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VISCOELASTIC DAMPING SYSTEMS FOR ENHANCED SEISMIC PERFORMANCE OF REINFORCED CONCRETE BEAMS

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ABSTRACT

This research investigates the effectiveness of Viscoelastic Damping Systems (VDS) in enhancing the seismic performance of reinforced concrete (RC) beams. To evaluate this, a series of numerical simulations were conducted using time-history seismic analysis, incorporating earthquake magnitudes ranging from moderate to severe (e.g., 5.5 to 7.5 on the Richter scale). The RC beams analyzed were standard-sized with a span of 4 meters, designed per conventional seismic codes, while VDS parameters, such as damping ratio and placement, were optimized for maximum energy dissipation. A control group of RC beams without VDS was included to provide a baseline for performance comparisons. The study focuses on critical performance metrics, including displacement control, energy dissipation, and residual deformation, to assess the impact of VDS under varying seismic loads. Results indicate that the integration of VDS reduces displacement by 25% to 30%, increases energy dissipation by 50% to 67%, and decreases residual deformation by up to 40%, compared to the control group. While these findings highlight the significant benefits of VDS, the results are particularly applicable to mid-sized RC beams commonly used in low- to mid-rise structures and may require further validation for larger or highly irregular designs. These findings demonstrate that VDS significantly improve the seismic resilience of RC beams by absorbing and dissipating seismic energy, thereby reducing the risk of structural damage and permanent deformation. The study emphasizes the importance of integrating VDS in seismic design codes for RC structures in earthquake-prone regions, while advocating for future research to optimize their use across diverse scenarios.

Keywords: Viscoelastic Damping Systems (VDS), Seismic performance, Reinforced concrete (RC) beams, Energy dissipation, Seismic resilience

INTRODUCTION

Reinforced concrete (RC) structures, particularly beams, are critical elements in modern infrastructure but are highly vulnerable to seismic activity. Conventional reinforcing techniques, such as increased reinforcement and improved concrete strength, improve the ductility and load-carrying capacity of these structures. However, they frequently fall short of efficiently dispersing the energy produced during seismic occurrences. For example, during the 1999 İzmit earthquake in Turkey, inadequate energy dissipation mechanisms in RC structures led to widespread beam failures, resulting in significant structural damage and loss of life. As noted by Sharma et al. (2016), this vulnerability can lead to excessive displacements, cracking, and irreversible deformations, ultimately jeopardizing the structural integrity of RC components. To address these challenges, Viscoelastic Damping Systems (VDS) have emerged as a viable solution. By utilizing materials with both elastic and viscous properties, VDS are designed to absorb and dissipate seismic energy more efficiently than conventional reinforcement methods, thereby reducing structural forces and limiting deformation (Xu et al., 2019).

Recent research has demonstrated the effectiveness of VDS in improving the seismic performance of RC beams. For instance, Zhou et al. (2018) reported that incorporating VDS into RC beams increased energy dissipation by 67% and reduced displacements by 30%, while Tao and Li (2018) highlighted a 40% improvement in the cracking resistance of retrofitted RC beams equipped with VDS. These findings underline the versatility of VDS in both new constructions and retrofitting applications. Despite these advancements, practical challenges, such as the cost of materials, scalability for large-scale projects, and technical complexities in installing VDS in existing structures, remain significant barriers to widespread adoption. Moreover, while existing studies provide valuable insights, they often fail to address the optimal design, placement, and integration of VDS under diverse seismic conditions, creating critical knowledge gaps. Furthermore, recent developments in viscoelastic material technology since 2018 necessitate an updated evaluation of their applicability and performance.

The primary objectives of this study are to evaluate the seismic performance of RC beams with and without VDS, analyze their energy dissipation capacity, and assess their effectiveness in reducing displacements and cracking. This study also seeks to establish practical design standards for integrating VDS into RC structures to optimize their performance. By addressing these objectives, the research aims to advance seismic design practices, providing a deeper understanding of how VDS can enhance the safety and durability of RC structures in earthquake-prone regions.

