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Machine Learning-Based Prediction of Seismic Response in Buildings with Hybrid Dampers

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ABSTRACT: Earthquakes are among the most significant hazards affecting the safety and serviceability of civil infrastructure. Conventional earthquake-resistant design primarily relies on the strength, stiffness, ductility, and energy-dissipation capacity of structural members. However, increasing structural heights, irregular configurations, higher performance requirements, and uncertainties associated with earthquake ground motions have encouraged the development of supplemental vibration-control technologies. Damping systems provide an effective mechanism for dissipating seismic energy and reducing structural responses such as displacement, inter-storey drift, acceleration, and base shear. Hybrid damping systems, which combine two or more damping or vibration-control mechanisms, can provide complementary advantages compared with individual damping devices. Hybrid systems may combine passive devices such as viscous dampers, friction dampers, and tuned mass dampers, or may incorporate passive, semi-active, and active control mechanisms. Previous research has demonstrated the potential of hybrid vibration-control systems for reducing seismic and wind-induced structural responses.

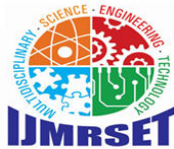
KEYWORDS: Machine Learning; Seismic Response; Earthquake Engineering; Hybrid Dampers.

I. INTRODUCTION

Earthquake-resistant structural design is one of the most important areas of modern civil and structural engineering. Earthquake ground motions impose dynamic forces on buildings that can produce large lateral displacements, inter-storey deformation, acceleration, member forces, and energy demands. When these demands exceed the capacity of structural components, significant damage can occur. In severe cases, structural damage may lead to partial or complete collapse. Consequently, the fundamental objective of seismic engineering is not only to prevent collapse but also to control structural damage and maintain acceptable levels of performance during and after earthquake events. Traditional seismic design approaches generally depend on the inherent strength, stiffness, and ductility of structural systems. Structural members are proportioned to resist expected seismic forces while allowing controlled inelastic deformation where appropriate. Although this approach remains fundamental to earthquake-resistant design, structural control technologies provide an additional means of improving seismic performance. Supplemental damping devices can absorb and dissipate part of the energy introduced into a structure by earthquake excitation, thereby reducing the amount of energy that must be dissipated through structural damage.

Damping can be introduced through various mechanisms. Viscous dampers dissipate energy through velocity-dependent resistance, while friction dampers dissipate energy through controlled sliding. Tuned mass dampers use an auxiliary mass, spring, and damping mechanism to modify the dynamic response of the primary structure. Other systems include viscoelastic dampers, metallic yielding devices, inerters, base-isolation systems, and semi-active or active control devices. The combination of two or more such mechanisms is commonly referred to as hybrid vibration control. A review published by ASCE describes hybrid vibration-control systems as combinations involving passive, active, and/or semi-active control mechanisms and discusses passive-passive, passive-semi-active, and passive-active configurations.

The concept of hybrid structural control is particularly attractive because individual damping technologies have different operating characteristics. A viscous damper, for example, can provide significant energy dissipation but its response is strongly related to velocity. A friction damper provides stable energy dissipation through sliding but may introduce nonlinear force-displacement characteristics. A tuned mass damper is effective when appropriately tuned to structural vibration characteristics but may experience changes in effectiveness when the structural properties vary.



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Combining these technologies may allow their respective advantages to complement one another. Early research demonstrated the potential of hybrid control systems for seismic protection. Yang, Danielians, and Liu proposed hybrid control systems combining base isolation with active or passive mass damping and investigated their ability to reduce the response of tall buildings subjected to strong earthquakes. Subsequent developments have produced increasingly sophisticated combinations of passive, semi-active, and active technologies.

Despite the development of these systems, predicting the seismic response of damped structures remains challenging. Earthquake excitation is inherently variable, and structural response depends on several interacting parameters. These include the amplitude and frequency content of ground motion, structural stiffness, mass distribution, natural periods, damping characteristics, nonlinear material behaviour, damper properties, damper locations, and structural irregularities. The nonlinear behaviour of damping devices can further increase the complexity of dynamic analysis. Conventional nonlinear time-history analysis is therefore computationally demanding. If a researcher wants to examine hundreds or thousands of combinations of earthquake records, structural properties, and damping configurations, a very large number of simulations may be necessary. This problem becomes more significant when optimization is included. For example, determining the appropriate damping coefficient, friction force, tuned frequency, damper mass ratio, and damper location may require repeated structural analyses.

