical damper specimens (Specimens I–IV) were prepared and tested to quantify both repeatability and large-strain behavior. Specimens I and II were tested under the same protocol to assess variability, while Specimens III and IV were reserved for the beyond-design shear strain condition (450%) at different ambient temperatures, as summarized in Table 1.

In terms of building-scale deformation demand, the prescribed design and over-design limits can be interpreted through the interstory drift ratio. For the present damper configuration, the VE shear deformation amplitude is $u = \gamma t$, where t is the total VE shear-layer thickness. With $t = 10 \text{ mm}$, $\gamma = 300\%$ and 450% correspond to $u \approx 30 \text{ mm}$ and 45 mm , respectively. When the TRCS panel damper is installed in a story (similar to a damper wall) with sufficiently stiff boundary connections, a large fraction of the interstory displacement can be transferred into the damper shear deformation; this can be expressed by a displacement transfer efficiency λ ($0 < \lambda \leq 1$), such that $\Delta_{\text{story}} \approx u/\lambda$. Therefore, for a typical story height of $h_{\text{story}} = 3.0\text{--}3.5 \text{ m}$ and $\lambda \approx 1$, the above limits correspond approximately to interstory drift ratios of $\theta = \Delta_{\text{story}}/h_{\text{story}} \approx 0.9\%\text{--}1.0\%$ (300%) and $1.3\%\text{--}1.5\%$ (450%). For applications expecting larger drift demands, the target shear strain level can be reduced by increasing the VE layer thickness, while the required force capacity and energy dissipation can be maintained through appropriate scaling of the shear area and/or the number of dampers in parallel.

2.3. Test Facility, Instrumentation, and Loading Protocol

All damper tests were conducted using the high-performance damper testing facility located at the Taipei Laboratory of the National Center for Research on Earthquake Engineering (NCREE), Taiwan, as shown in Figure 6. The facility provides a nominal maximum stroke of $\pm 600 \text{ mm}$ and a nominal maximum force capacity of $\pm 2 \text{ MN}$, which are sufficient to accommodate the large shear-deformation demands targeted in this study. To ensure stable and precise uniaxial motion during testing, the steel connection component between the mounted damper specimen and the horizontal hydraulic actuator incorporates a linear guide system, thereby minimizing parasitic rotations and out-of-plane movement that could contaminate the measured shear response.

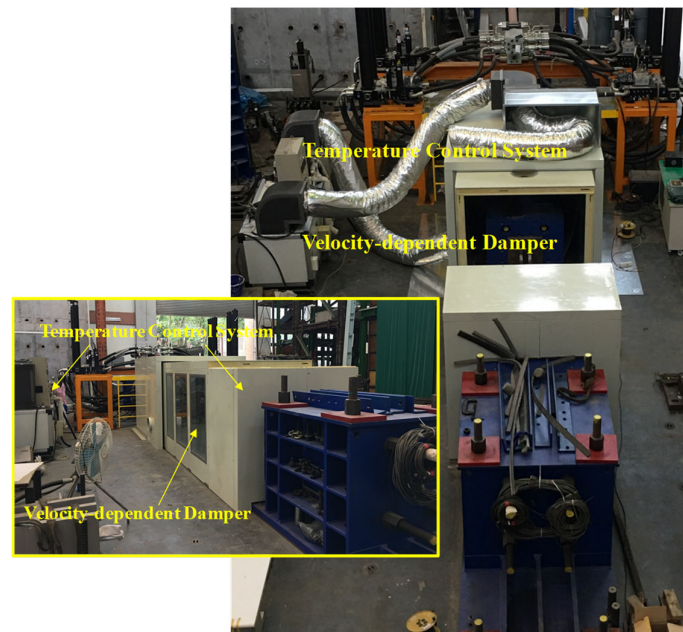


Figure 6. Testing facility at NCRE.

To investigate temperature-dependent behavior, the facility is equipped with a temperature-controlled chamber (nominal range 5 °C to 50 °C). During each test, both the ambient chamber temperature and the operating temperature of the mounted VE damper were monitored using thermocouples installed in the surrounding air and thermocouples embedded within the VE material layers, and these temperatures were varied and regulated via the temperature control system. The authors note that, for testing efficiency, the ambient temperature and maximum displacement were controlled to closely approach the target values rather than match them exactly, and the achieved values were reported accordingly (see Table 2).

The experimental setup and measurement configuration are shown in Figure 7. The damper shear deformation was measured directly using a linear variable differential transformer (LVDT) installed on the mounted specimen to capture its pure shear deformation response. The corresponding shear force response was recorded using the built-in load cell of the horizontal hydraulic actuator.



Figure 7. Test specimen and setup: (a) VE damper specimen; (b) test setup and measurement sensors.

Cyclic loading was applied as sinusoidal displacement histories under displacement control, and each test consisted of seven repeated cycles to establish stable hysteretic loops for property evaluation. The excitation frequencies adopted in the test program were 0.5 Hz (for 300% shear strain cases) and 1.0 Hz (for 450% shear strain cases), as summarized in Table 1. The primary response quantities used in subsequent data reduction therefore include (i) the measured force–displacement hysteresis from the actuator load

cell and specimen LVDT, and (ii) the monitored temperatures from the chamber and embedded thermocouples, enabling consistent interpretation of the damper's temperature- and deformation-dependent mechanical properties.

To account for potential self-heating of the polymer under large-amplitude cyclic shear, thermocouples were embedded in the VE material (in addition to the chamber temperature sensor) to monitor the internal temperature evolution during each loading protocol. The self-heating effect is discussed in Section 4.2 together with the temperature-dependence observations.

2.4. Test Matrix

The test matrix is summarized in Table 1. Four geometrically identical full-scale dampers (Specimens I–IV) were tested under a total of six loading conditions to quantify (i) repeatability under the same target condition and (ii) temperature and large-strain effects beyond the commonly adopted design shear strain level.

For the 300% shear strain condition, Specimens I and II were tested at an excitation frequency of 0.5 Hz with a target displacement of approximately 30 mm, under two ambient-temperature settings (20 °C and 30 °C), enabling assessment of specimen-to-specimen variability and temperature dependence.

For the 450% shear strain condition, Specimens III and IV were tested at an excitation frequency of 1.0 Hz with a target displacement of approximately 45 mm, under nominal ambient temperatures of 10 °C and 20 °C, respectively.

In addition to the target parameters listed in Table 1, the achieved temperatures and displacements were recorded and reported for each test (see Table 2), because the ambient temperature and maximum displacement were controlled to closely approach the target values for testing efficiency.

