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# Advanced Multilayer Viscoelastic Dampers for Structural Vibration Control

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**Abstract:**
advanced multilayer viscoelastic (VE) dampers offer a cost-effective solution for reducing vibrations in large scale structures without expensive modifications. Nevertheless, accurate modeling of their frequency-dependent behavior remains a challenge. Since simplified analytical models often fail to predict real-world performance, this paper develops and experimentally validates a validated numerical framework based on Finite Element Analysis (FEA). Based on generalized Maxwell law of frequency-dependent material properties, a two-layer FEA model of VE damper utilizing Sorbothane was built in COMSOL environment. The target VE model tested using a custom hydraulic experimental setup. The FEA predictions were rigorously compared against experiment measurements across a frequency range of 3 - 7 Hz. The result showed good agreement for both damping and stiffness characteristics. Besides, a structural frame case study under wind loading demonstrated the effectiveness of the VE damper highlighting its dual benefit of energy dissipation and structural stiffening. This "stiffening-plus-damping" effect is crucial for resilient infrastructure since it both reduces resonant response and shifts natural frequency away from critical excitation ranges.
In summary, the developed numerical FEA framework effectively captures the complex behavior of multilayer VE dampers, making it a reliable tool for designing high-capacity systems for controlling vibrations in large-scale structures. Future work will explore temperature-dependent behavior to further enhance deployment of these systems in structure vibration control.

**Keywords**: multilayers viscoelastic dampers, frequency-dependent behavior, finite element analysis, structural vibration mitigation, experimental validation.

# المخمدات اللزجة المرنة المتقدمة متعددة الطبقات للتحكم في اهتزازات المنشآت

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**الملخص**

توفر المخمدات اللزجة المرنة المتقدمة متعددة الطبقات (**Advanced Multilayer Viscoelastic (VE) Dampers**) حلاً فعالاً من حيث التكلفة لتقليل الاهتزازات في المنشآت كبيرة الحجم دون الحاجة إلى تعديلات مكلفة. ومع ذلك، لا يزال النمذجة الدقيقة لسلوكها المعتمد على التردد تمثل تحديًا. ونظرًا لأن النماذج التحليلية المبسطة غالبًا ما تفشل في التنبؤ بالأداء الحقيقي في التطبيقات الواقعية، تطور هذه الورقة إطارًا عدديًا قائمًا على تحليل العناصر المحددة (**Finite Element Analysis - FEA**) وتم التحقق منه تجريبيًا.

اعتمادًا على قانون ماكسويل المعمم (**Generalized Maxwell Model**) لتمثيل الخواص المادية المعتمدة على التردد، تم بناء نموذج ثنائي الطبقات لمخمد لزج مرن باستخدام مادة **Sorbothane** ضمن بيئة برنامج **COMSOL**. كما تم اختبار نموذج المخمد اللزج المرن المستهدف باستخدام منظومة هيدروليكية تجريبية مصممة خصيصًا لهذا الغرض.

تمت مقارنة تنبؤات نموذج العناصر المحددة بشكل دقيق مع القياسات التجريبية ضمن نطاق ترددي يتراوح بين **7–3هرتز** .

وأظهرت النتائج توافقًا جيدًا بين النموذج والتجارب لكل من خصائص التخميد والصلابة.

بالإضافة إلى ذلك، أظهرت دراسة حالة لإطار إنشائي تحت تأثير أحمال الرياح فعالية المخمد اللزج المرن، موضحة فائدته المزدوجة المتمثلة في **تبديد الطاقة وزيادة صلابة المنشأ** .ويُعد تأثير **"زيادة الصلابة مع التخميد- (Stiffening-plus Damping Effect) "** مهمًا بشكل خاص للبنية التحتية المرنة، لأنه يساهم في تقليل الاستجابة الرنينية وإزاحة التردد الطبيعي بعيدًا عن نطاقات الإثارة الحرجة.

باختصار، ينجح إطار النمذجة العددي المطور باستخدام تحليل العناصر المحددة في تمثيل السلوك المعقد للمخمدات اللزجة المرنة متعددة الطبقات، مما يجعله أداة موثوقة لتصميم أنظمة عالية السعة للتحكم في اهتزازات المنشآت كبيرة الحجم. وستركز الأعمال المستقبلية على دراسة تأثير درجة الحرارة على السلوك الديناميكي لهذه الأنظمة لتعزيز استخدامها في مجال التحكم باهتزازات المنشآت.

**الكلمات المفتاحية:** المخمدات اللزجة المرنة متعددة الطبقات؛ السلوك المعتمد على التردد؛ تحليل العناصر المحددة؛ الحد من اهتزازات المنشآت؛ التحقق التجريبي.