Machine learning provides a potential solution to this computational challenge. Machine learning algorithms identify relationships between input and output data without requiring an explicit analytical equation for every relationship. In structural engineering, ML has been applied to structural response prediction, performance assessment, damage detection, structural health monitoring, and design optimization. Reviews of ML applications in building structural engineering have identified structural response prediction as one of the major application areas. Recent studies have specifically demonstrated the feasibility of using ML to predict seismic responses of damped structures. A 2024 Engineering Structures study used a large database generated from numerical simulations of a damped steel frame and compared seven interpretable ML methods with deep-learning approaches for predicting maximum inter-storey displacement. This demonstrates that data-driven models can potentially act as computationally efficient surrogate models for conventional dynamic analysis.

II. LITERATURE REVIEW

The development of earthquake-resistant structures has progressed from conventional strength-based approaches toward performance-based design and structural control. Supplemental damping and vibration-control technologies have become important components of this development. At the same time, advances in artificial intelligence and machine learning have created new possibilities for predicting structural behaviour. This section reviews research related to hybrid damping systems, seismic response prediction, machine learning in structural engineering, and the integration of these technologies.

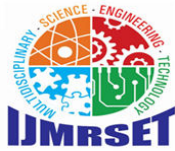
Supplemental Damping Systems

Supplemental damping systems are designed to increase the energy-dissipation capacity of a structure. During an earthquake, part of the seismic energy entering a building can be dissipated through damping devices rather than through irreversible damage to primary structural members. Fluid viscous dampers are one widely studied technology. They generate resisting forces related to the relative velocity across the device and have been applied both in new structures and seismic retrofitting. Friction dampers operate using controlled friction between structural components. They can exhibit nonlinear force-displacement behaviour and dissipate energy through repeated sliding. Tuned mass dampers operate differently: they use a secondary mass system tuned to selected structural frequencies. Their effectiveness depends on the relationship between the damper's dynamic characteristics and the structure's modal properties.

A major advantage of combining different devices is that their response mechanisms can complement each other. Hybrid damping systems may therefore provide a broader range of response control than a single device.

Hybrid Vibration-Control Systems

Hybrid vibration-control systems have received substantial research attention. Stanikzai, Elias, and Chae reviewed developments in hybrid vibration control and classified systems into passive-passive, semi-active-passive, and active-



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passive categories. Their review highlighted potential advantages of hybrid systems while also identifying challenges related to weight, size, cost, maintenance, and design complexity. An important historical contribution was made by Yang, Danielians, and Liu, who proposed hybrid seismic-control systems combining base isolation with mass dampers. Their theoretical and numerical investigation showed the potential of such combinations for reducing the response of tall buildings under strong earthquake excitation. More recent research continues to explore combinations involving tuned mass dampers, viscous damping, friction isolation, and inerter-based systems. For example, recent work has investigated optimized combinations of friction isolation and tuned viscous mass damping for base-isolated buildings. These developments demonstrate that hybrid control is not restricted to one particular damper combination. Instead, the term represents a broader design philosophy in which multiple mechanisms are combined to address different aspects of structural vibration.

Machine Learning in Structural Engineering

Machine learning has increasingly been applied to structural engineering because structural behaviour often involves nonlinear relationships that can be difficult to represent using simple analytical equations. ML algorithms can learn relationships directly from numerical simulations, laboratory experiments, monitoring data, or combinations of these sources. Sun, Burton, and Huang reviewed ML applications in building structural design and performance assessment. Their review identified structural response prediction, experimental-data interpretation, information retrieval, and structural-health-monitoring applications as major categories. The authors also highlighted challenges involving data availability, explainability, and overfitting. ML methods applicable to structural engineering include linear and nonlinear regression, decision trees, Random Forest, Support Vector Machines, Artificial Neural Networks, gradient boosting, convolutional neural networks, recurrent neural networks, and transformer-based approaches.

Different algorithms offer different advantages. Linear regression is easy to interpret but may be inadequate for strongly nonlinear behaviour. Decision trees can represent nonlinear relationships, while Random Forest improves robustness by combining multiple decision trees. Gradient-boosting methods such as XGBoost can capture complex nonlinear relationships and interactions between variables.

III. MATERIAL AND METHODS

Research Framework

The methodology consists of five principal stages:

Structural modelling → Earthquake simulation → Dataset generation → Machine-learning development → Model evaluation

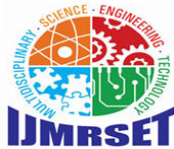
The research begins with the development of a numerical building model. The building is subsequently equipped with a hybrid damping system and subjected to multiple earthquake records. The resulting structural responses form the dataset used for machine-learning development.

Structural Model

A multi-storey reinforced-concrete or steel building can be selected as the reference structure. For a thesis-level numerical investigation, a building containing approximately 10–20 storeys may provide sufficient structural complexity while remaining computationally manageable.

The model should include:

- Building height
- Number of storeys
- Storey mass
- Column and beam stiffness
- Floor diaphragm characteristics
- Material properties
- Structural damping
- Fundamental natural period
- Modal properties
- Boundary conditions



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The structure can be modelled using structural-analysis software such as ETABS, SAP2000, or OpenSees. OpenSees is particularly suitable when detailed nonlinear dynamic modelling and automated parametric analysis are required.

