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Optimum performance of structural control with friction dampers

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ABSTRACT

Friction-based structural control is an available strategy for reducing the seismic response of buildings. The friction dampers in such systems can be operated using passive and semiactive control. Passive dampers with constant, pre-defined capacity are effective and simple, but their adaptability to a broad range of frequency excitations is limited and their optimal configuration is complex. Semiactive control provides a means to vary the dampers' capacity to their optimum levels in real-time, but time delays in the control action may affect their performance. In this investigation, a passive system is initially introduced in a multi-storey steel frame to identify a threshold of optimum control force demand related to the limits of the building's elastic response. A new semiactive algorithm is then introduced to adjust the dampers' capacity based on the current deformation state across the building. From simulations of the non-linear response of the frame, the semiactive system reduced the structural response to levels similar to the optimum passive control, with more uniform distributions of storey drift. The control system had optimum performance when a range of time delays was included to simulate different regulator mechanisms.

1. Introduction

A mechanism for dissipation of the seismic energy exerted in buildings during strong earthquakes is through damage at specific locations in the structure. The damage, in the case of moment resistant frames, develops in the form of plastic hinges at the ends of beam elements. This may induce degradation of the structural resistance, with associated costs of repair and aesthetic degradation. As an alternative mechanism, passive and semiactive control systems are of particular interest due to their high energy dissipation capability. By using such systems, the dissipative capacity of the structure is increased, without modifying its original design strength.

An extensive description of control systems can be found in Housner et al. [1]. Symans et al. [2] give a good treatment of passive control and its applications, and Parulekar and Reddy [3] present the state-of-the-art of passive systems. Description of semiactive systems and examples of applications are described by Morales-Beltran et al. [4], Casciati et al. [5], Spencer and Nagarajaiah [6], Symans and Constantinou [7], and Spencer and Sain [8]. Amezquita-Fuentes et al. [9] present a review of control laws implemented in semiactive systems.

Passive control systems are activated by the action imposed by the main structural system. After the control device is installed, it has no ability to regulate itself under different ground motions. Control systems with frictional mechanisms (e.g., [10–14]) are simple and cost-effective. However, the optimum performance of friction-based passive control is given by a unique configuration of slip-load capacity and placement of the dampers [15]. Filiatrault and Cherry [16] noted different performance between systems with slip-loads that were either proportional to the inter-storey shear force or uniformly distributed, and proposed a design slip-load spectrum to determine the optimum slip-load directly. Dowdell and Cherry [17] proposed a proportional distribution of the dampers' slip-load based on the structural deformation of the fundamental mode and the mass of the building. Apostolakis and Dargush [18] used genetic algorithms to identify the optimum capacity and placement of friction dampers in low-rise moment resistant steel frames. Min et al. [19] proposed the design of a single storey structure with friction damper based on a target equivalent damping ratio derived from the frictional hysteretic mechanism into a viscous damping mechanism at the steady-state response condition in the structure, which was subjected to harmonic ground motion. Lee et al. [20] studied the optimisation of damper capacity and allocation based on the normalisation of the ratio of slip-load to shear force in the building, either by considering the damper-braced frame or the bare frame, and proposed an empirical equation to determine the optimum quantity of dampers. Miguel et al. [21] studied the simultaneous optimisation of damper slip-load and placement by means of the backtracking search optimisation algorithm [22] with an objective function (e.g., maximum reduction of inter-storey drift for a shear

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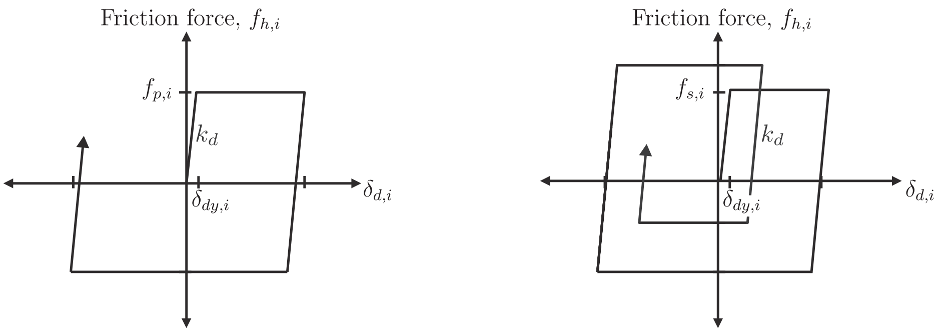

a) Passive slip-load $f_{p,i}$ b) Semiactive slip-load $f_{s,i}$

Fig. 1. Hysteretic behaviour of friction damper using different control schemes.

