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A new analytical model for viscous wall dampers and its experimental validation

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ABSTRACT

This paper presents a new analytical model for viscous wall dampers (VWDs) and their effectiveness in reducing seismic structural distress. A series of performance tests on VWDs is conducted to measure the response of the dampers under various loading conditions. Based on the non-linear responses elicited in these mechanical tests, a generalised Maxwell model for VWDs with time-varying stiffness and damping is proposed to assess their amplitude dependencies. Shaking table tests are conducted on a 3-storey steel space frame at a 1:4 scale with and without VWDs, using three types of earthquake excitations, to study the effectiveness of these devices. The additional stiffness of VWDs can significantly increase the natural frequencies of the steel frame, and the effect of vibration control on the displacements of the structural model is remarkable. The added damping contributed by VWDs can significantly reduce the acceleration responses and the inter-storey shear forces of the steel frame. The proposed VWD model is implemented using the OpenSees software, and is subsequently used for the dynamic simulation of the shaking table tests. The effectiveness and good adaptability of the proposed model are verified based on the agreement between the numerical simulation and shaking table test results.

1. Introduction

Strong earthquakes cause many casualties worldwide every year. Traditional seismic designs have focused on the optimisation of the design of structural members, and have usually increased the strength and stiffness of buildings, thereby leading to increased material consumptions. Nevertheless, the increase of stiffness would lead to larger seismic action which makes these designs less cost-effective. In view of this situation, many researchers have turned to new alternatives. Energy dissipation devices, such as active and passive controllers, are considered as effective additional devices used to improve the seismic performance of structures. Many scholars and engineers have expended efforts on the development of control strategies, and on numerical studies of structural control systems [1–5] for active [6,7], semi-active [8–10], and passive [11–13] control devices. Adeli and Saleh [14] developed a robust parallel-vector algorithm for the recursive evaluation of the responses of bridge structures with active, smart control systems. Nigdeli and Boduroglu [15] used active tendons to control torsionally irregular single-storey and multi-storey structures under excitation using a near-fault ground motion.

Compared with active control systems, or semi-active control systems, passive control systems are easier to implement and more reliable. Passive energy dissipation devices, like viscous fluid or metallic dampers, do not need maintenance, and they are effective and easy to use, while the problem of the non-synchronised application of the actuator force for active control is completely eliminated. Many studies have been conducted for various energy dissipation devices. Benavent-Climent et al. [16] conducted shaking table tests on a reinforced concrete frame at a 2:5 scale with hysteretic metallic dampers which absorbed energy based on the plastification of the yielding metal, and provided empirical data on the response and damage of this system type. In addition to hysteretic devices, dampers have proven to be efficient energy dissipation systems, such as the telescopic or wall-shaped fluid viscous dampers. Karavasilis [17] conducted incremental dynamic analysis (IDA) for steel moment-resisting frames with and without telescopic viscous dampers to evaluate their plastic mechanisms. The results showed that frames with viscous dampers are prone to column plastic hinging in comparison to those without viscous dampers. Viscous wall dampers (VWDs) are another typical type of passive damping devices used for the seismic protection of new constructions, and the seismic retrofitting of existing buildings. VWDs can generate high-damping forces during frequent and rare earthquakes owing to the high-viscosity fluid between their inner and outer steel plates. Furthermore, VWDs can greatly enhance the level of the initial horizontal stiffness of the originally flexible structure with a slight modification of the building. Moreover, owing to the physical characteristics of the

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high-viscosity fluid, and the wall-shaped configuration of the device, there are no fluid leakages issues in high-speed, or high-pressure, and in fatigue damage, which are commonly observed in traditional telescopic viscous dampers. Thus, the performance of VWDs can be easily recovered, and the repair expenses of buildings after an earthquake can be greatly reduced.

Miyazaki et al. [18] first proposed the VWDs and confirmed the effectiveness of this energy dissipation device via dynamic response analyses. Two years later, Arima et al. [19], studied a 4-storey full scale steel frame model with five types of energy dissipation devices using an earthquake simulator, and found out that VWDs could provide sufficient damping to this structure. Miyazaki and Mitsusaka [20] studied the dynamic responses of the SUT-building in Shizuoka, Japan, which was the first building equipped with VWDs, using numerical simulations. A classical Kelvin–Voigt unit, in which a spring and a dashpot are connected in parallel, was used to capture the main mechanical properties of VWDs in the simulation. It was found that the use of 170 VWDs in the building led to a damping of 20–35% in the elastic range, and the dynamic response of the structure was reduced by 70–80%. Note that this building endured the Kobe earthquake in 1995 and maintained an intact main structure, thereby demonstrating the excellent damping effect of VWDs in practice. Yeung and Pan [21] verified the effectiveness of VWDs for controlling wind vibrations in a scaled 4-storey steel frame via a series of tests, including the wind tunnel test. Afterwards, VWDs were used for the seismic retrofitting of existing buildings, like the Kagoshima airport terminal in Kagoshima, Japan. Lu et al. [22] compared the dynamic responses of two 3-storey reinforced concrete (RC) frames with and without VWDs using shaking table tests to assess the effects of VWDs on seismic response mitigation. Their test results were also simulated numerically with a satisfactory accuracy using empirically obtained force–displacement and force–velocity relations for the VWDs. The first implementations of VWDs in the U.S.A. were evidenced in a hospital located in San Francisco, California. VWDs were selected because they could considerably reduce the cost of construction and maintenance, and concurrently improve the safety of the structure, aspects that are always of major concern to structural engineers. Newell et al. [23] and Love et al. [24] investigated the mechanical characteristics of a VWD by prototype testing, and then calculated the dynamic history response of the aforementioned hospital building equipped with VWDs by modelling them as classical Maxwell units consisting of a spring and a serially connected dashpot. Sasaki et al. [25] tested the performance of a VWD before and after subjecting it to harmonic waves and found that the damper was not damaged after approximately 20 h of operation, and was ready to be used again during earthquakes.

