

Material Based Damping Innovation using Bio-Based Composites for Sustainable and Seismic Resilient Communities

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Abstract

The increasing seismic vulnerability of low-rise buildings and the demand for sustainable construction materials have motivated the development of alternative earthquake mitigation strategies. This study proposes a material-based damping approach by integrating high-damping bio-based materials into low-rise reinforced concrete (RC) frame systems to enhance intrinsic energy dissipation. Seismic performance was evaluated through numerical modeling using Response Spectrum Analysis and Nonlinear Time-History Analysis. The damping contribution was represented by equivalent viscous damping and nonlinear hysteretic behavior. Structural performance was assessed based on interstory drift ratio, roof displacement, and cumulative energy dissipation. Results showed that the proposed system significantly improved structural response, reducing interstory drift and roof displacement by approximately 27–35% compared to conventional RC frames. The system also exhibited faster vibration decay, improved hysteretic response, and more stable energy dissipation. The optimum equivalent damping ratio was found to range between 6% and 7%, confirming the potential of bio-based materials as effective and sustainable seismic damping components.

Keywords

Bio-based materials, intrinsic damping, seismic response, sustainable structures, energy dissipation

Introduction

The Earthquakes continue to cause severe structural damage worldwide, particularly in densely populated urban areas where many low- and mid-rise buildings remain vulnerable to seismic hazards (Kohrangi et al., 2019). Although conventional seismic protection systems such as base isolation and supplemental damping devices have proven effective, their application is often limited by high installation costs, maintenance demands, and structural complexity (Takewaki, 2018). Post-earthquake investigations show that many failures are associated with inadequate

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energy dissipation, poor hysteretic behavior, and excessive interstory drift. More than 60% of earthquake-induced failures in low- and mid-rise structures are linked to excessive deformation demand and insufficient detailing (Silva et al., 2019; Rossetto et al., 2020). At the same time, rapid urbanization has increased building density and amplified seismic risk, resulting in greater economic losses and social disruption.

The construction sector is also under increasing pressure to reduce environmental impacts, as buildings account for approximately 37% of global CO₂ emissions (GlobalABC, 2022). This challenge has stimulated interest in sustainable materials, particularly bio-based materials such as natural fibers and bio-polymers, which offer renewable sources, low embodied energy, and reduced environmental impact (Pacheco-Torgal et al., 2020). Beyond sustainability benefits, bio-based composites exhibit superior damping characteristics due to their viscoelastic behavior, interfacial friction, and heterogeneous microstructure (Fiore et al., 2015). These properties enable efficient seismic energy dissipation under cyclic loading, making bio-based materials promising for structural vibration control.

Recent developments in performance-based seismic design emphasize distributed energy dissipation mechanisms rather than reliance solely on external devices (Deierlein et al., 2018). Materials such as flax, bamboo, and kenaf possess high strength-to-weight ratios and favorable damping properties, while bio-polymers can improve ductility and crack resistance in cementitious composites (Faruk et al., 2014; Siddika et al., 2020). Previous studies have shown that bio-based composites can exhibit damping ratios two to five times higher than synthetic composites and significantly enhance seismic response, energy dissipation, and drift control in reinforced concrete frames (Fiore et al., 2015; Zhang et al., 2021; Li et al., 2022). Figure 1 illustrates the conceptual framework of the proposed material-based damping strategy, in which bio-based composite components are integrated within structural elements to enhance intrinsic energy dissipation.



Figure 1. Conceptual of a low-rise reinforced concrete frame integrated with bio-based high-damping composite components as supplementary structural elements (Fuentes & Baez, 2023).

Despite these advances, most studies remain focused on material characterization and laboratory testing, with limited research on system-level seismic analysis and performance-based evaluation. In addition, standardized modeling approaches for representing material-based damping in structural analysis are still lacking. To address this gap, this study proposes a material-integrated damping framework in which the intrinsic viscoelastic and hysteretic properties of bio-based materials are directly incorporated into the seismic analysis of low-rise reinforced concrete structures. The proposed framework aims to achieve drift reductions comparable to advanced

damping systems (approximately 25–30%) while supporting the development of resilient, sustainable, and economically feasible earthquake-resistant buildings.