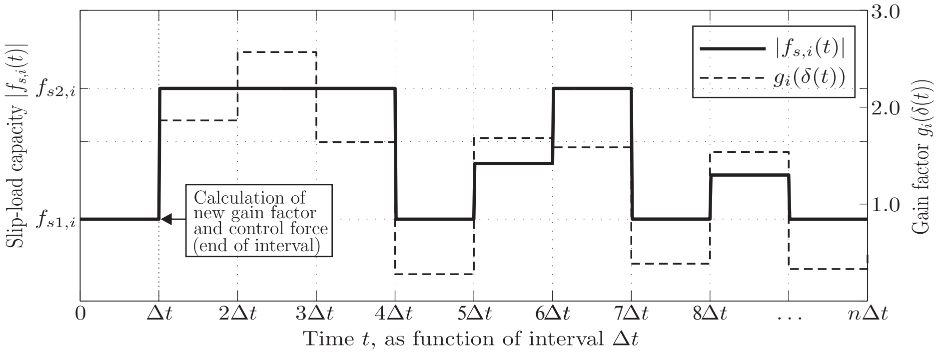

Fig. 2. Schematic functioning of *AδVG* semiactive control.

building, or top displacement for a transmission line tower) and by feeding the optimisation algorithm only with the maximum capacity and placement of dampers available. For robust optimisation, Miguel et al. [23] introduced random variables to represent uncertainty in the material properties, ground motion and damper forces in each run of the backtracking search algorithm. From those studies, it can be concluded that the optimum passive slip-load is related to the characteristics of the earthquakes and thus, varies for different ground motions. Since it is tuned to a certain earthquake, the performance of passive systems may be affected for a broader range of excitation frequencies. Thus, rendering the design to sub-optimal performance as there is no way to predict ground motions. Furthermore, the optimisation process generally assumes an elastic structural response, which is non-realistic for design and maximum considered earthquakes.

Semiactive control is a possible solution to overcome the sub-optimal performance of passive dampers under different earthquakes. A semiactive control scheme is a means to manipulate the friction dampers in real-time during the earthquake to adjust the slip-loads to the most efficient level. The level of complexity and efficiency of the semiactive system depends on the control law implemented. Algorithms that require a full model of the structure may yield the best performance, but with an associated cost of implementation. Furthermore, the optimisation may be limited to elastic models of the structure. Algorithms that utilise a control architecture where minimal or no information is exchanged between each local controller are a compromise between good performance and fast computational response, but they may adapt more efficiently to non-linear response. Using the latter strategy, Akbay and Aktan [24] and Kannan et al. [25] proposed an algorithm based on bang-bang control to modify the slip-load of the so-called “active slip-bracing device” at fixed time and force increments. Dowdell and Cherry [17] developed an “off-on” control to modify the slip-load from a near-zero value (i.e., “off” phase) to a pre-set value (i.e., “on” phase). Inaudi [26] developed the modulated homogeneous control to modify the slip-load only at peaks of inter-storey deformation, and He et al. [27] enhanced this controller by introducing either linear or hyperbolic tangent functions as boundary layer factors to allow smoother changes of the slip-load in the vicinity of motion reversal. Chen and Chen [28] developed an algorithm to include both viscous and Reid damping by defining different gain factors for the deformation phase and its rate. Ng and Xu [29] developed the non-sticking friction control to modify the slip-load up to a pre-defined maximum level proportionally to the hyperbolic tangent function of the velocity. Ozbulut et al. [30] developed adaptive control algorithms using fuzzy logic to control friction dampers installed as supplemental devices for base isolated systems.

A possible drawback of the semiactive system is the unavoidable time lag that occurs during the feedback data acquisition, processing and transferring, and during the control force build-up in the control devices [31,32], which does not occur in passive systems.

In the investigation presented in this paper, a new semiactive control algorithm is introduced to modify the slip-loads based on the combination of local and global response parameters, which ensures adjustment of control forces based on knowledge of the whole building’s response without requiring a model of the full structure. The new algorithm increases the system’s adaptability to a variety of seismic excitations and eliminates the problem of optimum placement configuration by utilising a narrow range of control forces related to optimum passive slip-loads. The investigation of the effects of the time delays in the performance of the semiactive system is also presented.

2. Description of semiactive control algorithm

Modelling of the dynamic response of multi-degree-of-freedom (MDOF) structures with friction-based dissipation devices is given by Eq. (1) [33]:

$$M\ddot{x}(t) + C\dot{x}(t) + K(u)x(t) + F_h(t) = -ML\ddot{x}_g, \tag{1}$$

where M, C and $K(u)$ are the mass, damping and non-linear stiffness matrices, respectively; $x(t)$ is the vector of displacement relative to the ground and ˙ indicates derivative with respect to time; the input to the