

Recent Progress in Taiwan on Seismic Isolation, Energy Dissipation, and Active Vibration Control

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2017 NZSEE
Conference

ABSTRACT: In Taiwan, seismic isolation and energy dissipation technology has been extensively applied in new and retrofitted buildings and infrastructures against seismic attacks after the 1999 Chi-Chi Earthquake. In the beginning, most applications involved critical structures such as medical and emergency response facilities that are required to remain fully functional during and after earthquakes. Since 2009, the use of such technology has been greatly expanded to residential buildings for better seismic protection and life quality. To date, the numbers of building projects adopting seismic isolators and velocity-dependent dampers are more than 120 and 400, respectively. Recently, isolating equipment and facilities from damage due to earthquakes also attracts growing attention and has been implemented in practice. In this paper, several representative applications of passive control technology to buildings and critical facilities or equipment in Taiwan are illustrated first. The practical performance of some seismically isolated buildings and equipment during the 2016 Meinong Earthquake is also reviewed. Then, several new and advanced testing facilities of the National Center for Research on Earthquake Engineering (NCREE) are briefly introduced. By applying the existing and new testing facilities at NCREE, some current and future research topics relevant to passive control technology in Taiwan are discussed.

1 REPRESENTATIVE APPLICATIONS OF PASSIVE CONTROL TECHNOLOGY IN TAIWAN

1.1 Seismic isolation

More than half of seismically isolated buildings in Taiwan adopt the mid-story isolation design. As implied in the name, the isolation system is incorporated into the mid-story (mostly installed on the top of the first story) rather than the base of the building, as illustrated in Figure 1. The mid-story isolation design, of course, has lots of advantages over the base isolation design in terms of construction efficiency, space use, maintenance, and etc. Nevertheless, its dynamic behavior might become more complex and its analysis should be paid more attention compared to the base isolation design, especially when the isolation system is installed at a higher story or the substructure is more flexible (Wang et al. 2012; Wang et al. 2013). In Taiwan, currently, the highest mid-story isolation system is installed above the fourth story of a residential building (B6F~16F), as presented in Figure 2. For base-isolated buildings, currently, the tallest one is a precast reinforced concrete (RC) residential building with a total height of 133.2m (B3F~38F) and an aspect ratio of 3.17 in New Taipei City (Liou 2010), as shown in Figure 3. The isolation system is installed underneath 1F and consists of 43 lead rubber (LR) bearings in which the maximum cross-section diameter is 1.5m. The separation between the superstructure and surrounding retaining wall is 50cm. The elastic period before isolation and the effective period after isolation under design basis earthquake (DBE) shaking are 3.29sec and 5.18sec, respectively.

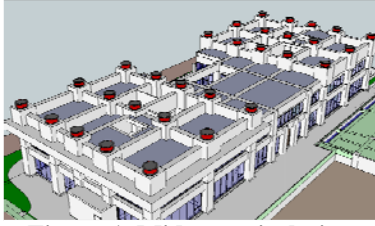


Figure 1. Mid-story isolation design.



Figure 2. The highest mid-story isolation system in Taiwan.



Figure 3. The tallest seismically isolated building in Taiwan.

Lead rubber (LR) bearings are still the most commonly used seismic isolators in Taiwan. Recently, high-damping rubber (HDR) and friction pendulum sliding bearings have also been implemented in several seismically isolated buildings. Taking the 12-story residential building with a 3-story basement in Taipei City shown in Figure 4 as an example, the base isolation system consists of 18 HDR bearings (Yao et al. 2012). Friction pendulum sliding bearings feature their lateral effective stiffness proportional to the imposed axial load (Earthquake Protection System, Inc. 1985), which is very useful for solving the problem of eccentricity between the center of mass of the superstructure and the center of rigidity of the isolation system, a considerably irregular superstructure in particular. Besides, the effective period of the isolation system composed of friction pendulum sliding bearings is irrelevant to the variation of axial loading, which can make the seismic isolation design simpler. Three well-known buildings, the Taipei Performing Arts Center in Taipei City, the Tao Zhu Yin Yuan Mansion in Taipei City, and the Southern Branch of the National Museum in Chiayi County respectively presented in Figures 5 to 7, are designed with friction pendulum sliding bearings. Observed from these figures, the superstructures are very complex and irregular architecturally and structurally. The Taipei Performing Arts Center is a 12-story steel structure with a 1-story basement. The isolation system is installed beneath B1F and consists of 89 friction pendulum sliding bearings in which the maximum diameter is 2.2m. The maximum horizontal displacement capacity of the bearings is 700mm. The Tao Zhu Yin Yuan Mansion is a 21-story structure with a 5m high roof outrigger truss, a 3-story roof protrusion, and a 4-story basement. The isolation system is installed beneath B4F and consists of 48 friction pendulum sliding bearings. The isolation system of the Southern Branch of the National Museum is installed underneath 1F and comprises 210 friction pendulum sliding bearings in which the maximum diameter is 1.9m. The maximum horizontal displacement capacity of the bearings is 500mm.



