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Design of a variable stiffness bracing system: Mathematical modeling, fabrication, and dynamic analysis

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ABSTRACT

This paper presents a new bracing system with variable stiffness springs; this adaptive structural control system is designed to protect buildings against severe vibration and ground movement. The developed variable stiffness bracing (VSB) system comprises four nonlinear steel leaf springs that provide nonlinear and variable stiffness capacity at different frame displacements. The inelastic actions of the VSB system's nonlinear leaf springs keep the energy dissipation characteristics and ductility of moment-resisting frames. At large vibration amplitudes, the VSB device restrains unallowably story drift. Therefore, frames display ductile performance. We developed a mathematical model to simulate the mechanical behavior of the system, including the stiffness nonlinearity of the springs. Moreover, we evaluated the efficiency of the VSB implementation in a single-degree-of-freedom system by dynamically analyzing different models: a moment-resisting frame, a conventional braced frame, and a frame using the VSB system. This article discusses and proves the effectiveness of the proposed system through numerical analysis.

1. Introduction

Active variable stiffness (AVS) system has attracted increasing attention in recent decades. Previous studies have reported the desirable effects and the enhanced seismic performance of structures equipped with AVS systems. One such system was analyzed experimentally with its implementation in a full-scale test building in Japan [1,2]. Moreover, AVS action was optimized in a multi degree structure using a computational algorithm. Previous studies [3–5] mainly focused on the optimization of structural control systems without considering damper device design and function. Two structural systems were considered: the AVS system, which uses electric power to change the device's stiffness, and a viscous damper device, a passive control system, which lacks the ability to change the device's stiffness during seismic excitation.

The development of an adaptive earthquake energy dissipation device has become essential to optimize control of structures without depending on electric power, which is not reliable during seismic excitation. When a structural system becomes complicated and earthquake motion becomes stronger, increased energy is required to run force-type schemes. Numerous hybrid and semi-active methods have been introduced to overcome this energy problem. These methods used stiffness control devices have been used to adjust the rigidity and consequently modify the dynamic characteristics of structures. These AVS systems have been studied by several researchers [6–8]. In particular, the AVS system comprises locking and unlocking parts that are attached to the brace to withstand seismic excitation. The system's control algorithm can lock some of its parts to increase story stiffness at a particular time to decrease the structural seismic response [9]. A new semi-active variable stiffness (SAVS) device has been developed to overcome the constraints of the conventional on-off form of variable stiffness systems. The SAVS device can smoothly and continuously change between minimum and maximum stiffness. The efficiency of a miniature scale model of the SAVS device as a variable stiffness component in a system with a single degree of freedom (SDOF), has been tested. It also verified to reach a nonresonant state by switching the stiffness continuously and consequently, this process reduces displacement and acceleration [10]. Others have proposed a control system that alters the structure's response to a nonresonant state during earthquakes by modifying the buildings' stiffness [11]. Stiffness is altered via locking or unlocking of certain devices located between the beams and/or the diagonal braces of a structure. However, delivering a defective signal to a variable stiffness device (VSD) system remains possible, and the activation of a VSD will modify the structural dynamic behaviors without inducing peripheral vibrations or applying unwanted forces to it. The performance of a variable stiffness mount device has been proven experimentally. The VSD was constructed by the pre-stress stiffness of a cable-based mechanism. Changing pre-stress using a piezo actuator

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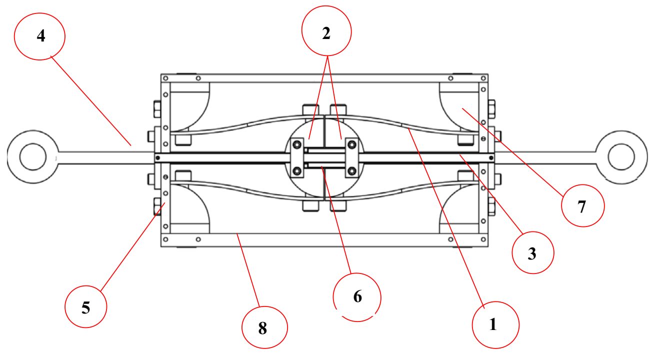

Fig. 1. Schematic body of the VSB System.

Fig. 2. Prototype of the VSB System (PI NO:2014701608).