2.5. Data Reduction and Evaluation Indices

The cyclic response of VE dampers was interpreted using the Kelvin–Voigt model, which idealizes the damper as a linear elastic spring and a viscous dashpot connected in parallel [16–23]. The corresponding constitutive relationship in the stress–strain domain is given by Equation (1).

$$\sigma(t) = E\varepsilon(t) + \eta \frac{d\varepsilon(t)}{dt}, \quad (1)$$

All specimen-level quantities are reported in kN, mm, s, and °C (thus K_{eff} in kN/mm, C_{eff} in kN·s/mm, and W_d in kN·mm), while Equation (1) is presented in the stress–strain form for completeness. For structural applications, the force–displacement relationship of the mounted VE damper specimen was simplified as Equation (2), where $F(t)$ and $u(t)$ were obtained from the actuator load cell and the specimen LVDT measurements, respectively.

$$F(t) = K_{\text{eff}}u(t) + C_{\text{eff}}\dot{u}(t), \quad (2)$$

To quantify the damper performance under cyclic loading, three key mechanical properties were evaluated based on the measured hysteresis loops: effective stiffness K_{eff} , effective damping coefficient C_{eff} , and effective damping ratio ζ_{eff} .

- (1) Effective stiffness. The effective stiffness was defined using the force and displacement at the two peak deformation points of a cycle, as shown in Equation (3).

$$K_{\text{eff}} = \frac{|F_{u,\text{max}}| + |F_{u,\text{min}}|}{|u_{\text{max}}| + |u_{\text{min}}|}, \quad (3)$$

where u_{max} , u_{min} are the maximum and minimum displacement and $F_{u,\text{max}}$, $F_{u,\text{min}}$ are the corresponding force at u_{max} , u_{min} , as illustrated in Figure 8.

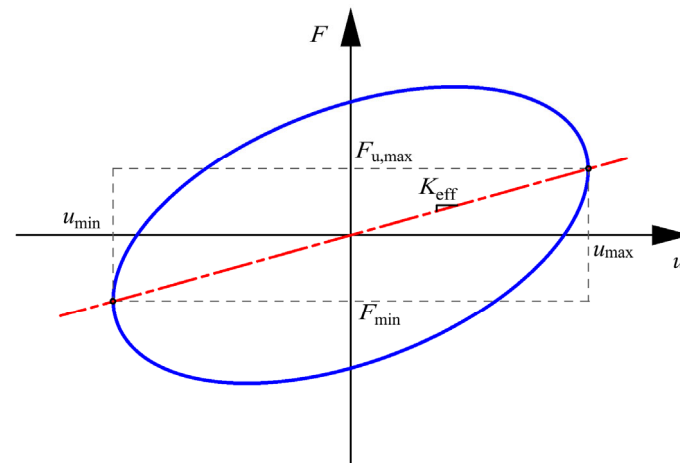


Figure 8. Illustration of effective stiffness K_{eff} .

- (2) Effective damping coefficient. For harmonic loading with angular frequency ω , the effective damping coefficient was determined using the dissipated energy per cycle W_d (i.e., the hysteresis loop area) and the average displacement amplitude u_{ave} defined as $(u_{\text{max}} + |u_{\text{min}}|)/2$, as shown in Equation (4).

$$C_{\text{eff}} = \frac{W_d}{\pi \omega u_{\text{ave}}^2}, \quad (4)$$

In this study, W_d was computed from the discrete experimental force–displacement data by numerical integration over one closed cycle, i.e., $W_d = \oint F du$; practically, a trapezoidal-rule summation was applied along the recorded loop points to obtain the enclosed area.

- (3) Effective damping ratio. The effective damping ratio was calculated by comparing the dissipated energy per cycle to the maximum strain energy, as given in Equation (5).

$$\zeta_{\text{eff}} = \frac{1}{2\pi} \frac{W_d}{K_{\text{eff}} u_{\text{ave}}^2}, \quad (5)$$

For harmonic loading, ζ_{eff} can be equivalently expressed as $\zeta_{\text{eff}} = C_{\text{eff}} \omega / (2K_{\text{eff}})$, which is used for post-processing when ζ_{eff} is derived from K_{eff} and C_{eff} . Because each cyclic test consisted of seven repeated cycles, the reported mechanical properties were obtained by averaging the values computed from the intermediate five cycles to reduce the influence of initial transient behavior and end effects.

2.6. Normalization and Correction Model

As noted in Section 2.3, the ambient temperature and maximum displacement during testing were controlled to closely approach the targets for testing efficiency rather than to match them exactly. To enable consistent comparisons of the fundamental mechanical properties derived in Section 2.5 under different test conditions, the experimental results were therefore systematically corrected using adjustment formulas. These corrections normalize the data to a reference condition of 20 °C and a shear strain of 200% corresponds to the baseline loading protocol and shown in Figure 9.

The correction formulas were provided by the manufacturer and were derived from coupon tests using non-structural, double-layer VE specimens (plan size 70 mm × 40 mm, thickness 5 mm per VE layer). Therefore, the displacement variable in the manufacturer regression (Equations (7) and (8) and Figure 10) refers to the maximum shear displacement of a 5 mm VE layer, denoted as u_{eq} , or equivalently, the maximum shear strain $\gamma_{\text{max}} = u_{\text{eq}}/5 \text{ mm}$. For the present full-scale dampers with a 10 mm VE layer

thickness, the equivalent displacement used in the regression is $0.5 u_{\text{damper}}$. Under this definition, the regression range up to $u_{\text{eq}} = 35 \text{ mm}$ corresponds to γ_{max} up to 700% (e.g., $u_{\text{eq}} = 30 \text{ mm} \Rightarrow \gamma_{\text{max}} = 600\%$), which covers the deformation demand of the full-scale tests up to 450% shear strain.

The manufacturer-provided regression relations were derived from coupon tests using non-structural double-layer VE specimens (70 mm $\times$ 40 mm plan size, 5 mm thickness per VE layer). Accordingly, the displacement variable used in the regression is defined at the VE-layer level for a 5 mm layer. To avoid confusion with the full-scale damper displacement, the maximum displacement measured from the full-scale damper tests is denoted as $u_{\text{d,max}}$ (10 mm VE layer), and the regression input displacement is expressed as an equivalent displacement $u_{\text{eq}} = u_{\text{d,max}} (t_{\text{eq}}/t_{\text{d}}) = 0.5 u_{\text{d,max}}$, where $t_{\text{eq}} = 5 \text{ mm}$ and $t_{\text{d}} = 10 \text{ mm}$.