Figure 4. The residential building isolated by HDR bearings.

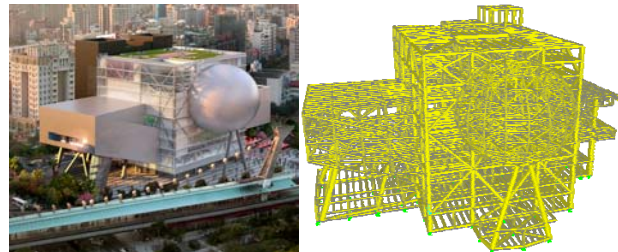


Figure 5. The Taipei Performing Arts Center isolated by friction pendulum sliding bearings.



Figure 6. The Tao Zhu Yin Yuan Mansion isolated by friction pendulum sliding bearings.



Figure 7. The Southern Branch of the National Museum isolated by friction pendulum sliding bearings.

In addition to office and residential buildings, emergency operation centers, hospitals, schools, museums, and temples, many other critical facilities in Taiwan, such as high-tech factories and

emergency response facilities (ERFs) in nuclear power plants (NPPs), have gradually been aware of the effectiveness of seismic isolation technology and have considered adopting such technology for safety and functionality purposes (Chang et al. 2015). To achieve a higher performance level for existing anti-seismic structures, applying seismic isolation technology to the housed critical equipment can yet be regarded as one of the most efficient, practical, and cost-effective strategies. An often seen case is to incorporate seismic isolators into a raised floor system, i.e. an isolated raised floor system (Hamidi & El Naggat 2007). The sloped rolling-type seismic isolator developed by the National Center for Research on Earthquake Engineering (NCREE), as illustrated in Figure 8, features the constant acceleration control performance regardless of earthquake intensities (Wang et al. 2014). It has been practically applied in the internet data center of the National Center for High-performance Computing (NCHC), the internet data center of the National Disasters Prevention and Protection Commission (NDPPC), the antique storage cabinets of the Institute of History and Philology, Academia Sinica, the supercomputer of the Central Weather Bureau (CWB), the network and telecommunication servers of Chunghwa Telecom, the data storage equipment of Chunghwa Post, the high-precision equipment of several semiconductor factories, and etc., as shown in Figure 9.

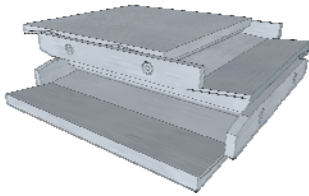


Figure 8. Schematic view of sloped rolling-type seismic isolators.

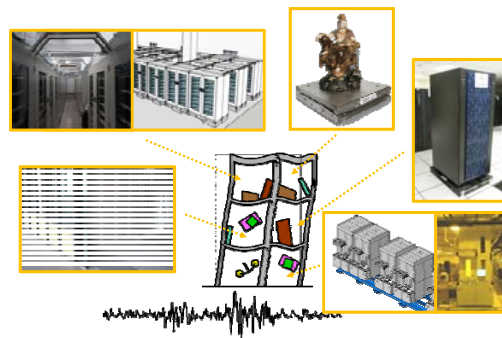


Figure 9. Practical applications of sloped rolling-type seismic isolators.