One can realise that the aforementioned research studies focused on the evaluation of the vibration control effect of dampers, but ignored the changes of the dynamic characteristics of the VWDs. Additionally, the variation of the dynamic properties of VWDs could result in different vibration control effects in different excitation scenarios. Specifically, the value of the stiffness and viscous exponent of the traditional Maxwell model could change with the input magnitude and frequency, aspects that were not considered in previous studies.

Viscous fluid dampers can be divided into two types, namely, those with linear and those with non-linear viscous behaviours. Different mathematical models for VWDs have been proposed to predict their behaviour. The classical Maxwell and Kelvin–Voigt models mentioned above, in which the values of the damping exponent are respectively equal to 1.0, or less, for both linear and non-linear types were the most popular models for viscous fluid dampers in past decades. However, for some types of non-linear viscous fluid dampers, the variation of their stiffness and damping values at various loading conditions—which are caused and affected by the change of their fluid material and configuration forms—increase their non-linearity. Therefore, some scholars proposed some generalised models to obtain better simulation results. Makris et al. [26] proposed a fractional derivative Maxwell model, which can describe the damper's behaviour over a large frequency range. Lu et al. [22] proposed a generalised Kelvin–Voigt model, which can consider frequency and temperature dependencies. However, these two models did not consider the amplitudes of the deformation and velocity dependencies. Hejazi et al. [27] developed a new analytical model for VWD, for which the damping coefficient of the VWD model was redefined by taking full account of all six spatial degrees-of-freedom of VWDs. This model was very complex and difficult to be applied in practice without its associated finite element algorithm, and the maximum error for the lateral floor displacement between numerical simulations and shaking table tests were found graphically to be approximately equal to 28%.

The present study introduces a type of VWD with a new viscous fluid that possesses an improved capacity of energy dissipation, but also features strong non-linear characteristics. The results of the performance tests show that the use of any existing mechanical model for VWD is imprecise because of its strong non-linear characteristics owing to the deformation and velocity amplitude dependencies of its stiffness and damping. The main purpose of this investigation is to develop a new analytical model for the newly introduced VWD, validate it experimentally, and study its response in controlling effectiveness in steel space frames using tests and simulations. Specifically, a performance test of a scaled VWD is first conducted to obtain the variation dependencies of its mechanical properties, and a generalised Maxwell model with time-varying stiffness and damping is developed for this VWD to consider its amplitude dependency. A series of shaking table tests are then conducted systematically to study the control effects of VWDs on the seismic response of a three-storey steel space frame, and to verify the models obtained in the aforementioned performance test. It is also observed for the first time that for different excitation conditions, the variation of the dynamic characteristics of the steel frame equipped with VWDs cannot be neglected.

This study also discusses in detail the impact of the added stiffness, damping, and vibration control effect, contributed by the VWD on the steel frame, at various seismic wave excitations. According to the shaking table test, it is verified that the proposed VWD is an excellent damper, which can adapt to different excitation magnitudes. Moreover, the proposed analytical model for VWD is implemented in the OpenSees program [28], and is subsequently used for numerical simulations of the steel frame equipped with the VWDs, under seismic excitations. Thus, the present study not only extends the work of Lu et al. [22] from RC frames to steel frames, but also develops in a rational way a mechanical model for a new, more effective VWD, and studies its seismic response controlling effectiveness in a more general, in-depth manner. The results show that the simulations agree well with the shaking table tests, thereby verifying the accuracy of the generalised mechanical model and its proper implementation in OpenSees.

2. Performance tests of the VWD device

The scaled VWD specimen consisted of an external steel box, an inner steel plate, and a high-viscosity fluid filling a 2 mm clear space between them, as shown in Fig. 1. The high-viscosity fluid was a proprietary material developed by the FUYO TECH Corporation [29].

The loading facility shown in Fig. 2 was designed and built for the measurement of the VWD responses under various working conditions. In this setup, a single-ended electro-hydraulic servo actuator, manufactured by the Beijing FTS Corporation [30], was employed to drive the damper. It has a maximum capacity of ± 52 kN in terms of force and 400 mm in terms of displacement. A linear variable differential transformer (LVDT) from the German Novotechnik Corporation [31] was used to measure the relative displacement between the inner steel plate and the external steel box of the VWD, and a load cell with a range of ± 50 kN from the American Celtron Corporation [32] was included in series with the damper to measure the output force. Using this experimental setup, the dynamic responses of the damper could be