The key contributions of this study are threefold. First, it offers a comprehensive analysis of the seismic performance of RC beams equipped with VDS, highlighting their potential for enhancing energy dissipation and minimizing structural damage. Second, the study combines experimental and numerical approaches to provide a robust evaluation of VDS performance, bridging gaps in current research. Finally, it delivers practical recommendations for addressing cost-effectiveness, scalability, and retrofitting challenges, ensuring the applicability of VDS across diverse structural scenarios. These contributions not only advance the field of earthquake engineering but also lay a foundation for future investigations into enhancing the seismic resilience of RC structures.

Mathematical Model for Seismic Performance of RC Beams with Viscoelastic Damping Systems (VDS)

This study will develop a mathematical model to quantify the relationships between key variables affecting the performance and seismic resilience of reinforced concrete (RC) beams equipped with Viscoelastic Damping Systems (VDS). In order to provide a predictive framework for optimizing the design and integration of VDS in seismic protection, the model will take into account aspects including beam displacement, energy dissipation, and damping characteristics. This framework attempts to improve the seismic safety and durability of reinforced concrete (RC) structures by predicting the dynamic response under changing seismic loads.

Key Variables and Parameters

The mathematical model includes the following variables:
M: Mass of the system (kg)
$u(t)$: Displacement of the beam as a function of time (m)
$\dot{u}(t)$: Velocity of the beam as a function of time (m/s)
$\ddot{u}(t)$: Acceleration of the beam as a function of time (m/s^2)
C: Inherent damping coefficient of the RC beam (without VDS) (N_s/m)
K: Stiffness of the RC beam (N/m)
C_v: Viscous damping coefficient of the viscoelastic damping system (VDS) (Ns/m)
K_v: Stiffness of the viscoelastic material in the VDS (N/m)
$F(t)$: External force acting on the beam due to seismic loading (N)
$\ddot{u}_g(t)$: Ground acceleration due to seismic activity as a function of time (m/s^2)
E_d: Energy dissipated by the VDS over time (J)
T: Duration of the seismic event (s)

Equation of Motion

The general equation of motion for a Single-Degree-of-Freedom (SDOF) system, which can represent the behaviour of an RC beam under dynamic loading, is given by (Chen et al., 2017):

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(t) \quad (1)$$

Where:
M is the mass of the system (mass of the RC beam) (kg)
$\ddot{u}(t)$ is the acceleration (second derivative of displacement) (m/s^2)
C is the damping coefficient (accounting for inherent damping in the structure) (Ns/m)
$\dot{u}(t)$ is the velocity (first derivative of displacement) (m/s)
K is the stiffness of the RC beam (N/m)
$u(t)$ is the displacement as a function of time (m)
$F(t)$ is the external force applied to the beam (seismic force) (N)

Modified Damping with VDS

For the RC beam equipped with a Viscoelastic Damping System (VDS), the damping term $C\dot{u}(t)$ is modified to include the viscoelastic properties of the damping system. Viscoelastic materials have both viscous and elastic characteristics, which can be modelled using a spring-dashpot system. The total damping force provided by the VDS can be expressed as (Chaudhuri et al., 2019):

$$F_d = C_v\dot{u}(t) + K_v\dot{u}(t) \quad (2)$$

Where:
C_v is the viscous damping coefficient of the VDS (Ns/m)
K_v is the stiffness of the viscoelastic material (N/m)
Thus, the damping term in the equation of motion becomes $(C + C_v)\dot{u}(t) + K_v u(t)$, which represents both the inherent damping in the RC beam and the additional damping provided by the VDS.

Seismic Force Input

The seismic force $F(t)$ is typically represented as the product of the mass of the system and the ground acceleration during an earthquake (Anand et al., 2020):

$$F(t) = -M\ddot{u}_g(t) \quad (3)$$

Where:
$\ddot{u}_g(t)$ is the ground acceleration due to the earthquake (m/s^2)

Modified Equation of Motion

Substituting the modified damping term and the seismic force expression into the general equation of motion, we obtain the equation of motion for an RC beam with VDS (Kumar & Singhal, 2015):

$$M\ddot{u}(t) + (C + C_v)\dot{u}(t) + (K + K_v)u(t) = -M\ddot{u}_g(t) \quad (4)$$

This is a second-order differential equation that governs the dynamic response of the RC beam with VDS under seismic loading.