1.2 Energy dissipation

Linear and nonlinear viscous dampers, viscoelastic (VE) dampers, and bilinear oil dampers are the most commonly used velocity-dependent dampers in Taiwan. The installation schemes encompass diagonal brace, chevron brace, toggle brace, panel, and other types (Hwang et al. 2008). In Taiwan, for new construction, velocity-dependent dampers are mostly applied to further upgrade the seismic performance of the building rather than to reduce the minimum total lateral force for design. Some other applications are to mitigate the undesirable vibrations (e.g. wind-induced vibrations to high-rise residential buildings, as presented in Figure 10) or to enhance the serviceability and functionality performance (e.g. micro-vibration control for high-tech factories, as shown in Figure 11) (Hwang et al. 2004). In Taiwan, velocity-dependent dampers have also been applied to retrofit many existing buildings which were unable to meet the performance requirement specified in the latest design code before retrofitting.



Figure 10. Application of velocity-dependent dampers to high-rise buildings.



Figure 11. Application of velocity-dependent dampers to high-tech factories.

In Taiwan, Taipei 101 and Nan Shan Plaza, as presented in Figure 12, are currently two representative buildings of applying tuned mass damper (TMD) systems to mitigate the wind-induced vibration and enhance the serviceability performance. Both are skyscrapers which possess shopping malls, offices,

restaurants, and hotels. The total height of the former is 508m (B5F~101F). As shown in Figure 13, the TMD system is installed at 87F to 92F. It consists of a 660ton ball shaped mass block, 8 sets of high strength steel cables for suspension of the mass block, 8 sets of primary viscous dampers around the cradle for energy absorption, a bumper ring, and 8 sets of snubber dampers underneath the mass block for suppression of unexpected oscillation amplitude. The latter now is under construction and will be completed in 2017. Its total height is 272m (B5F~45F). As shown in Figure 14, there are two TMD systems at two opposite corners of 44F to 45F. Each system consists of a 250ton steel mass block, 8 sets of high strength steel cables for suspension of the mass block, 8 sets of nonlinear viscous dampers for energy absorption, and a snubbing system for suppression of unexpected oscillation amplitude.



Figure 12. Taipei 101 and Nan Shan Plaza.



Figure 13. TMD in Taipei 101.

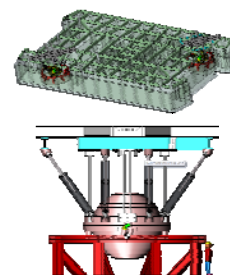


Figure 14. TMD in Nan Shan Plaza.

2 PRACTICAL PERFORMANCE OF SEISMICALLY ISOLATED BUILDINGS AND EQUIPMENT DURING 2016 MEINONG EARTHQUAKES

On February 6, 2016, the Meinong Earthquake hit Tainan City, Taiwan. In this event, the effectiveness of seismic isolation technology was practically demonstrated once again. In Tainan City, before the quake occurred, four seismically isolated structures have been finished, of which one is a national laboratory and the other three are residences. The distances from these four buildings to the epicenter of the Meinong Earthquake are presented in Figure 15. In addition, a raised floor system in a national laboratory and high-precision equipment in a high-tech factory have been designed with seismic isolation technology. During the quake, as expected, these isolated buildings exhibited excellent performance, thus effectively protecting the housed human life and property respectively from injury and damage. Furthermore, the isolated equipment remained functional during and after the quake, thus significantly reducing production losses and downtime cost in the high-tech industry. However, as shown in Figure 16, some slight damage in expansion plates, piping, cable trays, and decorations were observed, owing to insufficient buffer space between the isolated and non-isolated structures (or components), which should be carefully designed and reserved to accommodate isolation displacement. The majority of cases were caused by users' inappropriate obstructions for their special purposes. Although these inappropriate obstructions did not affect the overall seismic isolation performance, repairs made after quakes are still inconvenient to users. Learning from these lessons, in the future, the details in standard maintenance and inspection should be paid more attention.

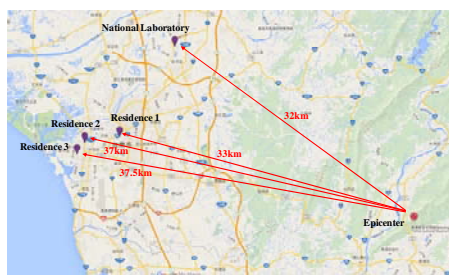


Figure 15. Epicentral distances of the four seismically isolated buildings in Tainan City.



Figure 16. The highest mid-story isolation system in Taiwan.