Specifically, the temperature-dependent regression relation for the effective stiffness K_{eff} , effective damping coefficient C_{eff} , and maximum force P_{max} is expressed as:

$$K_{\text{eff}}(T_{\text{amb}}), C_{\text{eff}}(T_{\text{amb}}), P_{\text{max}}(T_{\text{amb}}) = aT_{\text{amb}}^2 + bT_{\text{amb}} + c, \quad (6)$$

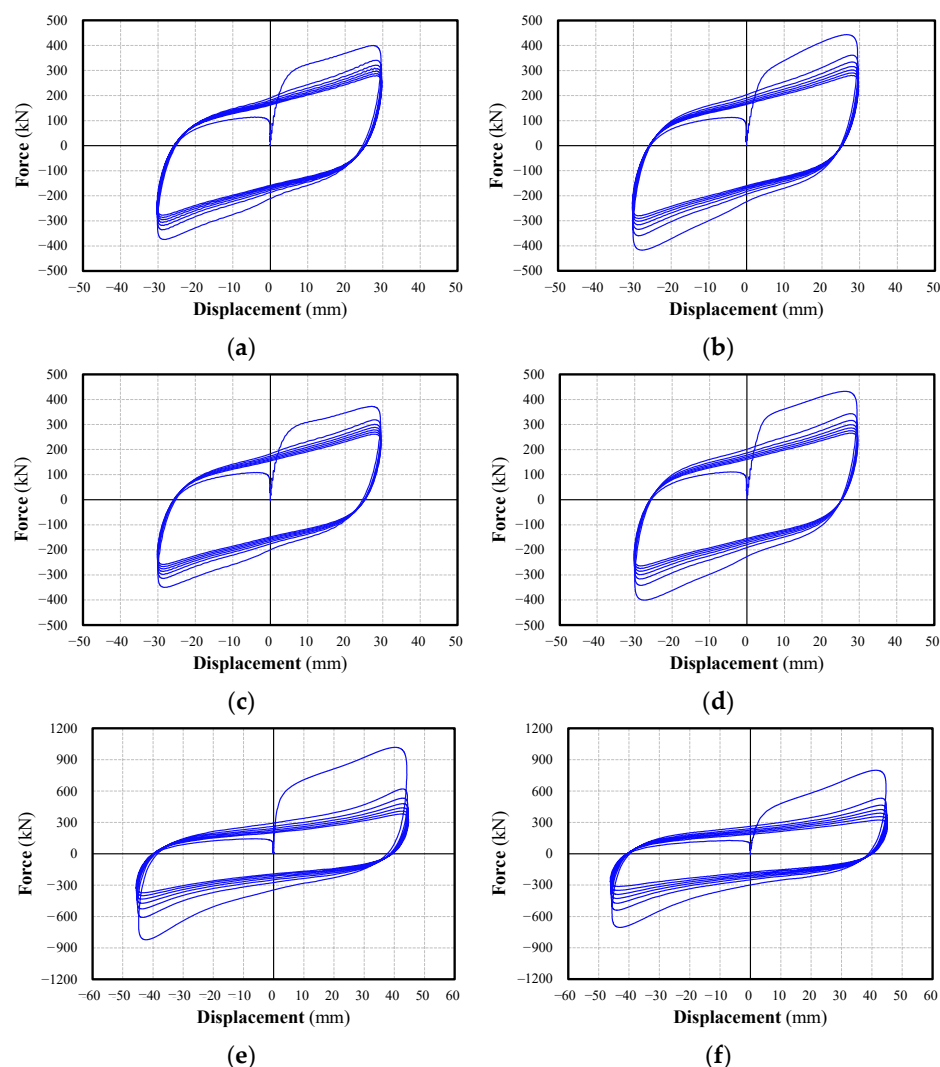


Figure 9. Experimental hysteretic loops of: (a) Specimen I, test Item 1; (b) Specimen I, test Item 2; (c) Specimen II test Item 3; (d) Specimen II test Item 4; (e) Specimens III test Item 5; (f) Specimens IV test Item 6.

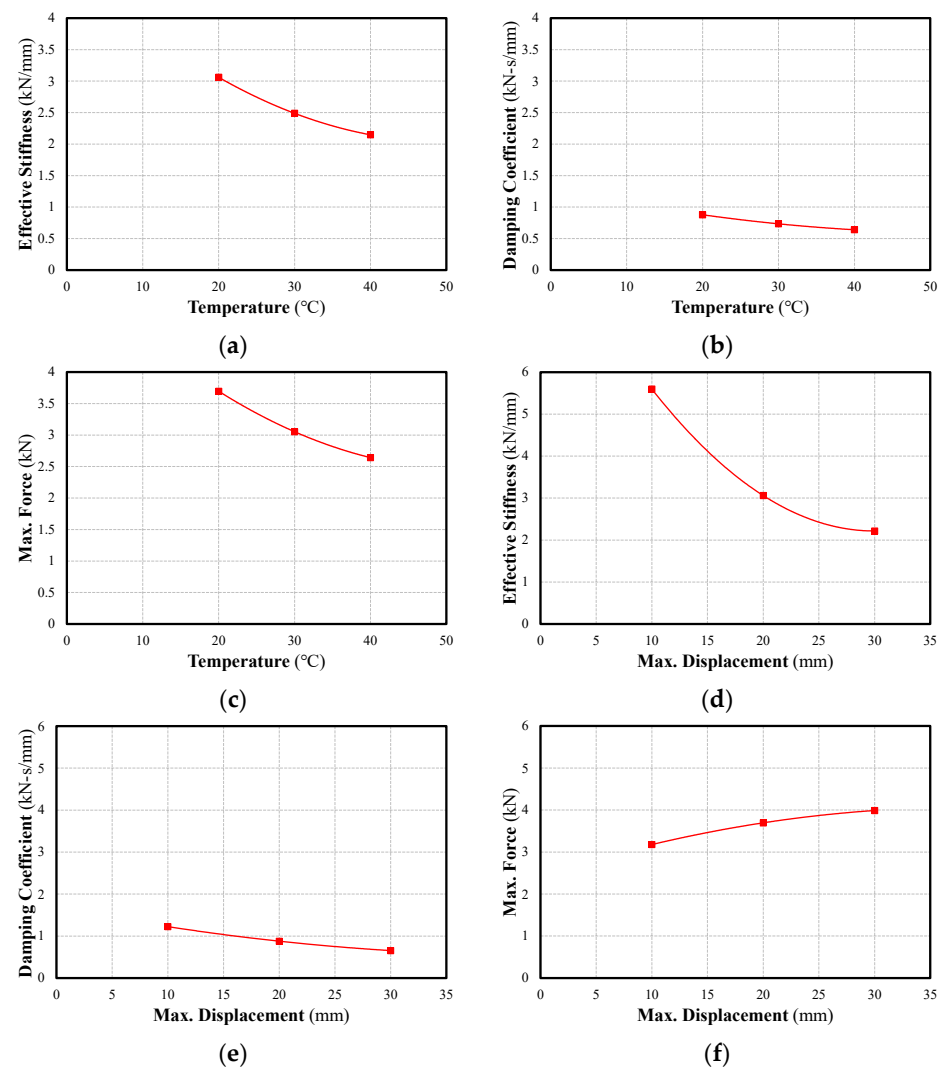


Figure 10. Regression curves of normalized damper performance parameters under various temperatures and displacements: (a) $K_{\text{eff}}(T)$; (b) $C_{\text{eff}}(T)$; (c) $P_{\text{max}}(T)$; (d) $K_{\text{eff}}(u_{\text{eq}})$; (e) $C_{\text{eff}}(u_{\text{eq}})$; (f) $P_{\text{max}}(u_{\text{eq}})$.