Earthquake Ground Motions

A representative set of earthquake ground motions should be selected to cover a range of amplitudes and frequency characteristics. Ground-motion records can be scaled or selected according to the requirements of the research framework and applicable seismic provisions.

Important earthquake parameters include:

- Peak Ground Acceleration (PGA)
- Peak Ground Velocity (PGV)
- Peak Ground Displacement (PGD)
- Spectral acceleration
- Significant duration
- Arias intensity

IV. DATA ANALYSIS

Descriptive Analysis

The first stage of analysis involves examining the distribution of the generated seismic-response dataset. Descriptive statistics should be calculated for every input and output variable. These statistics include minimum, maximum, mean, median, standard deviation, and coefficient of variation. The analysis is important because seismic response variables can have highly non-uniform distributions. For example, maximum inter-storey drift may remain relatively small under low-intensity earthquakes but increase rapidly as earthquake intensity increases. Similarly, damper forces may increase significantly when relative velocities or displacements become large. Histograms and probability-density plots can be used to visualize the distributions. Scatter plots can be used to examine relationships between individual input variables and structural response.

For example, a plot of PGA against maximum inter-storey drift is expected to provide information about the general relationship between earthquake intensity and structural deformation. However, the relationship is unlikely to be perfectly linear because structural response also depends on frequency content, structural period, damping properties, and nonlinear behaviour.

Correlation Analysis

Pearson or Spearman correlation analysis can be used to determine the relationship between input variables and response variables.

For example, maximum inter-storey drift may show positive correlation with PGA and spectral acceleration. The relationship between damping coefficient and response may be negative over an appropriate parameter range because increasing supplemental damping generally increases energy dissipation.

However, correlation should not be interpreted as proof of causation. A variable with moderate individual correlation may still be important because it interacts with other variables.

A correlation matrix can therefore be prepared for:

- PGA
- PGV
- spectral acceleration
- fundamental period
- number of storeys
- damping coefficient
- friction force
- damper location
- maximum displacement
- maximum IDR



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- base shear
- floor acceleration.

V. RESULT AND DISCUSSION

5.1 Overview

The results of the proposed investigation should be presented in two complementary parts. The first part evaluates the effect of hybrid damping on structural seismic response. The second part evaluates the ability of machine-learning models to predict the resulting response. Because the actual numerical dataset is not supplied here, the discussion below is written as a **results framework** rather than as fabricated experimental findings.

5.2 Effect of Hybrid Damping

The numerical structural analyses are expected to demonstrate that the incorporation of supplemental damping modifies the dynamic response of the building. Compared with an uncontrolled building, a properly designed hybrid damping system can increase energy dissipation and reduce selected response quantities. The most important parameters for evaluation are maximum roof displacement, maximum inter-storey drift, base shear, floor acceleration, and damper force. Roof displacement provides an indication of the overall lateral movement of the building. Inter-storey drift is particularly important because excessive drift can cause structural and non-structural damage. Therefore, maximum IDR should be treated as one of the principal engineering demand parameters.

The response of the hybrid system should also be examined against individual damping systems. For example, three configurations may be considered:

- Building without supplemental damping
- Building with viscous damping
- Building with hybrid viscous-friction damping.

This comparison allows the contribution of the hybrid configuration to be quantified.

VI. CONCLUSION

The present study proposes a machine-learning-based framework for predicting the seismic response of buildings equipped with hybrid damping systems. The research combines two important developments in modern structural engineering: supplemental vibration control and data-driven prediction. Hybrid damping systems provide an opportunity to improve structural seismic performance by combining the energy-dissipation mechanisms of different devices. Viscous dampers, friction dampers, tuned mass dampers, and other control technologies have different response characteristics. Their combination can therefore provide a flexible approach to reducing structural response under dynamic excitation. Previous studies have demonstrated the potential of hybrid systems for seismic and wind response mitigation. The proposed methodology begins with the development of a numerical building model. The structure is equipped with a selected hybrid damping configuration and subjected to a diverse collection of earthquake ground motions. The resulting nonlinear dynamic analyses generate a database containing structural properties, earthquake intensity measures, damping parameters, and seismic response quantities. The database forms the foundation of the machine-learning component of the research. Several supervised-learning algorithms can be trained to establish relationships between the input parameters and engineering demand parameters. Maximum roof displacement, maximum inter-storey drift ratio, base shear, floor acceleration, and damper force are appropriate target variables for the proposed analysis. The study proposes comparison among Multiple Linear Regression, Random Forest, Support Vector Regression, Artificial Neural Networks, and XGBoost. Their performance can be evaluated using R^2 , MAE, RMSE, and MAPE.

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