3 NEW TESTING FACILITIES AT NCREE LABORATORIES

3.1 NCREE Taipei laboratory

The dynamic tri-axial testing facility, as shown in Figure 17, is composed of a reaction frame, a bilateral sliding system, and one vertical and two lateral dynamic servo-hydraulic actuators. By using this facility, scale-down seismic isolators can be dynamically tested with different non-proportional plane loading paths under vertical compression force. The two lateral actuators are installed to be horizontally perpendicular to one another. Their maximum stroke and force capacities are $\pm 250\text{mm}$ and $\pm 250\text{kN}$, respectively. One swivel end is connected to the bilateral sliding platform, and the other end is mounted on a reaction wall or support. Two in-plane mutually orthogonal linear guide systems are designed for the bilateral sliding system; therefore, it can have an in-plane movement executed by the two lateral actuators. Specimens are installed on the bilateral sliding platform. The vertical actuator is mounted underneath the cross beam of the reaction frame. Its maximum stroke and force capacities are $\pm 50\text{mm}$ and $+250\text{kN}$ in compression (-150kN in tension), respectively. By employing a linear guide system to laterally restrain the vertical actuator, compression force exerted on specimens can be well controlled while subjected to non-proportional plane loading.

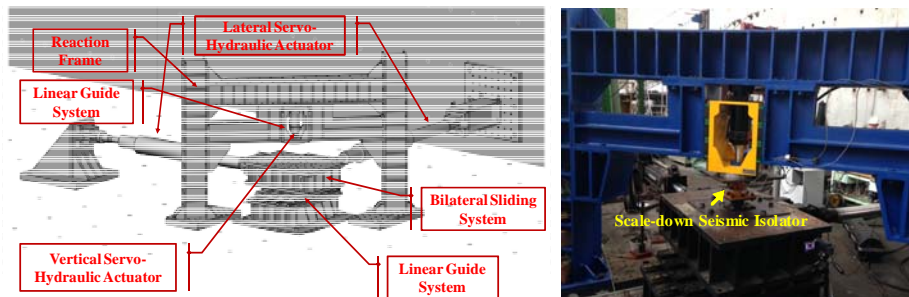


Figure 17. The dynamic tri-axial testing facility at NCREE Taipei Lab.

To experimentally verify the actual dynamic behavior and temperature-dependency of project-specific full-scale velocity-dependent dampers, a high performance energy dissipation device testing facility, as shown in Figure 18, was designed and established. This facility consists of three steel reaction components, a temperature control system, and a high-speed servo-hydraulic actuator with a maximum stroke capacity of $\pm 600\text{mm}$ and a maximum force capacity of $\pm 2\text{MN}$. The maximum velocity capacity is $\pm 1\text{m/sec}$ when the force applied reaches $\pm 1\text{MN}$. To effectively minimize any possible gaps between all contact surfaces during dynamic tests, prestressed rebars are employed to mount the three steel reaction components on the strong floor as well as assemble the actuator, steel reaction components, and any necessary fixtures. The steel reaction component connected to the piston end of the actuator is designed with a linear guide system, thus guaranteeing a nearly perfect uniaxial cyclic control with very limited friction force during dynamic tests. Specimens are installed horizontally between two steel reaction components. The space between the two steel reaction components can be adequately adjusted in compliance with the specimen size. By using the temperature control system, the ambient and operating temperature of specimens varying from 5°C to 50°C can be controlled and monitored in the chamber during dynamic tests.

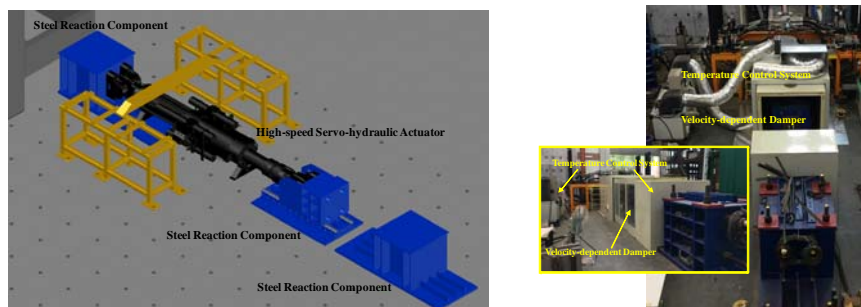


Figure 18. The high performance energy dissipation device testing facility at NCREE Taipei Lab.