Similarly, the displacement-dependent regression relation with respect to the equivalent maximum displacement u_{eq} (defined for a 5 mm VE layer in the manufacturer's coupon tests) is given by

$$K_{\text{eff}}(u_{\text{eq}}), C_{\text{eff}}(u_{\text{eq}}), P_{\text{max}}(u_{\text{eq}}) = au_{\text{eq}}^2 + bu_{\text{eq}} + c, \quad (7)$$

where a , b , and c are the regression coefficients with appropriate units.

The measured property X_{meas} (where $X \in \{K_{\text{eff}}, C_{\text{eff}}, P_{\text{max}}\}$) was corrected to the reference condition ($T_{\text{ref}} = 20^\circ\text{C}$, u_{ref} corresponding to $\gamma_{\text{ref}} = 200\%$ for a 5 mm layer, i.e., $u_{\text{ref}} = 10$ mm) using

$$X_{\text{corr}} = X_{\text{meas}} \cdot \frac{X_T(T_{\text{ref}})}{X_T(T_{\text{amb}})} \cdot \frac{X_u(u_{\text{ref}})}{X_u(u_{\text{eq}})}, \quad (8)$$

where $X_T(\cdot)$ and $X_u(\cdot)$ are given by Equations (6) and (7), respectively. Note that u_{ref} corresponds to $\gamma_{\text{ref}} = 200\%$, i.e., $u_{\text{ref}} = 10$ mm for the 5 mm layer definition used in the regression.

After applying the above correction procedures, the normalized fundamental mechanical properties are reported and compared in the subsequent Results section, and the regression relations are also used to support property estimation under specified $u_{\text{d,max}}$ and T_{amb} . No frequency correction was performed in this study. Therefore, the corrected P_{max} , K_{eff} , and C_{eff} remain conditional on the original test excitation frequency.

Accordingly, ξ_{eff} reported in Table 5 was computed from the corrected K_{eff} and C_{eff} using ω corresponding to each test (Table 1), and is provided as an auxiliary indicator rather than a frequency-normalized metric.

3. Results

Figure 9 presents the measured force–displacement hysteretic loops of the four TRCS500T-10 VE damper specimens under the six test items. Based on the data reduction procedure described in Section 2.5, the experimental measurements (ambient temperature T_{amb} , maximum displacement $u_{d,\text{max}}$, maximum force P_{max} , force corresponding to $u_{d,\text{max}}$ and the corresponding mechanical properties (K_{eff} , W_d , C_{eff} , and ξ_{eff}) were computed using the average values from the intermediate five cycles and are summarized in Tables 2 and 3.

Table 3. Experimental mechanical properties.

Test Specimen	Test Item	K_{eff} (kN/mm)	W_d (kN·mm)	C_{eff} (kN·s/mm)	ξ_{eff}
I	1	8.634	19,561	2.209	0.402
	2	8.858	20,257	2.291	0.407
II	3	7.974	18,482	2.106	0.415
	4	8.290	19,564	2.232	0.424
III	5	9.135	42,482	1.066	0.367
IV	6	7.871	39,563	0.972	0.390

3.1. Repeatability and Specimen-to-Specimen Variability

Repeatability was first examined by comparing the responses of Specimens I and II under nominally identical loading conditions at similar ambient temperatures. Specifically, Test Items 1 and 3 represent the 300% shear strain condition at approximately 20–23 °C with nearly identical maximum displacements ($u_{d,\text{max}} = 29.91$ mm vs. 29.79 mm), while Test Items 2 and 4 correspond to the 300% shear strain condition at approximately 32–33 °C with similarly matched maximum displacements ($u_{d,\text{max}} = 28.89$ mm vs. 29.75 mm).

As shown by the hysteretic loops in Figure 9a–d, Specimens I and II exhibited closely comparable loop shapes and force levels under the paired conditions. Consistently, the mechanical properties listed in Tables 2 and 3 indicate that specimen-to-specimen differences were modest for the paired tests. For the ~20–23 °C condition (Items 1 vs. 3), the relative differences between Specimens I and II were within approximately 8% for K_{eff} (8.634 vs. 7.974 kN/mm) and 6% for W_d (19,561 vs. 18,482 kN·mm), with C_{eff} differing by about 5% (2.209 vs. 2.106 kN·s/mm) and ξ_{eff} differing by 0.013 in absolute value (0.402 vs. 0.415). Under the ~32–33 °C condition (Items 2 vs. 4), the corresponding differences were similarly small: about 7% for K_{eff} (8.858 vs. 8.290 kN/mm), 4% for W_d (20,257 vs. 19,564 kN·mm), 3% for C_{eff} (2.291 vs. 2.232 kN·s/mm), and an absolute difference of 0.017 for ξ_{eff} (0.407 vs. 0.424).

Overall, the paired comparisons of Figure 9a–d together with Tables 2 and 3 indicate that Specimens I and II showed almost identical mechanical behavior under the same testing conditions, and the variability among different TRCS500T-10 dampers was considered acceptable.

3.2. Temperature Dependence (300% Shear Strain)

The temperature dependence of the TRCS500T-10 dampers at 300% shear strain was evaluated by comparing the paired tests conducted at two ambient-temperature levels for each specimen, i.e., Test Items 1 vs. 2 for Specimen I and Test Items 3 vs. 4 for Specimen II, as

defined in Table 1. The corresponding measured ambient temperatures were approximately 20.2 °C and 33.1 °C for Specimen I, and 22.7 °C and 32.4 °C for Specimen II (Table 3).

As shown in the hysteresis loops (Figure 9a,b for Specimen I and Figure 9c,d for Specimen II), the overall loop shapes remain stable across the two temperature levels, with only modest changes in the force amplitude and loop area.

Quantitatively, when the ambient temperature increased from ~20 °C to ~33 °C, Specimen I exhibited a slight increase in the measured maximum force $P_{\max}$ from 309.9 kN to 320.8 kN (Table 2), together with small increases in K_{eff} (8.634 → 8.858 kN/mm), W_d (19,561 → 20,257 kN·mm), and C_{eff} (2.209 → 2.291 kN·s/mm) (Table 3). The effective damping ratio ξ_{eff} remained essentially unchanged, increasing marginally from 0.402 to 0.407.

A consistent trend was observed for Specimen II. With the ambient temperature increasing from ~22.7 °C to ~32.4 °C, $P_{\max}$ increased from 289.9 kN to 303.8 kN (Table 2), while K_{eff} , W_d , and C_{eff} increased from 7.974 to 8.290 kN/mm, 18,482 to 19,561 kN·mm, and 2.106 to 2.232 kN·s/mm, respectively (Table 3). The corresponding ξ_{eff} increased slightly from 0.415 to 0.424.

Overall, within the investigated temperature interval (approximately 20–33 °C) and at 300% shear strain, the temperature dependence was modest for both specimens, with the effective damping ratio remaining around 0.40–0.42 and the other evaluated properties varying only slightly between the two temperature levels.

