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EXTENDED ABSTRACT

Seismic Control of Structures Based on the Controllability and Stability of the Controlling System Criteria

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1. Introduction

In the present paper, the effect of controllability and control system stability was investigated. For this purpose, three, six, ten, and twenty-one-story structural models equipped with Chevron braces, viscous fluid dampers, and active regulators were selected in uncontrolled, passive-controlled, and hybrid-controlled structures. In order to stabilize the hybrid control system, the linear quadratic regulator algorithm was utilized to calculate the state feedback gain matrix and actuator response. Broadly, the results revealed that if a sufficient number of braces, dampers, and actuators are utilized in the stabilized hybrid control system, the response of braces and dampers is converged and the seismic displacement of braces and floors is decreased properly.

2. Dynamics and Control Methodology

This paper begins by elucidating the equation of motion for structures with n degrees of freedom, followed by introducing the state-space model as a mathematical framework for dynamic systems depiction. Structural buildings are represented as time-invariant linear systems within this model, with state equations defined by distinct parameters. Matrices for characterizing the state space are computed based on mechanical attributes, then applied in seismic control methodologies (Xu et al., 2016). The state feedback gain matrix derivation utilizes the Linear Quadratic Regulator (LQR) algorithm (Ghaffarzadeh et al., 2015; Xu et al., 2017; Chacko et al., 2022). Controllability denotes a structure's ability to confine seismic responses and revert post-earthquake. Its assessment involves scrutinizing matrices and strategically deploying control forces across floors. Stability relies on minor fluctuations in ground motion or structural variables not inducing significant system dynamics shifts (Xu et al., 2016).

2.1. Simulation and stability analysis

This study undertook a systematic evaluation of the seismic response within a controlled system. Initially, the structural model was developed without any control measures. Subsequently, key parameters and equations governing motion were incorporated into the model. Using MATLAB, essential matrices were computed for simulation purposes. Simultaneously, an analysis of the structure's controllability was conducted, alongside an exploration of diverse seismic control methodologies. Ensuring structural safety and post-earthquake functionality were prioritized, assuming linear structural behavior and negligible axial stiffness of dampers. The study culminated in a comprehensive simulation, integrating provided data and assumptions, to assess the stability of the dynamic system facilitated by seismic response mitigation tools.

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2.2. Structural models

In assessing the seismic response of building structures regarding controllability and stability within the control system framework, employing diverse models is essential. These models should include controllable nominal models as well as those with stable and unstable control systems, encompassing both inactive and semi-active control states. For this investigation, the Chevron brace system equipped with a viscous fluid damper served as the inactive control mechanism, while the hybrid configuration incorporated an active controller or actuator into the structural seismic control system. Structural models of varying heights (3, 6, 10, and 21 stories) were analyzed in three states: uncontrolled primary structure, structure with inactive control, and structure with hybrid or combined control. Control mechanisms were positioned differently across various levels of the structure. The study aimed to explore structural controllability and stability concepts within control systems, assessing their impact on seismic responses such as displacement time histories and forces exerted by control mechanisms on structure floors. MATLAB software facilitated the simulation of selected models, following the specification of assumptions, boundary conditions, and mechanical and geometrical details. Figure 1 provides an illustrative overview of the selected models.

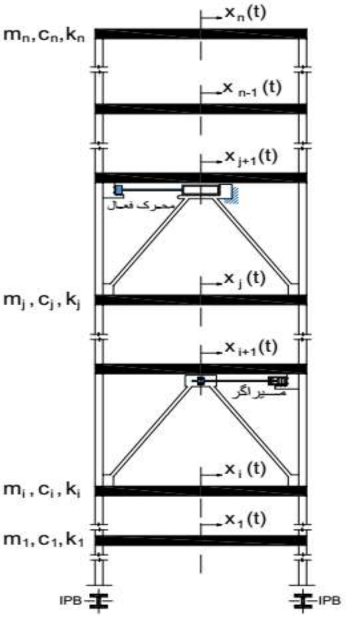

Fig. 1. Overview of Structural Models

3. Results and discussion

3.1. Seismic Responses of Three-Story Models

This section analyzes the seismic response history of three-story structures (Models 1 through 4), encompassing various parameters such as floor displacements, brace displacements, brace forces, and active control forces. The assessment begins with Model 1's controllability and stability, followed by an examination of its seismic response. Similar evaluations are then conducted for models equipped with control mechanisms, revealing that passive control of brace displacements and forces led to instability during earthquakes, which was mitigated by employing active control, resulting in reduced responses. Noteworthy reductions in floor displacements were observed in controlled states compared to uncontrolled ones. However, Model 4, utilizing hybrid control, exhibited divergent responses, indicating inefficiency. Numerical data is provided to elucidate the performance of different control strategies on three-story structures.