## 1.Introduction

In recent years, structural vibration control has received increasing attention, especially in tall structures such as high-rise buildings, long span bridges, and large industrial facilities [1][2][3]. These structures have been put under dynamic loads from natural events such as earthquakes and wind, in addition to operational forces from machinery and human use [4]. Excessive vibration may cause discomfort to occupants using the structure, damage to nonstructural elements, and in serious cases structural failure can occur. Therefore, engineers need to use a effective strategy for mitigating these dynamic responses in order to guarantee structural integrity, safety, and serviceability [1].

Historically, the approach for dealing with dynamic forces has been to design structural elements to be stiffer and stronger. However, by increasing stiffness and strength, structures are typically made heavier and more expensive. Moreover, they are less adaptable for future changes. In recent years, the focus has been placed on the use of passive and active control systems, in order to dissipate the vibrational energy of a structure or to counteract its dynamic movements [5] [6]. Among the various passive control systems, which do not require any external power, the use of auxiliary damping systems has been particularly emphasized, due to their reliability, cost-effectiveness and ease of implementation [7] [8].

Viscoelastic (VE) materials that exhibit both viscous and elastic characteristics both viscous which is energy dissipative and elastic which is energy storage have widespread application in passive damping systems [9] [10]. In hereafter referred to as viscoelastic dampers which usually see VE layers put between stiff confining plates, we see that these elements dissipate vibration energy via shearing deformation when put to dynamic loading [11] [12]. Viscoelastic dampers offer a dual mechanism for structural protection: they enhance the total damping matrix of a structure thereby mitigating resonant amplitudes while simultaneously contributing to structural stiffness, which shifts natural frequencies away from critical excitation ranges. This combined mechanical behavior is what makes viscoelastic dampers highly effective for enhancing a structural dynamic performance [13] [14]. Fig. 1, illustrates a layered viscoelastic damper composed of alternating steel plates and viscoelastic layers. Under opposing shear forces, the viscoelastic material dissipates vibrational energy while the steel plates provide rigidity, highlighting the dual role of enhanced damping and increased stiffness in structural performance.

*Problem Statement:* While there may be many benefits of using VE dampers, their practical use in large scale structures becomes difficult due to modeling and performance prediction issues. Though simplified analytical approaches can provide some insight into the behavior of the damping material, in many cases these approaches are unable to model the complex and temperature sensitive frequency dependent behavior of multilayer VE dampers properly. This can result in inaccuracies in prediction of the performance of such dampers leading to risks in crucial applications. Therefore, there is an urgent need for reliable numerical models which can characterize the behavior of multilayer VE dampers based on experimental tests.

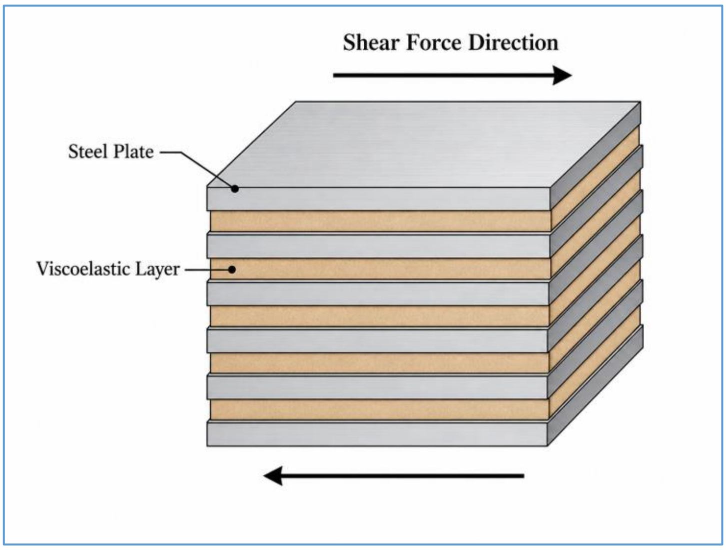



**Figure 1:** Typical multilayer configuration of a viscoelastic damper.

## 1. LITERATURE REVIEW

The application of viscoelastic (VE) materials in structural vibration control has undergone major expansion, driven by their distinct ability to dissipate energy and enhance structural performance. Recent research has focused on developing advanced VE damper designs and sophisticated modeling techniques to precisely predict their behavior under dynamic loading. For instance, Hao et al. [10] proposed multi-performance oriented seismic design methods for retrofitting reinforced concrete structures with VE dampers, demonstrating their practical efficacy. Zhang et al. [11] conducted experimental and numerical analyses on the interface cohesive behavior in VE dampers, emphasizing the importance of accurate material and interface modeling for validated performance prediction. Aly [12] subsequently explored the synergistic effects of bracing stiffness and VE damping in tall buildings, highlighting the potential for integrated damping solutions to augment overall structural resilience.