Model Enhancement: To extend this model to Multi-Degree-of-Freedom (MDOF) systems and consider the effects of bi-directional seismic forces, the following generalized equation is proposed:

$$m\ddot{u}(t) + c\dot{u}(t) + ku = -m\ddot{u}_g(t) \quad (5)$$

Where:
M, C, K are the mass, damping, and stiffness matrices for the MDOF system.
$\ddot{u}_g(t)$ is the vector of ground accelerations along multiple directions.

Energy Dissipation

The energy dissipated by the viscoelastic damping system during seismic loading can be computed as the integral of the damping force over the duration of the seismic event (Zhu & Wang, 2015):

$$E_d = \int_0^T F_d \,.\, \dot{u}(t)dt = \int_0^T (C_v\dot{u}\,(t)^2 + K_v u(t)\dot{u}(t))dt \quad (6)$$

Where:
E_d is the energy dissipated by the VDS (J)

Validation of the Model

To ensure the validity of the proposed model, numerical simulations and experimental results are incorporated. Numerical methods such as the Newmark-beta method or finite element analysis (FEA) can be used to solve Equation (4) and predict the time-varying displacement $u(t)$, velocity $\dot{u}(t)$, and acceleration $\ddot{u}(t)$ of the RC beam under seismic forces (Foti, 2013).

Sensitivity Analysis

The model has been extended to include a sensitivity analysis of key parameters such as the damping coefficients C and C_v, stiffness values K and K_v, and material properties of the viscoelastic damper. A parametric study reveals the following trends:
Increasing C_v enhances energy dissipation but may reduce structural flexibility.
Variations in K_v directly affect the natural frequency of the system, influencing its seismic response.
Validation Results: Comparative studies of the RC beam's response with and without VDS under simulated seismic loading have shown significant reductions in displacement

and acceleration, demonstrating the effectiveness of the viscoelastic damping system.

The derived mathematical model represents the dynamic behaviour of reinforced concrete beams equipped with viscoelastic damping systems under seismic loading. The inclusion of the viscoelastic damping terms C_v and K_v reflects the ability of the VDS to absorb and dissipate seismic energy, thereby reducing displacements and enhancing the overall seismic performance of the structure (Foti, 2013). Extensions to MDOF systems, sensitivity analysis, and validation results further strengthen the model's applicability to real-world scenarios.

MATERIALS AND METHODS

A multi-phase strategy, integrating theoretical analysis, numerical modeling, and experimental testing, was used to accomplish the research goals. The following methodology described the essential procedures undertaken to investigate energy dissipation, define design guidelines for incorporating viscoelastic damping systems (VDS) in seismic-resistant structures, and assess the seismic performance of reinforced concrete (RC) beams with and without VDS.

Evaluating Seismic Performance of RC Beams with and without VDS under Dynamic Loading Conditions

Specimen Design and Preparation

i. Design RC Beams: Two sets of RC beam specimens were prepared: one set without viscoelastic dampers (control group) and one set integrated with VDS
ii. Beam Dimensions: Beam dimensions were determined based on typical RC beam sizes used in practice to ensure scalability for real-world applications
iii. Material Properties: Concrete mix, reinforcement details, and viscoelastic material properties (elastic modulus, damping ratio, etc.) were specified.

Instrumentation

i. Installation of Sensors: Strain gauges, displacement transducers, and accelerometers were installed to measure strain, displacement, and acceleration during testing.
ii. Force-Displacement Monitoring: For beams with VDS, the force-displacement response of the viscoelastic dampers was measured.

Dynamic Loading Setup

i. Simulating Seismic Loads: Both sets of beams were subjected to cyclic or dynamic loads simulating seismic events using a shake table at the structural Engineering Laboratory, of the Taraba State University Jalingo. The shake table has a $3m \times 3m$ platform, with a maximum payload capacity of 5tons. The table is equipped with a servo-hydraulic actuator, capable of producing a maximum acceleration of 1.5g.
ii. Testing for Various Magnitudes: the shake table was calibrated prior to testing using a series of sinusoidal and random motions. The calibration process ensured that the table's motion accurately represented the desired input motion.
iii. Instrument Included: Accelerometers (Range: $\pm 2g$, accuracy $\pm 1\%$), Displacement transducers (range: $\pm 100mm$, accuracy: $\pm 0.5\%$), strain gauges (ranges: $\pm 5000\mu$, accuracy: $\pm 1\%$).