3.2. Seismic Responses of Six-Story Models

This segment extends the investigation to six-story structures (Models 5 through 8), following the evaluation framework applied to three-story models regarding controllability and stability. Seismic responses, particularly concerning floor displacements, are analyzed for Models 5, 6, and 7, highlighting the predominant impact of passive control on first-floor displacement, while hybrid control led to reductions across all floors. Model 8, relocating the actuator to the third floor, emphasizes the importance of consolidating control mechanisms on a single floor for effective seismic response management. Additionally, the influence of control mechanism placement on displacement is discussed, along with illustrations depicting seismic responses of various control components, emphasizing the impact of the actuator's positioning on response dynamics. Comprehensive numerical data is provided for comparative analysis of seismic responses for six-story models.

3.3. Seismic Responses of Ten-Story Models

This section investigates the efficacy of stable passive control systems and compares them with unstable passive and stable hybrid control systems in ten-story structures (Models 9 through 12). Seismic response analyses are conducted, initially evaluating the controllability and nominal stability of the uncontrolled structure. Models 10 and 11, configured with unstable passive and stable hybrid control systems, respectively, demonstrate significant reductions in floor displacement responses under stable hybrid control compared to the uncontrolled structure. Model 12 introduces variations in brace and damper placements, resulting in stability as indicated by the negative real parts of the structure's system matrix, particularly with a brace installed on the sixth floor. Illustrations depict seismic responses of control components, emphasizing discrepancies in first-floor brace and damper forces under unstable passive control. Furthermore, response time history plots for the ten-story models are provided, accompanied by corresponding numerical values for detailed analysis.

3.4. Seismic Responses of Twenty-One-Story Models

Concluding the discussion, a 21-story structure is selected in accordance with Models 13, 14, and 15, deploying various control mechanisms on different floors to mitigate seismic responses. The assessment begins with evaluating the controllability and nominal stability of the uncontrolled structure, followed by addressing instability through the establishment of a stabilized hybrid control system. The significant reduction in seismic responses with the stable hybrid control system is demonstrated through comparisons with the inactive control system. Illustrations and analyses of seismic responses highlight the effectiveness of both active and inactive control mechanisms within the hybrid system. Finally, an analysis of seismic responses of the 21-story models underscores the substantial reduction achieved with the stable hybrid control system.

4. Conclusions

In seismic control strategies, the initial configuration significantly influences the efficacy of passive, semi-active, and active control methods. To ensure effectiveness, structural parameters and control device placement, such as mass, stiffness, and damping, must be carefully considered. Initial steps involve expressing controllability concepts and forming matrices for nominal models. Given the impact of control device number and placement on system behavior, ensuring the effective performance of selected control systems is paramount. This research emphasizes stability as a key descriptor of control system performance. It investigates models with stable and unstable control systems, particularly focusing on the secondary dynamic system resulting from integrating primary structures with seismic control devices. Key findings are highlighted.

The study's conclusions underscore the critical influence of control device number and placement on the dynamic behavior of secondary systems, highlighting the imperative to address stability and instability separately in each structure according to its intended control system. Stability in the control system is identified as crucial for facilitating the proper performance of energy absorption and dissipation devices, resulting in significant reductions in seismic responses, thus emphasizing the necessity of ensuring stability in each structure's control system. Furthermore, the study advocates for avoiding the utilization of unstable control systems due to the notable increase in seismic responses observed in certain floors. Additionally, in structures employing inactive control systems, careful positioning of restraint and energy absorption devices is essential to maintain system stability. Lastly, the simultaneous installation of actuators and control devices on the same floor is recommended to mitigate increased shear force and displacement, which may occur when the actuator is separated from the inactive control device.

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