Numerical modeling, specifically through the application of Finite Element Analysis (FEA), has demonstrated its crucial importance in clarifying the elaborate, frequency-dependent characteristics of viscoelastic (VE) materials. Studies by Zang et al. [13] and Mohammed [14] have utilized advanced numerical techniques to investigate the seismic resilience of structures enhanced with hybrid VE dampers, demonstrating the predictive power of FEA. Experimental validation persists as a fundamental step in confirming the accuracy of these numerical models. Research by Wang et al. [15] and Al-Rumaih and Kashani [16] comprised extensive experimental and numerical investigations of diverse VE dampers configurations, including those with well-characterized nonlinear characteristics and tuned mass damper configurations.

Moreover, current reviews, specifically the comprehensive overview by Zhang et al. [17] in 2024, synthesize varied experimental and numerical approaches to establish a state-of-the-art understanding of VE dampers for building structures.

*Research Gap*: Despite these substantial advancements, a critical research gap persists in the comprehensive and experimentally validated numerical modeling of multilayer viscoelastic dampers, particularly concerning their complex, frequency-dependent behavior, and optimized application in large-scale structural systems. While individual components and simplified configurations have been extensively studied, a holistic framework that seamlessly integrates advanced numerical techniques with rigorous experimental validation for complex, multilayer VE damper designs are nevertheless predominantly underdeveloped. Current analytical models typically oversimplify the material's inherent frequency and temperature sensitivities, as well as the geometric complexities of multilayer assemblies, leading to possible inaccuracies in predicting practical performance and hindering their widespread adoption in essential infrastructure projects.

*Objective and Contributions:* This study aims to bridge this identified research gap by developing and experimentally validating a robust numerical framework specifically tailored for the analysis and design of multilayer viscoelastic dampers. The specific objectives are (I) To develop a comprehensive finite element analysis (FEA) model capable of accurately predicting the frequency-dependent damping and stiffness characteristics of multilayer VE dampers, incorporating advanced material constitutive laws. (II) To experimentally validate the developed FEA model using a custom-built hydraulic test setup, ensuring the reliability and accuracy of the numerical predictions across a broad range of operating frequencies and amplitudes. (III) To demonstrate the enhanced effectiveness of the proposed multilayer VE damper in mitigating structural vibrations through a detailed comparative case study of a structural frame under various dynamic loading conditions.

*Contributions:*

(a) Novel, experimentally validated numerical framework that precisely accounts for the complex, frequency-dependent behavior of multilayer VE materials, offering a superior predictive tool compared to existing simplified models.

(b) Comprehensive experimental data derived from a custom-designed test setup, providing crucial empirical validation for the numerical model and demonstrating the practical performance and reliability of multilayer VE dampers.

(c) A clear and quantitative demonstration of the dual benefits of multilayer VE dampers—significantly enhanced energy dissipation and effective structural stiffening—through a rigorous comparative case study, unequivocally highlighting their superior performance over traditional viscous damping solutions.

(d) The establishment of a robust and transferable methodology for the optimized design and advanced analysis of VE damping systems, thereby facilitating their broader and more confident adoption in critical structural applications and contributing to the development of more resilient infrastructure.

## 2. METHODOLOGY

This section details the comprehensive methodology employed for the design, numerical modeling, and experimental validation of the multilayer viscoelastic VE damper. The approach integrates theoretical formulations with advanced computational techniques and rigorous experimental testing to ensure the accuracy and reliability of the proposed framework. To provide a high-fidelity roadmap of this process, Fig.2, illustrates the integrated flowchart for FE synthesis and the extraction of critical dynamic parameters used throughout this research.