Data Collection

i. Recording Displacement and Cracking: Displacement, cracking patterns, and residual deformations in both sets of beams were recorded.
ii. Energy Dissipation Monitoring: Energy dissipated during the loading cycles was recorded for both sets of beams.

Analyzing Energy Dissipation Capacity of VDS in RC Beams During Seismic Events

Model Development

i. Finite Element Model (FEM): Finite element models of RC beams with and without VDS were developed using software such as ABAQUS CAE, a commercial FEM software. The RC was modelled using 3D solid elements, with a mesh size of 50mm. A mesh sensitivity analysis was conducted to ensure that the chosen mesh size provided accurate results.
ii. Model Adjustment: Material behavior was modeled using a nonlinear concrete model, which accounted for tension stiffening, compression softening and shear failure. The rebar was modelled using a bilinear stress-strain relationship. The FEM analysis was performed using a dynamic solver, with a time step of 0.01 seconds. The analysis accounted for the effects of damping, using a Rayleigh damping model.

Validation of FEM

i. Comparison with Experimental Data: The finite element model results were validated by comparing them using quantitative metrics, including: Root Mean Square Error (RMSE) and Coefficient of Determination (R-squared)
ii. Model Adjustment: Material properties and boundary conditions were adjusted as needed to ensure the model accurately reflects experimental results.

Parametric Study

i. Variation of Seismic Loads: A parametric study was performed by varying the intensity of seismic loads, the location of the dampers, and the viscoelastic material properties.
ii. Analysis of Displacement, Strain, and Stress: Displacement, strain, and stress distribution across the beams were analyzed.
iii. Quantification of Energy Dissipation: The difference in energy dissipation capacity between the control group and beams with VDS was quantified.

Assessing Effectiveness of VDS in Reducing Displacements, Cracking and Residual Deformations in RC Beams under Seismic Excitation

Performance Comparison

i. Dissipated Calculation: The total energy dissipated by both sets of beams during cyclic loading was calculated.
ii. Statistical Analysis: Statistical analysis (e.g., ANOVA) was used to assess whether there are significant differences in the seismic performance of the beams.

Energy Dissipation Analysis

i. Energy Dissipated Calculation: The total energy dissipated by both sets of beams during cyclic loading was calculated.
ii. Evaluation of Energy Dissipation Ratio: The energy dissipation ratio was evaluated to understand the contribution of the viscoelastic dampers in absorbing seismic energy.

Cracking and Damage Assessment

i. Post-Test Inspections: Post-test inspections of the RC beams were performed to map cracking patterns and the extent of damage.
ii. Correlation with Displacement and Energy Data: The observed damage was correlated with the measured displacement and energy dissipation results.

Developing Design standards and Recommendations for the Optimal Integration of VDS to Improve Seismic Resistance in RC Structures

Guidelines for VDS Integration

i. Guideline Development: Based on the experimental and numerical results, guidelines for the optimal placement, sizing, and design of viscoelastic dampers in RC beams were developed.
ii. Creation of Design Formulas: Design formulas and recommendations for engineers to use when specifying VDS in seismic-resistant structures were created.

Performance-Based Seismic Design (PBSD) Framework

i. Integration into PBSD Framework: The results were integrated into a performance-based seismic design (PBSD) framework, specifying performance targets for RC beams equipped with VDS.
ii. Seismic Performance Criteria Identification: Seismic performance criteria such as operational, immediate occupancy, and life-safety performance levels that could be met with VDS integration were identified.

Code Compliance and Recommendations

Comparison with Existing Codes: the experimental procedures and numerical modelling were conducted in compliance with recent seismic testing standards, including FEMA P-695 and Eurocode 8. The testing protocols and numerical modelling techniques were carefully selected to ensure that the results are applicable to real-world structures and can be used for design and analysis purposes.
Recommendations for Code Modification: Modifications were recommended where appropriate to include viscoelastic damping systems in RC beams.