3.3. Large-Strain Performance Beyond Design (450%)

To evaluate the beyond-design shear deformation capacity, Specimens III (Test Item 5) and IV (Test Item 6) were tested under a maximum shear strain of 450% at an excitation frequency of 1.0 Hz. These two tests were intentionally configured to exceed the commonly adopted 300% design-level shear strain and to visually assess beyond-design performance under different ambient-temperature conditions (10 °C and 20 °C targets).

The corresponding hysteretic responses are provided in Figure 9e,f), which shows stable force–displacement loops for both specimens at this large deformation level. In the experiments, the achieved maximum displacements were 44.72 mm (Specimen III) and 45.26 mm (Specimen IV), which are consistent with the intended 450% shear strain demand for a 10 mm VE layer. The measured peak forces reached 492.0 kN (Specimen III) and 434.8 kN (Specimen IV), confirming that the dampers maintained substantial load-carrying capacity under beyond-design deformation.

Based on the evaluation indices in Section 2.5, the large-strain tests also produced markedly larger hysteresis-loop areas than the 300% strain tests. Specifically, the dissipated energy per cycle W_d increased to 42,482 kN·mm (Specimen III) and 39,563 kN·mm (Specimen IV), compared with approximately 18,482–20,257 kN·mm for the 300% tests. This indicates that, even at 450% shear strain, the dampers continued to dissipate significant energy per cycle without loss of loop integrity as shown in Figure 9e,f.

An apparent temperature-related difference is observed between the two 450% tests. While the achieved ambient temperatures differed (12.6 °C for Specimen III and 24.4 °C for Specimen IV), the measured effective properties also differed, with lower values of K_{eff} , W_d , and C_{eff} recorded in the higher-temperature test, whereas ξ_{eff} showed a small increase. However, it should be noted that each temperature condition is represented by a single test on a different specimen; therefore, the present dataset supports only a qualitative indication of temperature sensitivity at 450% shear strain, rather than a quantified temperature-dependence trend.

Most importantly, the authors explicitly note that the VE material (styrene–olefin-based elastomer) remained intact at this large deformation demand, and the overall results at 450% shear strain demonstrate satisfactory beyond-design performance of the TRCS500T-10 dampers.

3.4. Corrected Properties and Standardized Table

To enable a consistent comparison of damper performance across different ambient temperatures and displacement amplitudes, the experimental results were corrected using the manufacturer-provided adjustment formulas. Specifically, the data were corrected to a reference condition of 20 °C and u_{ref} corresponding to 200% shear strain using second-order polynomial regression functions with respect to ambient temperature and the equivalent maximum displacement u_{eq} defined for a 5 mm VE layer in the manufacturer's coupon-based regression (Equations (6)–(8); Figure 10; Table 4). The manufacturer-provided adjustment functions are formulated as functions of ambient temperature and displacement amplitude only. Therefore, the present study standardizes the measured mechanical parameters to the reference temperature and displacement condition, while keeping the excitation frequency unchanged. No attempt is made to normalize the results to a common frequency or to infer frequency-dependent behavior beyond the tested frequencies. Accordingly, comparisons based on the standardized results are intended for within-protocol evaluation (i.e., reduction of temperature- and amplitude-induced scatter) rather than cross-frequency extrapolation. Accordingly, the corrected results are reported at the original test excitation frequencies listed in Table 1.

Table 4. Normalization regression parameters.

Function	<i>a</i>	<i>b</i>	<i>c</i>
$K_{\text{eff}}(T)$	1.152×10^{-3}	-1.148×10^{-1}	4.895
$C_{\text{eff}}(T)$	2.50×10^{-4}	-2.688×10^{-2}	1.315
$P_{\text{max}}(T)$	1.154×10^{-3}	-1.220×10^{-1}	5.674
$K_{\text{eff}}(u_{\text{eq}})$	8.470×10^{-3}	-5.080×10^{-1}	9.833
$C_{\text{eff}}(u_{\text{eq}})$	6.10×10^{-4}	-5.302×10^{-2}	1.693
$P_{\text{max}}(u_{\text{eq}})$	-1.120×10^{-3}	8.533×10^{-2}	2.438

Note: Unit for temperature-dependent fits: (a) $K_{\text{eff}}(T)$, a [kN/mm/°C²], b [kN/mm/°C], c [kN/mm]; (b) $C_{\text{eff}}(T)$, a [kN·s/mm/°C²], b [kN·s/mm/°C], c [kN·s/mm]; (c) $P_{\text{max}}(T)$, a [kN/°C²], b [kN/°C], c [kN]. For displacement-dependent fits: (d) $K_{\text{eff}}(u_{\text{eq}})$, a [kN/mm/mm²], b [kN/mm/mm], c [kN/mm]; (e) $C_{\text{eff}}(u_{\text{eq}})$, a [kN·s/mm/mm²], b [kN·s/mm/mm], c [kN·s/mm]; (f) $P_{\text{max}}(u_{\text{eq}})$, a [kN/mm²], b [kN/mm], c [kN]. °C.

The regression relations of the coefficients in Table 5 were obtained from an independent set of manufacturer coupon tests conducted on VE-layer specimens with reduced shear area to efficiently characterize the dependence on ambient temperature and displacement amplitude. The absolute magnitudes in Figure 9 therefore correspond to the coupon specimens and are not directly comparable to those of the full-scale TRCS500T-10 dampers; only the ratio-based correction factors derived from these regressions are transferred to the present full-scale damper tests.

Table 5. Temperature- and displacement-corrected experimental mechanical properties.

Test Specimen	Test Item	P_{max} (kN)	K_{eff} (kN/mm)	C_{eff} (kN·s/mm)	ζ_{eff}
I	1	288.1	11.98	2.98	0.39
	2	378.5	15.88	3.86	0.38
II	3	283.8	11.69	2.97	0.40
	4	355.2	14.71	3.71	0.40
III	5	387.8	5.82	1.49	0.81
IV	6	437.9	6.33	1.70	0.85

After applying these corrections, the fundamental mechanical properties (i.e., $P_{\max}$, K_{eff} , C_{eff} , and ζ_{eff}) of all test items are summarized in Table 5, providing a normalized basis for interpreting repeatability and condition-dependent variability. The regression curves used for the correction—including the fitted coefficients reported in the figure captions—are presented in Figure 10, which collectively describe the dependence of K_{eff} , C_{eff} , and $P_{\max}$ on temperature and displacement.