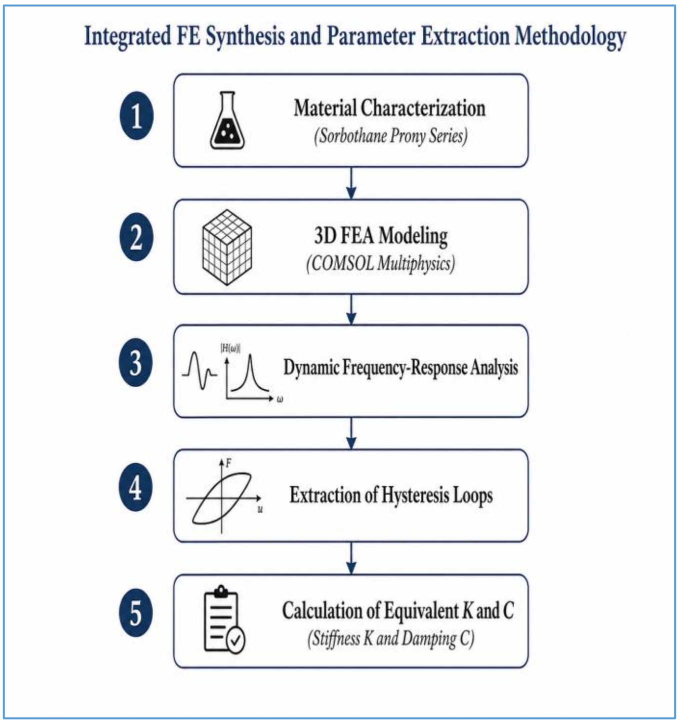



***Figure 2.*** *Flowchart of the integrated FE synthesis and parameter extraction methodology.*

### *A. Problem Formulation and Model Configuration:*

Viscoelastic dampers are passive energy dissipation devices typically composed of multiple layers of VE material bonded between rigid steel constraining plates. A comprehensive 3D finite element model was developed using the COMSOL Multiphysics software. The operational principle of VE dampers relies on the shear deformation of the VE layers when subjected to dynamic loading, thereby converting vibrational energy into heat. This study focuses on a multilayer configuration VE damper as shown in Fig. 1, to enhance damping capacity and optimize performance for large-scale structures.

The specific design under investigation is a two-layer VE damper, meticulously engineered to provide optimal damping characteristics. The VE model prototype, consisting of 0.5 inch (12.7 mm) thick VE core layers and 0.25 inch (6.35 mm) thick steel constraining plates. The model was subjected to harmonic force excitation across a frequency range of 3 Hz to 7 Hz, simulating typical operational conditions for high rise structures. Fig. 2, provides a detailed schematic of this configuration, highlighting the precise arrangement of the VE material layers and the steel constraining plates. The selection of Sorbothane polymer, was based on its established viscoelastic properties and suitability for structural damping applications.

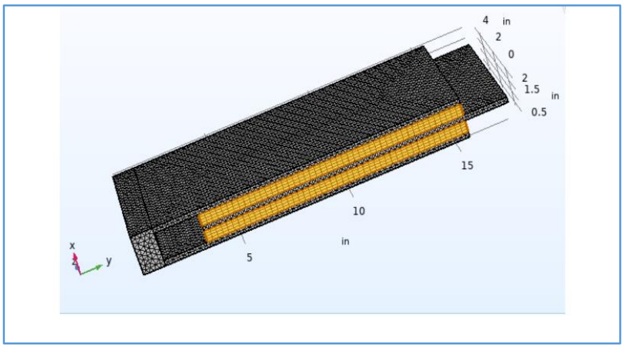



***Figure 3.*** *Detailed configuration of the two-layer viscoelastic damper, emphasizing the precise arrangement of VE material layers and steel constraining plates.*

## *B. Mathematical Modeling of Viscoelastic Materials*

- Constitutive Models:

In order to correctly model the viscoelastic behavior of materials within a simulation, mechanical analog models are generally used. These models consist of a combination of springs and dashpots, where the springs represent elastic behavior and the dashpots represent viscous behavior [10], [11]. The Kelvin-Voigt and Standard Maxwell models are two of the simpler models that can be used to provide an understanding of the behavior of a number of different viscoelastic polymers [16]. However, these models are unable to provide an accurate description of the frequency-dependent behavior of a large number of different materials [17]. A Generalized Maxwell model, also referred to as Prony series model, is a frequently used mechanical analog for the prediction of the viscoelastic behavior of polymers within a wide frequency range. A Generalized Maxwell model is composed of an equilibrium spring (in series with the sum of all other elements) connected in parallel to (n) different types of Maxwell elements. Each single Maxwell element consists of a spring and a dashpot in series [2] [15]. The relaxation modulus, G(t), of a Generalized Maxwell model is given by (in the time domain) as follows:

$$G(t) = G_\infty + \sum_{i=1}^{n} G_i * e^{-t/\tau_i}$$

Where $G(t)$ is the time-dependent shear relaxation modulus, $G_\infty$ is the long-term, equilibrium shear modulus, which is the material's shear modulus as time approaches infinity, $G_i$ are the shear moduli of the individual Maxwell branches, representing the contribution of each branch to the overall elastic response, $\tau_i$ are the corresponding relaxation times for each Maxwell branch, characterizing the rate at which stress relaxes in that branch, n is the total number of Maxwell branches used to approximate the material's behavior. The generalized Maxwell model, represented by the Prony series, provides a robust mathematical description.

This formulation allows for a precise fit to experimental relaxation data by adjusting the number of branches and their respective moduli and relaxation times, thereby capturing the complex time-dependent response of viscoelastic materials more comprehensively than simpler models.