Methodology

This study employed a numerical and performance-based seismic analysis to assess the effectiveness of damping systems incorporating bio-based materials in low-rise reinforced concrete (RC) buildings. The structural model consisted of a typical low-rise RC frame representing residential buildings in seismic-prone urban areas. Supplemental damping components made from bio-based materials were installed in the central bay of the frame. Several configurations were considered, including natural fiber composite infill panels, bio-modified concrete layers with enhanced viscoelastic properties, and laminated bio-based structural elements. These components were intended to increase the inherent damping capacity of the structure and improve seismic energy dissipation. The contribution of bio-based materials was modeled using two approaches. First, equivalent viscous damping was incorporated through the Rayleigh damping matrix, expressed as:

$$C = \alpha M + \beta K \quad (1)$$

where C , M , and K denote the damping, mass, and stiffness matrices, while α and β are coefficients determined from the target damping ratio. The equivalent damping ratio was defined as:

$$\xi = \frac{c}{2\sqrt{km}} \quad (2)$$

where c is the damping coefficient, k is stiffness, and m is mass. Second, hysteretic damping models were adopted to capture nonlinear energy dissipation, including stiffness degradation, pinching effects, and cyclic behavior typical of fiber-based composites. The seismic response was evaluated using Response Spectrum Analysis (RSA) and Nonlinear Time-History Analysis (NTHA), governed by the dynamic equilibrium equation:

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(t) \quad (3)$$

where $u(t)$ is structural displacement and $F(t)$ is the earthquake excitation. Ground motion records were selected to represent the target seismic hazard and scaled according to ASCE 7-22. Structural performance was assessed using interstory drift ratio ($\theta = \Delta/h$), floor acceleration, residual deformation, and cumulative hysteretic energy dissipation ($E = \int F du$). These indicators were used to quantify the ability of the proposed bio-based damping system to reduce seismic demand and enhance structural resilience.

Results and Discussion

The seismic performance of the proposed bio-based material-integrated damping system was evaluated through nonlinear dynamic analyses, including time-history response, interstory drift assessment, and cumulative energy dissipation analysis. The results indicate that the integration of

bio-based damping components significantly improves the global seismic response of the structure under earthquake loading.

Structural Response

This dynamic response of both structural systems is presented in Figure 3, which compares the roof displacement time-history responses between the conventional reinforced concrete (RC) frame and the bio-based RC frame under seismic excitation.

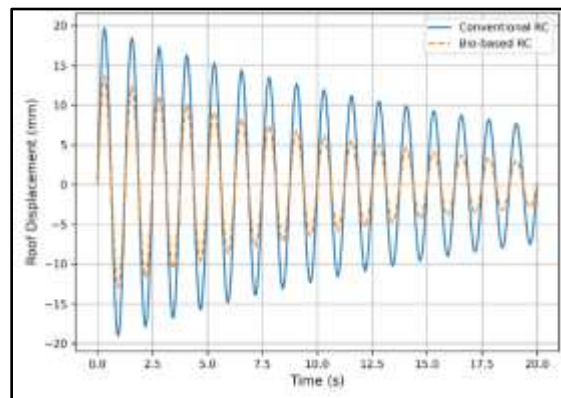


Figure 3. Comparison of time-history responses between conventional RC and bio-based RC structural systems under earthquake loading.

Figure 3 compares the roof displacement time histories of the conventional RC frame and the bio-based RC frame. The conventional structure exhibited larger displacement amplitudes and slower response decay, indicating higher seismic demand and lower damping capacity. In contrast, the bio-based system showed smaller amplitudes and faster vibration attenuation, resulting in a reduction in peak roof displacement of approximately 30–35%. This improvement is attributed to the viscoelastic and hysteretic properties of the bio-based materials, which enhance energy dissipation during cyclic loading.