Beyond post-processing of the test results, the regression models also provide a direct means to predict damper properties for specified operating conditions. As shown in Table 6, the regression relations can also be used to estimate damper properties for specified operating conditions. For the present TRCS500T-10 dampers, the regression input displacement is $u_{\text{eq}} = 0.5u_{\text{d,max}}$. For example, $u_{\text{d,max}} = 30$ mm and 45 mm correspond to $u_{\text{eq}} = 15$ mm and 22.5 mm, respectively, which remain within the regression displacement range shown in Figure 10d–f. At $u_{\text{d,max}} = 30$ mm, $T = 20$ °C, the predicted values are $P_{\max} = 368$ kN, $K_{\text{eff}} = 9.64$ kN/mm, and $C_{\text{eff}} = 2.41$ kN·s/mm; at $u_{\text{d,max}} = 45$ mm, $T = 20$ °C, the corresponding estimates are $P_{\max} = 437$ kN, $K_{\text{eff}} = 7.72$ kN/mm, and $C_{\text{eff}} = 0.94$ kN·s/mm.

Table 6. Estimation of mechanical properties based on the Kelvin–Voigt model and temperature/displacement regression.

Property	Test1	Test2
Maximum displacement (mm)	30	45
Ambient temperature (°C)	20	20
Maximum force (kN)	368	437
Effective stiffness (kN/mm)	9.64	7.72
Effective damping coefficient (kN·s/mm)	2.41	0.94
Equivalent displacement (mm)	15	22.5

3.5. Ultimate Shear Deformation Under Monotonic Loading

In addition to the cyclic tests up to 450% shear strain (Section 3.3), an ultimate shear deformation test was conducted to identify the deformation margin of the VE damper material under a progressively increasing demand. In this test, a consistently increasing shear deformation was applied to the VE damper until material failure occurred, as schematically shown in Figure 11.

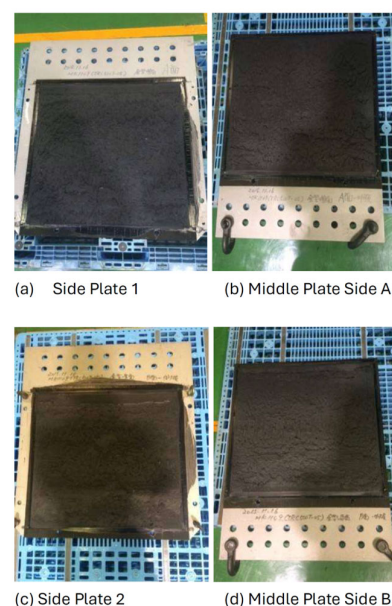


Figure 11. Ultimate shear deformation test.

The ultimate monotonic test was conducted using specimen TRC(S)500T-05, which has two VE layers with a thickness of 5 mm each and a shear area of 620×650 mm. The shear strain reported in this section is defined as $\gamma = u/t$, where $t = 5$ mm (per VE layer).

The resulting deformation capacity is summarized in Figure 12, which indicates that the maximum shear deformation is around 850%. It should be noted that this ultimate test employed uniaxial monotonic loading rather than cyclic loading, and thus it is used here as an indicator of the attainable deformation limit rather than as a direct measure of cyclic durability. Further discussion on monotonic vs. cyclic mechanisms is provided in Section 4.1.

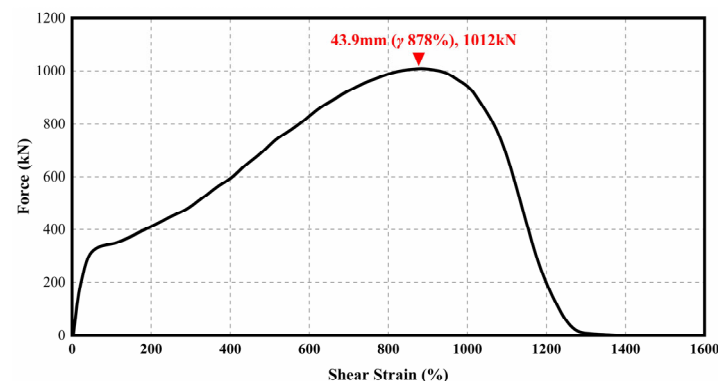


Figure 12. Test result for ultimate shear deformation.

A key observation from the monotonic ultimate test is the absence of detachment phenomena between the VE compound and the steel plates. This observation supports the engineering feasibility of implementing specified large shear deformations (e.g., 450%) without premature interface-related failure modes.

4. Discussion

4.1. Engineering Implications for Design Limit and Beyond-Design Margin

In practical applications, 300% shear strain is often treated as a typical design limit for VE dampers, while major earthquakes may impose larger deformation demands (e.g., for aging RC buildings). Against this background, the present results support a two-level engineering interpretation:

- Design-level (frequent/moderate events): the 300% tests demonstrate stable hysteresis and acceptable specimen-to-specimen variability, providing a reasonable basis for parameter calibration within the “normal” design domain (Sections 3.1 and 3.2; Tables 2 and 3).
- Beyond-design (rare/large events): the full-scale specimens sustained stable hysteretic behavior up to 450% shear strain, explicitly characterized as “beyond-design performance” in the manuscript, and the VE material remained intact under this demand. In addition, the monotonic ultimate test indicates a large deformation ceiling ($\approx 850\%$) for the material-level failure mode (Section 3.5), which can be interpreted as a deformation “reserve” beyond the cyclic test range (with the caveat of loading type; see Section 4.4).

From the broader perspective of VE dampers in civil engineering, the technology has long been recognized as effective (stiffness + damping), but wider adoption in building seismic retrofit/design is often constrained by practical issues such as strong sensitivity of properties to temperature/amplitude and the resulting need for iterative, device-specific characterization and modeling. [24–26] This paper’s “sell point” is therefore not merely demonstrating energy dissipation, but quantifying a credible beyond-design deformation margin at full scale (450% cyclic; $\sim 850\%$ monotonic) that directly targets one of the known

engineering pain points: uncertainty about reliable performance when interstory demands exceed the conventional 300% design domain.

From a material-mechanics standpoint, the large monotonic deformation capacity ($\approx 850\%$ shear strain) is consistent with the deformation mechanisms commonly reported for styrenic thermoplastic elastomers. In this class of triblock copolymers, the glassy polystyrene end blocks form nanophase-separated domains that act as physical crosslinks, while the rubbery mid-block provides extensibility; the resulting “hard/soft” morphology is widely recognized for enabling large reversible deformation and high toughness [27]. Under progressively increasing monotonic loading, substantial strain can be accommodated through domain stretching and chain rearrangement, whereas ultimate failure is often associated with cavitation followed by void growth/coalescence and final rupture, rather than immediate brittle fracture at small strains [28]. At the same time, monotonic capacity should not be interpreted as a cyclic capacity: repeated large-amplitude cycling can activate additional damage-accumulation mechanisms (e.g., Mullins-type stress softening and progressive microvoid/microcrack evolution), which are known to reduce stiffness and accelerate crack growth under cyclic loading compared with a single monotonic excursion. This distinction is also consistent with prior large-deformation VE damper studies that separately evaluate large-strain behavior and fatigue/low-cycle durability [29]. Accordingly, the $\approx 850\%$ result is best interpreted as an indicator of the attainable monotonic deformation limit of the material/system (and, in this study, as supporting evidence of robust interface integrity), rather than as a direct claim of cyclic durability at the same strain level.