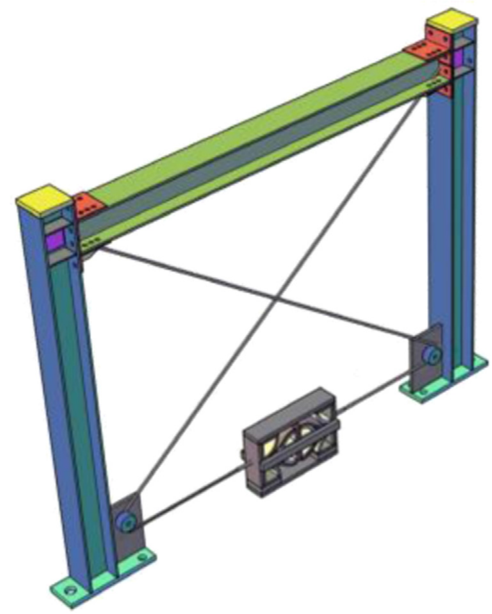

Fig. 3. VSB Installation layout in frame.

and a simple on–off controller significantly changes stiffness within a short time and at low energy outlays [12]. Moreover, a cable-driven manipulator (CDM) is a unique parallel manipulator in which the mobile platform is driven by cables as an alternative to rigid links. CDMs have been comprehensively investigated in prior studies [13].

Previous researchers have investigated various adjustable vibration absorbers with adaptable stiffness in which the frequency of excitation is changed. These adjustable absorbers can be implemented in buildings, automobiles, and floating rafts, where uncontrolled vibrations induce fatigue, inconvenience, expanded maintenance expenses, and reduced performance [14–17]. Recent studies related to variable stiffness actuators have mostly concentrated on four major techniques: pneumatic actuators, electroactive polymers (EAPs), electrical motors with active compliance, and adaptable stiffness components. EAPs change shape with the application of voltage. They can tolerate large amounts of deformation but possess high nonlinearity [18,19]. Pneumatic artificial muscles are normally contractile apparatuses that use pressurized air to control muscle stiffness. They necessitate an antagonist configuration to create a force or restore movement. Most such pneumatic machines are based on the McKibben muscle [20], which shortens, bulges, and produces a contraction force upon inflation. The static and dynamic behaviors of the McKibben artificial muscle pneumatic actuator have been evaluated by experimental tests [21]. However, these devices have several main defects, such as low efficiency, poor accuracy, and the need for an air compressor.

An actuator that incorporates an electrical DC motor and an elastic element with variable stiffness has been proposed [22]. The elastic part supplements the mechanical structure of the device to adapt to the dynamic effects of external forces. Another manipulator was designed with a variable stiffness system. The manipulator allowed the regulation of its stiffness and would befit various intended tasks. Device stiffness was a function of cable tension [23].

Another adjustable stiffness actuator was used as a robotic component. Modifying the shape of its springs allowed the alteration of the actuator's global stiffness of the actuator [24]. Another study proposed the design of a diagonal braced structure equipped with AVS and a control algorithm. The control algorithm would activate the brace action in the frame based on nonresonance theory. Therefore, brace stiffness would vary with frequency. The design approach and the efficiency of the control algorithm were investigated by numerical simulation, and the results demonstrated the response diminution of structures furnished by the developed controller device [25]. To date, little is known about techniques for retrofitting moment-resisting steel frame (MRSF) structures with smart VSB comprising a passive multivariable stiffness spring without reducing the effect of inherent ductility. The present study reports our development of a new adaptive variable stiffness device having no dependency on any sort of power or even on an active controller. The proposed device can alter stiffness, based on the load transferred to the curved steel spring, because of its geometric specifications. This property significantly distinguishes the VSB device from those reported in previous studies, which normally altered device stiffness using active controllers.

2. Development of a VSB system

This study set out to design an effective method of controlling a frame's structural response to dynamic loads and vibration. Based on the advantages of the variable stiffness concept, we developed a high-performance VSB system for framed structures. We adopted a Page: 3 design procedure that optimized different elements of the VSB system to increase its functionality and performance, thereby diminishing vibration and dynamic loading in the structure Fig. 1 shows the schematic of the VSB system, which implements four leaf springs to act in bending situations under a large displacement (Label 1). Label 2 refers to a cylindrical core that can move left and right in a longitudinal direction through a steel rail (Label 3). Rods (Label 4) pass through the side's plates (Label 5) and are fixed to the cubic core (Label 6). When force is applied to the cable, the steel core moves and makes contact with the C-shaped member (Label 2), where the spring is clamped. The C-shaped elements help to maintain the initial spring shape and change it during system performance. The global stiffness of the nonlinear spring should be protected from curvature extension. Therefore, four quarter solid cylinders (Label 7) and two C-shaped elements act as essential supports. Furthermore, the spring protection systems (Labels 2 and 7) guarantee that the springs do not yield when they reach the highest value of curvature. This system increases the lateral stiffness of a story without any reduction to the moment frame's ductility. The VSB system does not move too much at small or medium vibration amplitudes, but does move at large amplitudes, controlling unallowably large story drift. The