- Complex Modulus Formulation

For materials subjected to steady-state harmonic excitation, it is often more convenient and perceptive to analyze their properties in the frequency domain. The time-domain relaxation modulus can be transformed into a complex shear modulus, $G^*(\omega)$, which condenses both the elastic (storage) and viscous (loss) components of the material's response [2][10][15]. The complex shear modulus is defined as:

$$G^*(\omega) = G'(\omega) + iG''(\omega)$$

Where $G^*(\omega)$ is the complex shear modulus, a frequency-dependent complex quantity, $G'(\omega)$ is the storage modulus, representing the elastic or in-phase component of the material's stiffness. It quantifies the energy stored elastically per cycle of deformation, $G''(\omega)$ is the loss modulus, representing the viscous or out-of-phase component of the material's response. It quantifies the energy dissipated as heat per cycle of deformation. i is the imaginary unit, $\sqrt{-1}$, $\omega$ is the angular excitation frequency in radians per second.

From the Generalized Maxwell model, the storage and loss moduli can be rigorously derived as functions of the angular frequency ($\omega$):

$$G'(\omega) = G_\infty + \sum_{i=1}^{n} \frac{G_i * (\omega * \tau_i)^2}{1 + (\omega * \tau_i)^2}$$

$$G''(\omega) = \sum_{i=1}^{n} \frac{G_i * \omega\tau_i}{1 + (\omega * \tau_i)^2}$$

These equations demonstrate how the individual contributions from each Maxwell branch, characterized by $G_i$ and $\tau_i$, combine to form the overall frequency-dependent elastic and viscous responses. The storage modulus increases with frequency, reflecting the material's stiffer response at higher deformation rates, while the loss modulus typically exhibits a peak at frequencies corresponding to the relaxation times of the dominant branches. The material loss factor, (η), is a dimensionless parameter that serves as a critical index of the material's damping efficiency. It is defined as the ratio of the loss modulus to the storage modulus:

$$\eta = \frac{G''(\omega)}{G'(\omega)}$$

A higher loss factor indicates a greater capacity for energy dissipation relative to energy storage, making it a key metric for evaluating the performance of viscoelastic materials in damping applications.

***C. Dynamic Parameter Extraction***

Force-displacement hysteresis loops of the reaction force at the fixed boundary versus the prescribed displacement were created from the results of the frequency-response analysis. The equivalent viscous damping coefficient $C_{VE}$ and the dynamic stiffness $K_{VE}$ of the system were determined from the geometry of the hysteresis loop [16]. The energy dissipated by the system per cycle $E_d$, i.e. the area of the hysteresis ellipse, is equal to the energy dissipated by an equivalent linear viscous damper [19].

$$E_d = \pi C_{VE} \omega X_0^2$$

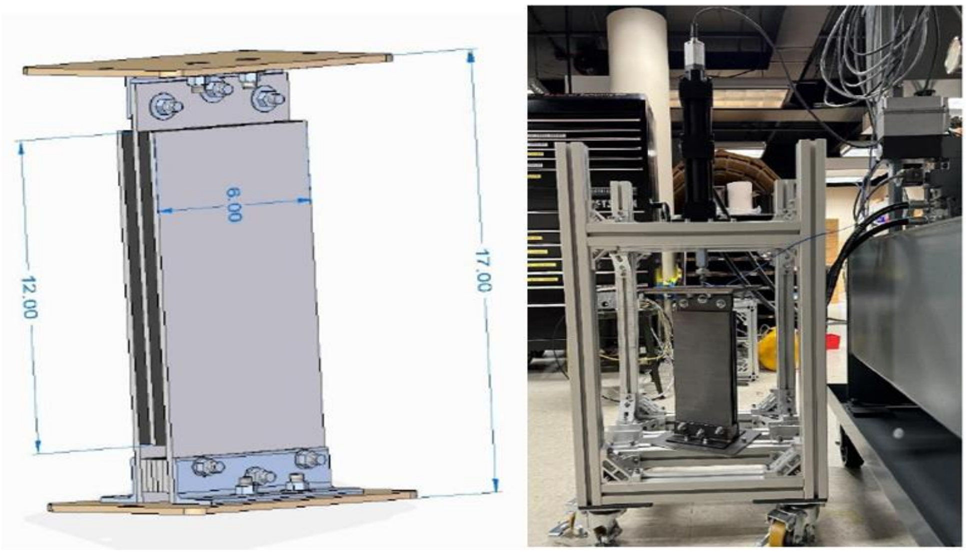
where ω is the excitation frequency and $X_0$ is the displacement amplitude. The effective dynamic stiffness $K_{VE}$ was evaluated from the major axis slope of the generated ellipse.

## 3. EXPERIMENTAL VALIDATION

A prototype two-layer VE damper was created and subjected to extensive experimental testing to critically validate the fidelity and predictive capacity of the created FEA framework. This validation process is crucial for establishing confidence in the numerical model's ability to represent real-word behavior.