4.2. Temperature and Displacement Effects

A central motivation for applying the manufacturer regression-based correction is that VE damper properties are condition-dependent, and (as implemented in this work), test control may aim to be close to target values rather than perfectly identical across runs. Normalizing results to a reference condition ($20\text{ }^{\circ}\text{C}$, 200% shear strain) serves two engineering purposes:

1. Comparability: it allows different tests (with slightly different achieved temperatures/displacements) to be compared on a consistent basis, strengthening conclusions about repeatability and trends.
2. Design usability: it converts raw test outcomes into a parameter-estimation workflow, enabling engineers to map $(T, u_{d,\max})$ into $P_{\max}$, K_{eff} , and C_{eff} for use in simplified Kelvin–Voigt analyses without repeatedly re-fitting from scratch.

This positioning is consistent with the broader literature: VE material/damper behavior is influenced by ambient temperature, and strain/displacement amplitude, and the lack of compact, uncertainty-aware “metamodels” can make design complicated and iterative [25,26]. Within this paper, the regression-based normalization is the mechanism that converts a small test matrix into something that looks closer to an engineering tool (standardized table), which is aligned with the stated goal of improving applicability rather than expanding experimentation. For the 450% shear-strain condition, the temperature-related observations are based on two single tests conducted on different specimens, and are therefore treated as indicative rather than definitive.

Internal heating (self-heating) can occur in viscoelastic materials during large cyclic deformations. In the present tests, the internal VE temperature was monitored using embedded thermocouples. The observed temperature increase within a seven-cycle protocol was modest, with a peak rise on the order of approximately $1\text{ }^{\circ}\text{C}$ at moderate-to-large deformation amplitudes ($\sim 350\%$ shear strain) and approximately $2\text{ }^{\circ}\text{C}$ at the 450% shear strain level. Given that the evaluated mechanical properties exhibited only modest variations over a much larger ambient-temperature interval (approximately $20\text{--}33\text{ }^{\circ}\text{C}$) at 300% shear

strain, with ζ_{eff} remaining essentially stable (Section 3.2), the above level of self-heating is not expected to materially influence the extracted effective properties under the present protocols. Nevertheless, long-duration cycling, cumulative heating, and potential degradation under many cycles are not addressed by the current seven-cycle tests and are therefore treated as a limitation of the study.

Uncertainty and sensitivity of the regression-based correction. The normalization in Section 2.6 relies on manufacturer-provided second-order regressions derived from coupon tests, and only ratio-based correction factors are transferred to the full-scale damper results rather than absolute coupon magnitudes. However, the underlying coupon dataset and regression residual statistics are proprietary and are not publicly available due to confidentiality agreements; therefore, a formal statistical quantification of the regression uncertainty (e.g., confidence bounds of the coefficients or prediction intervals) cannot be provided in this study. For practical interpretation, the corrected properties can be viewed as engineering estimates of the form $X_{\text{corr}} = X_{\text{meas}} \cdot F_T \cdot F_u$, where $F_T = X_T(T_{\text{ref}})/X_T(T_{\text{amb}})$ and $F_u = X_u(u_{\text{ref}})/X_u(u_{\text{eq}})$. Consequently, any relative uncertainty in the regression-based factors propagates approximately multiplicatively to X_{corr} . As an illustrative sensitivity check, if the correction factors F_T and F_u each carry an order-of-magnitude relative uncertainty of $\pm 10\%$, the resulting uncertainty in the corrected property is approximately $\pm 14\%$ (root-sum-square) or $\pm 20\%$ (worst-case linear sum). This level is comparable to, or moderately larger than, the specimen-to-specimen variability observed in the nominally identical 300% tests (typically on the order of $\sim 5\text{--}10\%$ for $K_{\text{eff}}/C_{\text{eff}}/W_d$ based on Table 4). Importantly, the primary findings of this paper—stable hysteresis at 450% shear strain and the absence of interface debonding—are based on the directly measured full-scale responses and are not contingent on the corrected values.

4.3. Comparison with Conventional Rubber-Based VE Dampers

To contextualize the damping and energy dissipation capacity of the present styrene-olefin thermoplastic VE damper, it is useful to compare its equivalent damping metrics with those reported for conventional rubber-based viscoelastic dampers. For chlorobutyl-rubber-based (CIIR) viscoelastic dampers, the reported material loss factor typically falls in the range of $\eta \approx 0.3\text{--}0.4$, which corresponds to an equivalent viscous damping ratio of approximately $\zeta \approx \eta/2 \approx 0.15\text{--}0.20$ under a Kelvin-Voigt representation [30]. High-damping rubber damper prototypes tested under cyclic shear loading have also been reported to maintain an equivalent viscous damping ratio on the order of $\zeta \approx 0.2\text{--}0.3$ over typical deformation ranges (e.g., $\zeta \approx 0.24\text{--}0.29$ in a 100% shear-deformation fatigue test) [31]. In contrast, the full-scale TRCS damper examined herein exhibited $\zeta_{\text{eff}} \approx 0.40\text{--}0.42$ at the design deformation (300% shear strain) and $\zeta_{\text{eff}} \approx 0.37\text{--}0.39$ at the over-design deformation (450% shear strain), together with stable hysteresis loops at 450% shear strain. Because the per-cycle energy dissipation is directly related to the equivalent damping ratio through $W_d = 4\pi\zeta_{\text{eff}}W_e$, these results indicate that, at large deformation demands, the present thermoplastic VE damper provides an energy dissipation capacity that is comparable to or higher than typical rubber-based viscoelastic dampers, while extending the stable cyclic deformation range beyond what is commonly reported for rubber-based devices.

The manuscript explicitly contrasts the proposed copolymer-type thermoplastic elastomer approach with conventional rubber-based VE dampers in three practical aspects:

- Manufacturing and interface reliability: the proposed VE compound does not require vulcanization; after heating, the bond is reported to be sufficiently strong such that failure occurs within the compound rather than at the interface.

- Usable deformation range: rubber-based VE layers are described as often detaching from steel plates under large deformation, which limits applicable shear deformation to approximately 250–300%; exceeding this may trigger unexpected failure modes.
- Behavior under severe events: the Conclusions note that under elevated seismic demands (e.g., drift angle reaching 2%), rubber-based VE dampers may exhibit strain hardening, permanent deformation, or rupture, reducing effectiveness in rare/severe earthquakes.

In this context, the key comparative contribution of this paper is the full-scale verification that stable hysteresis and effective energy dissipation can be maintained at 450% shear strain, beyond the commonly cited 300% design limit, and that an ultimate monotonic deformation capacity around 850% can be achieved without interface detachment in the reported test. This direction is broadly consistent with prior research efforts aimed at reducing temperature dependence and expanding the practical applicability of manufactured VE dampers, where temperature dependence is explicitly cited as a drawback that can limit applicability [26].