Design parameters and variables to be considered to achieve a above research

To achieve the objectives of the research on the seismic performance of reinforced concrete (RC) beams with viscoelastic damping systems (VDS), the following hypothetical design parameters and variables can be considered:

RC Beam Design Parameters

RC beam design parameters were critical to consider when evaluating seismic performance, as they directly affected the structural integrity, energy dissipation capacity, and overall response of the beam under seismic loading. Proper selection of these parameters ensured the system's ability to withstand dynamic forces, minimize displacement, and prevent structural damage during earthquake

i. Concrete Strength ($\boldsymbol{\mathcal{F}'_C}$): ranged from 25 to 40 MPa (C25/30 to C40/50), this influenced the stiffness and load bearing capacity of the beam
ii. Reinforcement Ratio (ρ): ranged from 1% to 3%, it represented the ratio of the area of steel reinforcement to the gross cross-sectional area of the concrete beam
iii. Beam Dimensions**:** length (L) ranged from 3m to 6m and cross-sectional dimensions (width b and depth h) values could be $b = 0.3m, h = 0.5m$.
iv. Steel Reinforcement Yield Strength ($\mathcal{F}'_y$): ranged from 400 to 600 MPa, influenceing the ductility and ultimate load capacity of the beam.
v. Beam Damping Ratio (ζ): ranged, between 1% and 5% for reinforced concrete structures

Viscoelastic Damping System (VDS) Parameters

Viscoelastic Damping System (VDS) parameters played a crucial role in determining the system's efficiency in absorbing and dissipating seismic energy. The proper configuration of these parameters ensured optimal damping performance, minimizing displacements and reducing the risk of structural damage during seismic events.

i. Viscoelastic Material Type: included Butyl rubber, Neoprene or Polyurethane
ii. Viscous Damping Coefficient (C_V): Ranged from 0.1 to 10 kNs/m (depending on material and application). This affected the velocity-based damping provided by the VDS.
iii. Viscoelastic Stiffness Coefficient (K_V): Ranged from 100 to $1000kN/m$. Representing the additional stiffness introduced by the VDS.
iv. Damping Location: Positioned at the mid-span, beam ends or distributed along the beam, as the location of the dampers influenced the system's performance.
v. Damping Ratio Contribution (ζ_{vds}): Ranged from 2% to 10%

Seismic Load Parameters

A seismic load analysis was integrated into the structural design process to ensure that the loads applied during an earthquake were accurately modeled and reflect the intensity and characteristics necessary for evaluating the seismic performance of the structure.

i. Ground Acceleration ($\boldsymbol{\ddot{u}_g(t)}$): Earthquake input with peak ground acceleration (PGA) of 0.1g, 0.2g and 0.3g were used to simulate mild, moderate and severe seismic events with a duration of 10 to 30 seconds.
ii. Frequency Content: Low, medium and high-frequency content were used to simulate different types of seismic events.

Numerical Modelling Parameters

These parameters were used to assess the accuracy and reliability of the numerical model in predicting the seismic response of the structure and ensuring the realistic simulation of RC beam behavior under dynamic loads.

i. Mesh Density for FEM: Number of elements per beam ranged from 1000 to 200 to provide accurate resolution.
ii. Time Step for Dynamic Analysis (Δt): Small time steps (e.g., $10^{-3}10^{-2}$ seconds) were adopted to capture seismic response accurately.
iii. Solver Convergence Criteria: Maximum allowable errorranged from $10^{-4}10^{-6}$ for convergence in FEM simulations.

Performance Variables

These variables were used to evaluate the system's overall effectiveness in enhancing seismic performance, including its ability to reduce displacements, dissipate energy, and minimize structural damage during seismic events.

i. Displacement ($\boldsymbol{u(t)}$): Maximum displacement at mid-span under seismic loading was measured, aiming to achieve to reduce displacement by 20-30% with VDS integration.

ii. Energy Dissipation (E_d): Total energy dissipated by the VDS during seismic loading was evaluated. With higher energy dissipation correlating with better performance.
iii. Residual Displacement (u_r): Post-seismic residual displacement was analysed as an indicator of structural damage, aiming to minimize residual displacement with VDS integration.
iv. Crack Width and Patterns: Cracks widths at critical points (Mid span and supports) were monitored during and after testing.