***A. Experimental Setup***

The experimental setup was custom-designed to accurately characterize the dynamic properties of the VE damper under controlled conditions. It comprised a robust rigid aluminum frame, providing a stable base for testing. A high-precision hydraulic cylinder was utilized to apply controlled cyclic displacements to the damper. Force measurements were acquired using a calibrated load cell, while displacement was precisely monitored by a Linear Variable Differential Transformer (LVDT). Fig. 4, presents a) a typical VE damper with sandwich configuration, b) an experimental setup, illustrating the integration of the hydraulic actuator, the damper specimen, and the data acquisition system. This setup allowed for the precise measurement of force-displacement hysteresis loops, which are essential for determining the damping and stiffness characteristics of the VE material.




(a) (b)

***Figure 4.*** *(a) a typical VE damper with sandwich configuration (b) an experimental setup*

*B.* ***Experimental Validation and Hysteresis Loop Analysis***

The fundamental mechanism of energy dissipationof VE dampers is characterized by the hysteresis loop generated under harmonic displacement-controlled loading at discrete frequencies ranging from 1 to 10 Hz. The area enclosed by this loop represents the energy dissipated per cycle, while its inclination indicates the effective stiffness. The resulting force-displacement data were recorded, and the hysteresis loop were analyzed to extract the dynamic stiffness and equivalent viscous damping coefficients. To validate the numerical framework, the experimentally derived hysteresis loops were rigorously compared against the FEA predictions and analytical fits. Fig. 5, demonstrates the exceptional agreement between the experimentally measured data (red) and the analytical fit (blue) for a representative 3 Hz run.

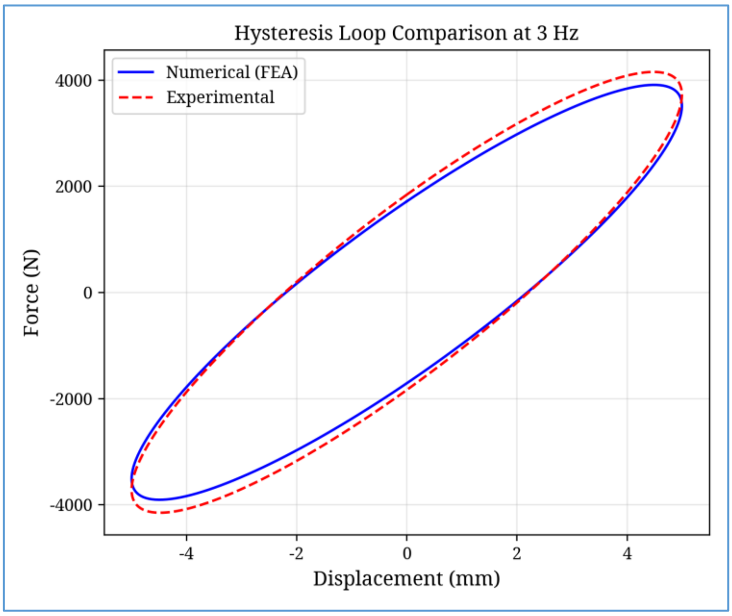



***Figure 5.*** *Comparison of numerical and experimental hysteresis loops.*

The 2D FE model had captured the 2 major parameters. The enclosed area gives damping coefficient, and the incline of the longest boundary (major axis) gives stiffness coefficient. For 3Hz test, the model predicted stiffness of 702.6N/mm and damping of 18.18 kN·s/m. These results matched well with corresponding test results of stiffness of 744.6 N/mm and damping of 19.52 kN·s/m. The model predictions remained within 8% error band for all test frequencies. The close agreement between the measured and fitted elliptical trajectories confirms the validity of extracting the equivalent viscous damping coefficient ($C_{VE}$) and the effective stiffness ($K_{VE}$) directly from the hysteresis area and tilt angle, respectively. This strong correlation validates the underlying assumptions of the FEA model, particularly the use of the generalized Maxwell presented as Prony series to represent the complex shear modulus.

## 4. Results and Discussion

This section presents a deep analytical interpretation of the experimental and numerical findings, highlighting the statistical significance of the results and comparing the performance of the proposed multilayer VE damper with existing literature benchmarks.

### *A. Frequency-Dependent Behavior*

A critical aspect of VE materials is their strong frequency dependence. Fig. 6, illustrates the variation of both the effective stiffness and the damping coefficient as a function of excitation frequency for the Sorbothane-core damper across a 1-10 Hz range.