3.2 NCREE Tainan laboratory

A high performance seismic simulation shaking table is being established to reproduce near-fault ground motions, as shown in Figure 19. It possesses six degrees of freedom to simulate earthquake motions in three axes. The size of the shaking table is $8\text{m} \times 8\text{m}$ with a self-weight of 1MN. Specimens with a maximum weight of 2.5MN can be accommodated on the shaking table. The shaking table is driven by eight high performance servo-hydraulic actuators. Four of them are installed horizontally and the other four are mounted vertically. The weight of the shaking table and the specimen above is balanced by four static supports; therefore, the four vertical actuators are barely responsible for applying dynamic loading. The hydraulic power is provided by five electrical pumps which can offer a total continuous flow rate of 3,500lpm. To achieve the test performance of near-fault ground motions, accumulator banks are equipped to provide the supplemental pressure and flow to operate the shaking table with a peak flow rate of 26,000lpm. The maximum horizontal stroke and velocity capacities of the shaking table are $\pm 1.0\text{m}$ and $\pm 2.0\text{m/s}$, respectively. The maximum acceleration capacities for the bare table in horizontal and vertical directions are correspondingly $\pm 2.5\text{g}$ and $\pm 3.0\text{g}$. The reaction forces of the actuators are provided by the reaction mass with a weight of 40MN. To reduce the vibration impact to the research building, the reaction mass is isolated from the fixed foundation by air springs and dampers.

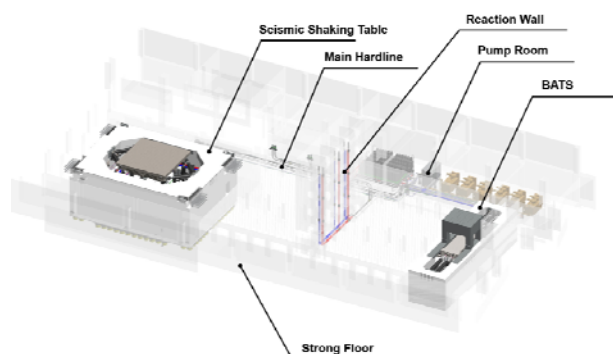


Figure 19. New testing facilities at NCREE Tainan Lab.

A dynamic biaxial testing system (BATS), whose overall appearance is similar but dynamic capacity is much superior to the existing Multi-Axial Testing System (MATS), is being established, as shown in Figure 19. It is mainly intended to dynamically test full-scale seismic isolators, especially for velocity-dependent ones. The maximum longitudinal stroke, velocity, and force capacities are $\pm 1.2\text{m}$, $\pm 1.0\text{m/s}$, and $\pm 4\text{MN}$, respectively. The maximum vertical stroke and velocity capacities are correspondingly $\pm 75\text{mm}$ and $\pm 150\text{mm/s}$. A maximum of 60MN vertical compression force which includes 30MN dynamic force and 30MN static force can be achieved. In addition, 8MN vertical tension force is obtainable to allow BATS to apply cyclic loading on specimens vertically. The hydraulic distribution system is designed to provide as much flexibility as possible to meet various testing scenarios in the laboratory. As a result, a peak flow rate of 18,620lpm is available in BATS when the shaking table is not conducting any tests.

4 CURRENT AND FUTURE RELEVANT RESEARCH TOPICS

By applying the existing and new testing facilities at NCREE as well as developing hybrid simulation technology, many research topics relevant to passive control technology have been conducted and launched in Taiwan, as described briefly as follows but not limited to the followings.

4.1 Impact of near-fault ground motion on passive control design

The design of structures with additional damping systems often involves the damping reduction factor, which is the ratio of a structural response (acceleration, velocity, or displacement) with a damping ratio of 5% to that with a damping ratio other than 5%. The damping reduction factors now provided

in building codes were developed based on the results of research using far-fault ground motion. Therefore, a series of response history analyses were conducted using single degree-of-freedom (SDOF) systems and 200+ pulse-like near-fault ground-motion records identified from NGA-West 2 strong-motion database. The damping reduction factors appropriate for the design of structures with additional damping systems subjected to near-fault ground motion were proposed. The results showed that the ratio of pulse period (T_p) of near-fault ground motion to the natural period of a structure (T) has significant impact on the damping reduction values (Huang & Liu 2016), as shown in Figure 20. In the future, the obtained numerical study results will be verified and some special design considerations against near-fault ground motion will be further discussed by testing passively controlled structure models on the high performance seismic simulation shaking table at NCREC, as illustrated in Figure 21.

