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Smart passive damper control for greater building earthquake resilience in sustainable cities

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ABSTRACT

Passive dampers are used recently in many mid and high-rise buildings. This trend is accelerated by the increased demand and desire for safer, more reliable and more comfortable buildings under uncertain external loading and environment. Viscous, visco-elastic, hysteretic and friction dampers are representatives of passive dampers. Such passive dampers also play a key role in the implementation of structural rehabilitation which is essential for the realization and promotion of sustainable buildings. The technique of structural health monitoring is inevitable for the reliable and effective installation of passive dampers during the structural rehabilitation or retrofit.

The design earthquake ground motions change from time to time when a new class of ground motions (e.g. long-period ground motions due to surface waves) is observed or a new type of damage appears during severe earthquakes. The concept of critical excitation is useful in responding to this change together with the usage of passive dampers from the viewpoint of sustainable buildings and cities.

In this paper, a historical review is made on the development of smart or optimal building structural control with passive dampers and some possibilities of structural rehabilitation by use of passive dampers are discussed.

1. Introduction

The structural rehabilitation or retrofit of buildings has been conducted for a long time all over the world and the structural control using passive dampers plays a key role in the implementation of the structural rehabilitation or retrofit which is essential for the realization of sustainable buildings and cities.

The structural control has a long and successful history in mechanical and aerospace engineering. This is because these fields usually deal with controllable external loading and environment with little uncertainty. However, in the field of civil engineering, it has a different background (Casciati, 2002; Christopoulos & Filiatrault, 2006; de Silva, 2007; Housner et al., 1994; Housner et al., 1997; Johnson & Smyth, 2006; Kobori et al., 1998; Soong & Dargush, 1997; Srinivasan & McFarland, 2000). Building and civil structures are often subjected to severe earthquake ground motions, wind disturbances and other external loading with large uncertainties. It is therefore inevitable to take into account these uncertainties in the theory of structural control and its application to actual structures. There are five important areas impacted by structural control (Soong, 1998), i.e. (a) systems approach, (b) deepening effect, (c) broadening effect, (d) experimental research and (e) creative engineering. Among these five areas, the broadening effect includes the smart use of passive dampers in building structures.

In the early stage of development in passive structural control, the installation itself of supplemental dampers in ordinary buildings was the central objective and many successful applications have been made. It seems natural that, after extensive developments of various damper systems, another objective and target were aimed at accelerating the development of smart and effective installation of supplemental passive dampers. This trend corresponds well to the promotion of new design methods for building structures from the viewpoint of sustainability and efficient use of materials.

Although the motivation was inspired and directed to smart and effective installation of supplemental passive dampers, research on optimal passive damper placement has still been very limited. The following studies may be relevant to this subject. Gurgoze and Muller (1992) presented a numerical method for finding the optimal placement and the optimal damping coefficient for a single viscous damper in a given linear multi-degree-of-freedom system. Zhang and Soong (1992) proposed a seismic design method to find the optimal location of viscous dampers for a building with specified story stiffnesses. While their method is based upon an intuitive

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Table 1
Pros and cons of passive dampers.

	Pros	Cons
Viscous damper	Do not introduce excessive additional force into structural frames (Phase delay and relief mechanism)	Cannot respond to impulsive loading
Visco-elastic damper	Cost effective	Introduce excessive additional force into structural frames; Temperature, frequency, amplitude-dependence
Hysteretic damper (shear, buckling-restrained brace)	Cost effective	Introduce excessive additional force into structural frames
Friction	Easy control of slippage force	Reliability of control of slippage force

criterion that an additional damper should be placed sequentially on the story with the maximum interstory drift, it is pioneering. Hahn and Sathiavageeswaran (1992) performed several parametric investigations on the effects of damper distribution on the earthquake response of shear buildings, and showed that, for a building with uniform story stiffnesses dampers should be added to the lower half floors of the building. Tsuji and Nakamura (1996) proposed an algorithm to find both the optimal story stiffness and damper distributions for a shear building model subjected to a set of spectrum-compatible earthquakes.

Rather recently Takewaki (1997, 1999a,b) opened another door of smart passive damper placement with the help of the concepts of inverse problem approaches and optimal criteria-based design approaches. He solved a problem of optimal passive damper placement by deriving the optimality criteria and then by developing an incremental inverse problem approach. For many years, this research played a role as a pioneering work in this area and many researchers referred to this article and compared the results by their methods with the result by Takewaki (1997). Subsequently, Takewaki and Yoshitomi (1998), Takewaki, Yoshitomi, Uetani, and Tsuji (1999) and Takewaki (2000) introduced a new approach based on the concept of optimal sensitivity. The optimal quantity of passive dampers is obtained automatically together with the optimal placement through this new method. The detailed explanation of this approach is made in Takewaki (2009, 2010).