4.4. Limitations

This Discussion is intentionally confined to the interpretation of the existing dataset; however, several limitations should be stated clearly to avoid over-claiming:

1. Monotonic vs. cyclic deformation capacity: the reported ~850% ultimate shear deformation was obtained under uniaxial monotonic loading, not cyclic loading; therefore it should be interpreted as a deformation limit indicator rather than a cyclic durability claim.
2. Short-term cyclic characterization only: each cyclic test consisted of seven repeated cycles, which is sufficient to form stable loops for effective-property extraction; therefore, the reported results reflect only short-term behavior under the specified sinusoidal loading condition and do not quantify fatigue behavior, long-duration cycling, cumulative heating, or degradation under many cycles.
3. Limited frequency coverage and frequency-conditional properties: the cyclic tests were conducted at only two discrete excitation frequencies (0.5 Hz for the 300% shear-strain cases and 1.0 Hz for the 450% cases; Table 2). No frequency normalization (e.g., master-curve construction) was performed; therefore, both the measured and regression-corrected properties remain conditional on the tested frequencies and loading waveform. Extrapolation to other dynamic regimes (e.g., wind-induced vibration, different seismic spectra, or higher-mode-dominated responses) should be made cautiously and preferably supported by additional frequency-specific characterization.
4. Normalization uncertainty and model dependence: the correction procedure relies on manufacturer-provided polynomial regressions derived from coupon tests and is used here to transfer ratio-based temperature- and amplitude-correction factors to the full-scale results. Because the underlying coupon dataset and regression residual statistics are proprietary and not publicly available, the uncertainty of the corrected properties cannot be rigorously quantified; therefore, the corrected values should be interpreted as frequency-conditional engineering estimates (Section 2.6) and should be independently calibrated when used for final design.
5. Model idealization: the Kelvin–Voigt representation and the effective-property extraction are useful for engineering practice, but they remain an equivalent linearization of potentially nonlinear, history-dependent polymer behavior.

The cyclic protocols adopted in this study were limited to seven cycles per loading condition and were intended to characterize short-term, stabilized hysteretic behavior for parameter extraction (i.e., K_{eff} , C_{eff} , ξ_{eff} , and W_d). Therefore, the reported results should

not be interpreted as representing fatigue performance, long-term durability, cumulative damage, or property evolution under a large number of cycles. Additional testing with extended-cycle protocols would be required to quantify degradation trends and long-term behavior.

5. Conclusions

This study investigated full-scale TRCS-type viscoelastic (VE) dampers using a styrene–olefin-based thermoplastic elastomer as the primary energy-dissipating material. Cyclic tests were conducted to quantify repeatability, temperature dependence, and large-strain behavior beyond conventional design limits, and a monotonic loading protocol was used to identify the ultimate shear deformation capacity.

The test results indicate that the TRCS-type dampers exhibit stable hysteretic responses and acceptable specimen-to-specimen variability under the same loading conditions. The mechanical properties are influenced by both ambient temperature and displacement demand, which motivates the use of a normalization/correction procedure for consistent evaluation across different test conditions. By incorporating the manufacturer’s regression-based correction models accounting for temperature and displacement effects, the corrected properties provide a practical basis for estimating damper performance under specified operating conditions and for producing a standardized table to support preliminary engineering applications.

A key outcome of this work is the demonstrated large-deformation capacity of the proposed VE damper system. The dampers maintained effective energy dissipation at shear strains up to 450%, exceeding the deformation range typically assumed for many rubber-based VE dampers in structural applications. In addition, the monotonic ultimate-deformation test indicated that failure occurred within the VE compound rather than through interface debonding, and the maximum shear deformation capacity approached approximately 850%. These findings suggest that the styrene–olefin-based VE material and its bonding approach can provide a wider usable deformation range and a larger beyond-design margin, while offering manufacturing advantages associated with avoiding vulcanization and enabling more controllable product quality.

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Data Availability Statement: The viscoelastic material test data and the detailed regression coefficients of the proprietary material model are not publicly available due to confidentiality agreements with the damper manufacturer. Aggregated statistics, design values of the viscoelastic properties, and all structural analysis results are provided within the article.

Conflicts of Interest: Author T.K. is an employee of Sumitomo Riko Co., Ltd. (the manufacturer of the investigated viscoelastic dampers). The remaining authors declare no conflicts of interest. To safeguard objectivity, the experimental protocols, data reduction procedures, and evaluation criteria were defined prior to testing, and the reported conclusions are drawn from the directly measured full-scale responses; all modeling assumptions and limitations (including the use of manufacturer-provided regression relations) are explicitly stated in the manuscript.

Nomenclature

$\sigma(t)$	shear stress (material level) [MPa]
$\varepsilon(t)$	shear strain (material level) [–]
E	elastic modulus in the Kelvin–Voigt model (material level) [MPa]
η	viscosity coefficient in the Kelvin–Voigt model (material level) [MPa·s]
t	time [s]
$F(t)$	damper shear force (specimen level) [kN]
$u(t)$	damper shear displacement (specimen level) [mm]
$\dot{u}(t)$	damper velocity [mm/s]
K_{eff}	effective (secant) stiffness extracted from hysteresis loop [kN/mm]
C_{eff}	effective viscous damping coefficient [kN·s/mm]
ξ_{eff}	effective damping ratio [–]
$u_{\text{max}}, u_{\text{min}}$	maximum/minimum displacement in one stabilized cycle [mm]
$F_{u,\text{max}}, F_{u,\text{min}}$	damper forces corresponding to u_{max} and u_{min} , respectively [kN]
u_{ave}	average displacement amplitude, $(u_{\text{max}} + u_{\text{min}})/2$ [mm]
W_d	dissipated energy per cycle (hysteresis-loop area), $\oint F du$ [kN·mm]
ω	angular frequency ($\omega = 2\pi f$) [rad/s]
f	loading frequency [Hz]
P_{max}	maximum force (peak force) in one cycle, if reported separately [kN]
T_{amb}	ambient temperature during test [°C]
T_{ref}	reference temperature for correction (20 °C) [°C]
u_{eq}	equivalent maximum shear displacement defined for a 5 mm VE layer in the manufacturer's regression [mm]
u_{ref}	reference equivalent displacement corresponding to $\gamma_{\text{ref}} = 200\%$ for a 5 mm layer ($u_{\text{ref}} = 10\text{mm}$) [mm]
X_{meas}	measured property ($X \in \{K_{\text{eff}}, C_{\text{eff}}, P_{\text{max}}\}$) [unit depends on X]
X_{corr}	corrected property at $(T_{\text{ref}}, u_{\text{ref}})$ [same unit as X_{meas}]
$X_T(\cdot)$	temperature-dependent regression function (returns K_{eff} , C_{eff} , or P_{max}) [same unit as the returned quantity]
$X_u(\cdot)$	displacement-dependent regression function (returns K_{eff} , C_{eff} , or P_{max}) [same unit as the returned quantity]
a, b, c	regression coefficients in Equations (6) and (7) [units depend on the fitted quantity; see Table 4 notes]

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