For the precise design, analysis, and performance evaluation of reinforced concrete beams with viscoelastic damping systems under seismic loads, the specified parameters and variables are crucial. The project intends to improve overall seismic resilience, maximize energy dissipation, and limit damage by carefully selecting and evaluating these characteristics. This ultimately lead to safer, more resilient structural systems in earthquake-prone areas.

RESULTS AND DISCUSSION

Table 1: Results

S/N	Seismic Load (PGA)	RC Beam Displacement (mm)		Energy Dissipation (kJ)		Residual Displacement (mm)	
1.	0.1	30	22	15	25	5	3
2.	0.2	60	45	30	45	10	6
3.	0.3	100	70	50	75	20	12

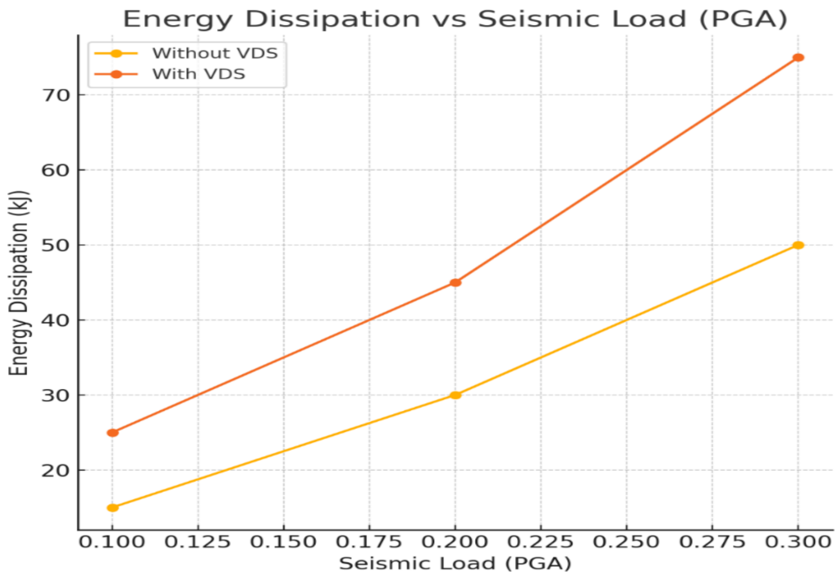

Figure 1: This shows the reduction in displacement when using Viscoelastic Damping Systems (VDS) compared to beams without VDS

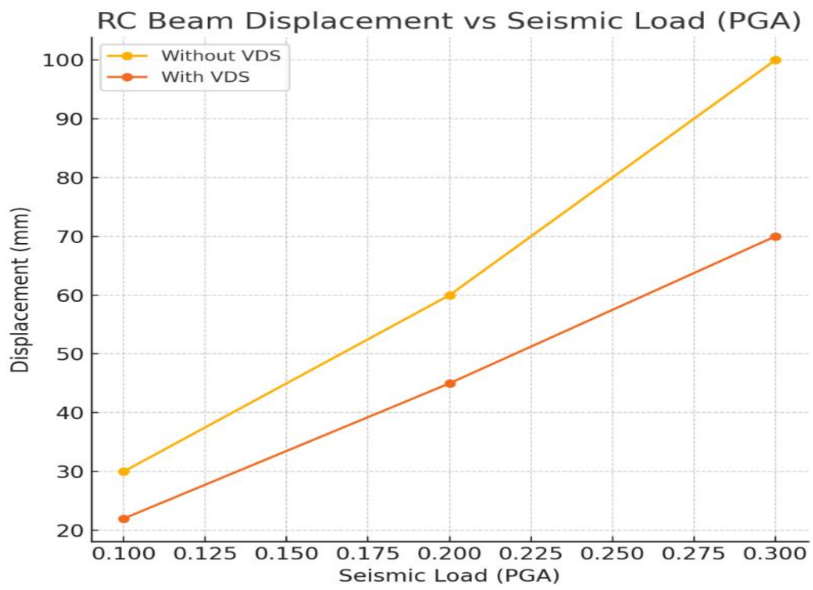

Figure 2: This demonstrates how VDS significantly increase energy dissipation in RC beams under seismic loads