After these researches, many related works have been developed (Aydin et al., 2007; Cimellaro, 2007; Fujita, Moustafa, & Takewaki, 2010; Fujita, Yamamoto, & Takewaki, 2010; Garcia, 2001; Lavan & Levy, 2006; Silvestri et al., 2003; Silvestri & Trombetti, 2007; Singh & Moreschi, 2001; Trombetti & Silvestri, 2004; Uetani et al., 2003; Yamamoto et al., 2010). Although most of the researches are based on gradient-based approaches, a GA-based approach is also investigated (Lavan & Dargush, 2009). Most of them investigated new optimal design methods of supplemental dampers and proposed effective and useful methods.

There are several textbooks dealing with the design of passive dampers. Connor and Klink (1996) introduced a concept of 'motion-based design' and provided versatile explanation on various passive and active control systems, i.e. visco-elastic, viscous and tuned-mass dampers, base-isolation systems and active control systems. Soong and Dargush (1997) explain the fundamental mechanical aspects of passive dampers and present many practical examples of application to realistic buildings. Hanson and Soong (2001) begin with basic concepts of passive dampers and present a few examples of application. Christopoulos and Filiatrault (2006) deal with passive energy dissipation systems and base-isolated buildings. They treat several different systems of supplemental dampers, i.e. metallic and friction dampers, viscous and visco-elastic dampers, self-centering characteristic dampers, tuned-mass dampers, etc. They also explain the energy principle and performance-based design principle. de Silva (2007) collects many useful chapters for passive damper systems and gives an up-to-date review. Takewaki (2009) provided several gradient-based approaches.

The design earthquake ground motions change from time to time when a new class of ground motions (e.g. long-period ground motions due to surface waves) is observed or a new type of damage appears during severe earthquakes. The concept of critical excitation is useful in responding to this change and should be used as a next-generation paradigm for unpredictable design ground motions together with the usage of passive dampers from the viewpoint of sustainable buildings and cities.

2. Realization of sustainable buildings from the viewpoint of structural engineering

The structural rehabilitation is essential for the cost-effective realization of sustainable buildings and many useful methods have been proposed. Passive dampers enable the structural rehabilitation inevitable for the realization and promotion of sustainable buildings. The most advantageous aspects of using passive dampers are to be able to use various types of passive dampers, i.e. viscous, visco-elastic, hysteretic and friction dampers, depending on the type of buildings to be rehabilitated. Each type of damper has its features and simultaneous usage of different dampers helps the compensation of demerits.

Table 1 shows the pros and cons of various passive dampers. The most important aspect is to prevent introducing excessive additional forces in the original frames to be rehabilitated. The phase delay and relief mechanism in viscous (oil) dampers and the series-type allocation of multiple passive dampers are regarded as key mechanisms.

In the structural rehabilitation, the structural health monitoring plays a significant role so as to maintain the effectiveness and reliability of rehabilitation. Many useful system identification methods have been proposed so far. Interested readers should read Boller et al. (2009). There are two types of system identification techniques, i.e. modal parameter system identification and physical parameter system identification (Takewaki & Nakamura, 2000, 2005).

The design earthquake ground motions change from time to time when a new class of ground motions (e.g. long-period ground motions due to surface waves) is observed or a new type of damage appears during severe earthquakes. Passive dampers are useful to respond to this change regardless of whether the object building is a newly constructed one or one to be rehabilitated. The concept of critical excitation is also useful to respond to this change together with the usage of passive dampers from the viewpoint of sustainable buildings and cities. The critical excitation method plays an important role in the point that it can incorporate inexperienced, undesirable inputs in the design stage (see Fig. 1).

There are various buildings in a city. Each building has its natural period and original structural properties. When an earthquake occurs, ground motions of various properties are induced in the city. The combination of the building natural period with the predominant period of the induced ground motion may lead to disastrous phenomena in the city. Many past earthquake ground motions exhibited such phenomena. To the authors' knowledge, the concept of 'critical excitation' and the structural design based upon this concept can become one of such new paradigms.

It may be natural to assume that earthquake has a bound on its magnitude. In other words, the earthquake energy radiated from