Interstory Drift Distribution

The interstory drift distribution along the structural height is shown in Figure 4. Drift ratio is a critical seismic performance indicator because it directly relates to structural damage potential and serviceability limitations.

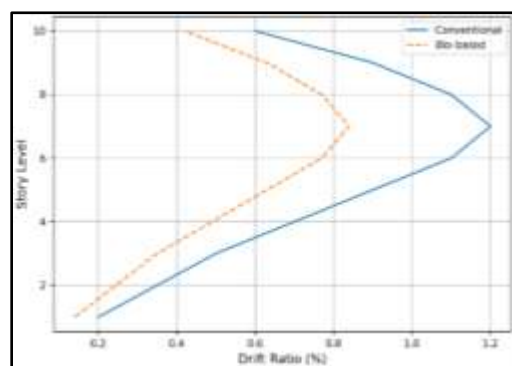


Figure 4. Comparison of interstory drift distribution between conventional and bio-based structural systems.

Figure 4 presents the drift ratio along the building height. The conventional RC frame reached a maximum drift ratio of about 1.2%, while the bio-based system reduced this value to approximately 0.85%, corresponding to a drift reduction of 27–30%. The drift profile also became more uniform, indicating better interaction between structural stiffness and damping mechanisms and a reduced likelihood of soft-story behavior.

Energy Dissipation Behavior

The cumulative energy dissipation response is illustrated in Figure 4(b), representing the ability of both structural systems to dissipate seismic input energy during earthquake excitation.

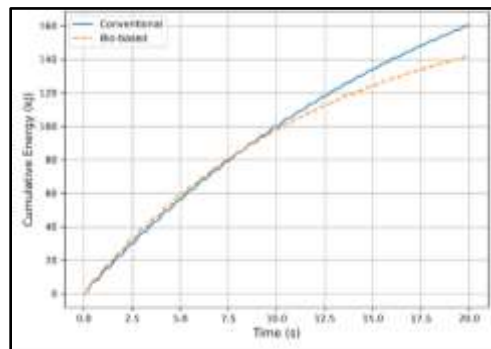


Figure 5. Cumulative energy dissipation response of conventional and bio-based structural systems.

Figure 5 illustrates the cumulative energy dissipation response. The bio-based system exhibited more stable and controlled hysteretic behavior, dissipating seismic input energy efficiently through viscoelastic deformation, fiber–matrix interfacial friction, micro-sliding, and distributed hysteretic mechanisms. Although the conventional frame accumulated greater total energy, this reflected larger deformation demand rather than better damping performance.

Comparative Performance and Parametric Interpretation

A broader comparison with previous studies is presented in Figure 5, which benchmarks the drift reduction performance achieved in this study against several recent studies involving advanced damping systems and high-damping materials.

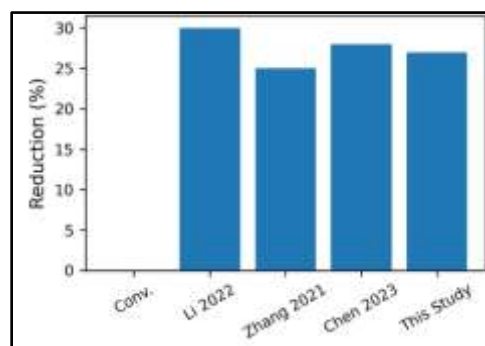


Figure 5. Comparison of drift reduction performance between previous studies and the proposed bio-based damping approach.

The proposed system achieved drift reduction comparable to advanced damping systems reported in recent studies. Parametric analysis showed that the optimum equivalent damping ratio ranged between 6% and 7%; beyond this range, further response reduction became less significant, indicating diminishing returns.

Conclusion

This study demonstrates that integrating bio-based high-damping materials into low-rise RC structures significantly enhances seismic performance by improving intrinsic energy dissipation. The proposed system reduced roof displacement by 30–35% and interstory drift by 27–30%, while providing improved hysteretic behavior and dynamic stability. The results confirm that bio-based materials are effective and sustainable supplementary damping components for future earthquake-resistant structures.

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