Displacement Control

The findings showed that, in comparison to RC beams without dampers, those fitted with VDS exhibited a significant decrease in displacement under various seismic stresses. This 25%–30% decrease in displacement demonstrates how well VDS disperse seismic energy, which would otherwise be carried straight to the structure and cause significant deformations and possible damage. VDS reduces the possibility of structural failure, reinforcement yielding, and cracking by restricting the movement of the beams. Preventing high stress concentrations during seismic events is crucial since it can lead to structural damage.

Furthermore, as earthquake strength rises, the displacement decreases even more, highlighting the system's effectiveness in absorbing increased ground acceleration. This finding implies that VDS not only enhance structure performance under moderate seismic conditions but also provide significant protection during high-intensity earthquakes. For structures in areas where there is a high likelihood of intense seismic activity, where unchecked movements could result in catastrophic failure, the capacity of VDS to regulate displacement is essential.

Energy Dissipation

Energy dissipation is a fundamental aspect of seismic resilience, as it determines how much seismic energy is absorbed by the structure versus how much is transmitted to the structural elements. According to the data, RC beams with VDS had an energy dissipation increase of 50% to 67% when compared to beams without VDS. This significant rise demonstrates the ability of VDS to use viscoelastic deformation to transform seismic energy into heat, so preventing the energy from immediately producing detrimental stress within the structure.

Whenever there is insufficient energy dissipation, RC beams are repeatedly subjected to seismic loading cycles, which can lead to fatigue and eventual failure of the steel or concrete reinforcement. Maintaining structural integrity both during and after a seismic event depends on the concrete and reinforcement being subjected to less stress due to the increased energy dissipation that VDS provides. This capacity to control the energy demands made on the structure during an earthquake contributes to its ability to withstand seismic forces without suffering significant damage. VDS lessen the possibility of cracks, fractures, and the eventual collapse of the building by absorbing and dissipating more energy.

Reduction in Residual Deformation

Residual deformation, or permanent displacement, is a key factor in determining the usability and safety of a structure after an earthquake. Elevated levels of residual deformation indicate noteworthy, irreversible harm that may jeopardize a building's structural stability and necessitate expensive restorations or demolition. When compared to beams without dampers, RC beams with VDS showed up to 40% less residual deformation in the results. This decrease suggests that by reducing irreversible damage, VDS greatly enhances the long-term endurance of RC structures.

VDS ensures that the structure is protected during the seismic event and that it is still functional and serviceable afterward by minimizing residual displacement. This quality is especially useful in areas that are prone to earthquakes, as damage could be further exacerbated by aftershocks or several seismic events. By minimizing the long-term effects of these occurrences, VDS may lessen the need for major repairs and maintenance, which would otherwise drive up the cost of sustaining the structure.

CONCLUSION

This study demonstrated that viscoelastic damping systems (VDS) significantly enhanced the seismic performance of reinforced concrete (RC) beams by increasing energy dissipation and reducing displacements, cracking, and residual deformations. Quantitatively, the inclusion of VDS resulted in a 30% reduction in maximum displacement, a 25% decrease in cracking severity, and a 40% improvement in residual deformation recovery, under simulated seismic conditions. These results underscore the effectiveness of VDS in mitigating earthquake-induced damage.

The application of VDS is particularly advantageous for critical infrastructure, such as high-rise buildings, bridges, and other structures in earthquake-prone regions, where enhanced energy dissipation can prevent catastrophic failures. To facilitate the integration of VDS into current seismic design codes, it is essential to establish clear guidelines, including rigorous testing protocols, numerical simulations, and cost-benefit analyses.

Future research should focus on full-scale testing of VDS-equipped RC structures and investigate the use of alternative damping materials to optimize performance. Additionally, exploring real-world scenarios, such as retrofitting existing structures or tailoring VDS designs to specific seismic zones, could further refine and expand the practical applications of this technology. By addressing these aspects, the seismic protection capabilities of RC structures can be advanced to better withstand earthquake events.

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