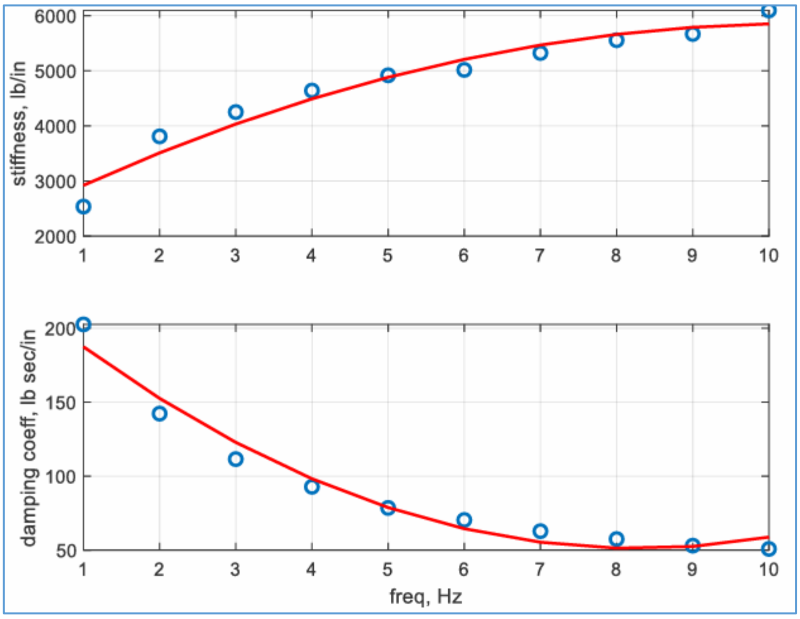



***Figure 6.*** *Damping and stiffness coefficients of the VE damper with two layers of 0.5-inch Sorbothane core measured at 10 frequencies.*

The analytical interpretation of Fig. 7 leads to the important result that, as the excitation frequency is increased, the effective stiffness of the VE damper increases whereas the equivalent viscous damping coefficient decreases. This behavior corresponds to the fundamental rheological properties of viscoelastic polymers and is particularly advantageous for civil engineering applications. Large civil engineering structures, such as high-rise buildings, or long-span bridges, have low fundamental natural frequencies, generally less than 2 Hz. For these structures, the VE damper delivers its largest damping contribution at the low frequencies that are of principal concern for the mitigation of wind or seismic loading induced vibrations.

### *B. Structural Application of the Devolped Multilayer VE Damper*

To assess the damping performance of the developed VE damper in a realistic framework, a computational single degree of freedom (SDOF) frame model was established and validated by means of experimental free vibration tests. The utilized numerical frame model features an underdamped structural behavior with an inherent damping ratio of (zeta = 1%) and a fundamental frequency of 2.3 Hz. Within the framework of a free vibration analysis, the chevron brace that is embedded in the investigated frame is equipped with a VE damper, in order to maximize the shear deformation by means of inter-story drift. The dynamic response of the frame was evaluated under three conditions: untreated (bare frame), equipped with a traditional linear viscous damper, and equipped with the proposed multilayer VE damper. Fig. 7, presents a comparative analysis of the free vibration response for these three configurations.

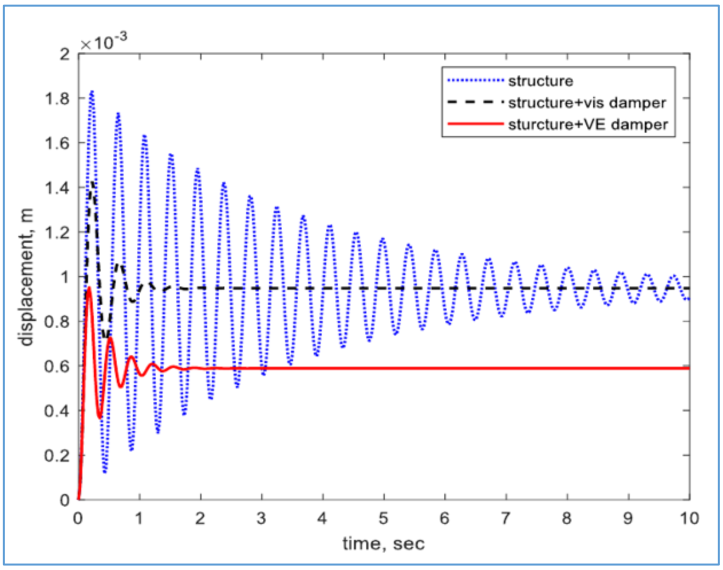
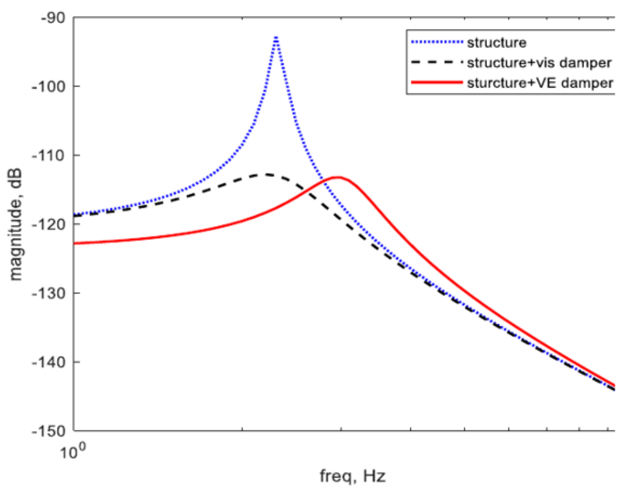



**Figure 7.** Free response of the frame without (blue/dotted line trace), frame treated by the VE damper (red/solid-line trace), and frame treated by a viscous damper (black/dashed-line trace) The untreated structure takes tens of seconds to decay under free vibration. While the addition of a purely viscous damper to the frame accelerates the decay, it leaves the structure to be very compliant at lower frequencies. However, by incorporating the multi-layer VE damper into the chevron brace, the structure's overall damping ratio was dramatically elevated to 12% under free vibration analysis. The FRF revealed that the peak had been reduced by a factor of eight, while the natural frequency of the structure had been more favorably elevated from 2.3 to 2.8 Hz, due to the additional stiffness of the VE damper.

### *C. The Frequency Response Function (FRF) and "stiffening-plus-damping" effect*

a key advantage of the VE damper is elucidated through the Frequency Response Function (FRF) analysis, shown in Figure 8.



The FRF magnitude plot of the structure equipped with a VE damper shows two major features of interest. The first one is the VE damper significantly reducing the peak of the resonant mode. The reduction of the resonant peak of the structure with the damper is in excess of 80% when compared to a structure without a damper. The second major feature of the FRF is the change in the natural frequency of the structure when the damper is added. Instead of decreasing (softening), the natural frequency of the structure's first mode of vibration is increased from approximately 2.3 Hz to about 2.8 Hz when the VE damper is added to the structure. This unique "stiffening-plus-damping" property of the VE damper is a characteristic that is fundamentally different from that of the traditional viscous (or visco-elastic) dampers. While the latter types of dampers only increase the amount of energy dissipated by a structure during dynamic response, the energy dissipated by a structure equipped with a VE damper also results in the increase of the effective stiffness of the structural system, or the "stiffening" of the structure. This unique property of the VE systems allows for two objectives to be achieved by the addition of the damper to a structure: 1) reducing the resonant amplitude of the structure for various load cases, and 2) shifting one or more of the natural frequencies of the structure to frequencies that are outside of the frequency range of the dominant components of the dynamic load of interest (e.g., wind loads that may contain a vortex shedding component, or seismic load with a specific design spectrum).

## 5. SUMMARY AND FUTURE WORK

The proposed multilayer VE damper is not a simple energy dissipation system, but a tunable component to control structural vibration by increasing the damping capacity of a system as well as its structural integrity (stiffness). The frequency-dependent material constitutive law of the VE layer is incorporated into a refined finite element model (FEM) to predict the complex stiffness and damping behavior of the multilayered VE damper. The numerical predictions are experimentally validated by a well-designed hydraulic testing system. reasonable summaragreements are obtained between the numerical results and corresponding experimental results over a frequency range of interest. Therefore, the proposed multilayer VE damper provides a robust, experimentally validated, and more effective solution for vibration control of high-rise buildings and bridges compared with existing passive control systems.

A principal innovation of the multilayer VE damper is found to possess superior performance to conventional viscous damping systems. The novel VE damper exhibits a unique "stiffening-plus-damping" behavior that facilitates the reduction of resonant amplitude by effectively dissipating the associated vibration energy, while simultaneously elevating associated natural frequencies of the associated structure, resulting in increased structural robustness against dynamic loading such as wind or seismic forces. These outstanding features are clearly revealed through a contrastive case study of vibration control in a model structure, which demonstrated significant reduction in associated transient as well as steady state vibration.

Practical application of the established numerical framework of a multilayer VE damper will support engineers in designing and installing optimal vibration mitigation systems for critical structures at minimum cost. The proposed concept offers the possibility of more effective vibration mitigation than current practice in a cost-effective manner, without requiring extensive modification of the structure. By increasing the damping of a structure and simultaneously its stiffness, the proposed multilayer VE damper presents a superior solution for vibration mitigation in comparison to existing passive systems.

**Limitations and Future Work:** Even though significant progress has been made in this paper, there are some limitations in the present framework. At first, the present framework is mainly based on frequency-dependent behavior of VE dampers at ambient temperature. Future studies should incorporate the effects of temperature variations and self-heating of VE materials into the framework to better predict the behavior of the multilayer VE dampers under dynamic loading over a long period of time. In addition, long-term durability and aging of VE materials should be studied, and semi-active or adaptive VE damping systems should be developed. Furthermore, application of the present framework to more complex 3D structures, i.e., multi-degree-of-freedom systems, and experimental and numerical investigation of optimal locations of multilayer VE dampers for seismic protection of structures should also be carried out in future studies.

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**Compliance with ethical standards**

*Disclosure of conflict of interest*

The authors declare that they have no conflict of interest.

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