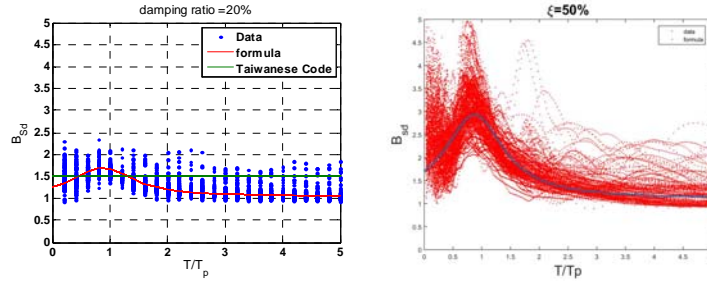


Figure 20. Variation of damping reduction factors with T/T_p .

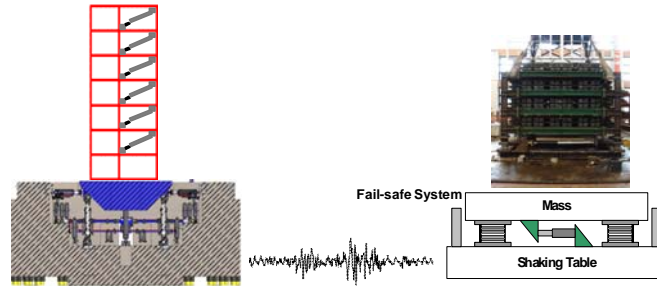


Figure 21. Shaking table tests on passively controlled structure models under near-fault ground motion.

4.2 Building mass damper for seismic design

A new seismic design manner, namely building mass damper (BMD), which is inspired from a combination of mid-story isolation and TMD design concepts, attracted immense attention in Taiwan. In the BMD design, the use of partial structural mass of the building as an energy absorber can overcome the drawback of limited response reduction due to insufficient added tuned mass in the conventional TMD design. Two optimum BMD (OBMD) design approach to seismically protect both the superstructure (or tuned mass) and the substructure respectively above and below the control layer, namely optimum dynamic characteristic and response control approaches, have been thoroughly studied in Taiwan (Chang et. al 2015), as illustrated in Figure 22. In addition to a series of sensitivity and numerical analyses, the practical feasibility of the BMD concept as well as the effectiveness of the proposed OBMD design approaches have been experimentally demonstrated, as shown in Figure 22. It is particular evident for a high-rise building which has a long period of vibration.

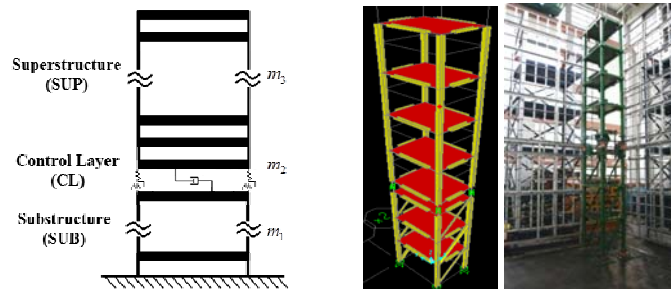


Figure 22. Numerical and Experimental Study on BMD.

4.3 Performance of Full-scale Seismic Isolators

In the future, by using BATS and MATS at NCREE, as well as developing network-collaborative pseudo-dynamic testing, as illustrated in the framework of Figure 23(a), the seismic performance of different full-scale isolators in a seismic isolation system under a combination of shear deformation, up-lift, and rotation can be examined in a static manner. Furthermore, by cooperating with other international laboratories which also have large-scale dynamic multi-axial testing systems, together with developing network-collaborative real-time hybrid testing, as illustrated in the framework of Figure 23(b), the dynamic behavior and realistic seismic performance of different full-scale isolators in a seismic isolation system can be verified and further investigated.

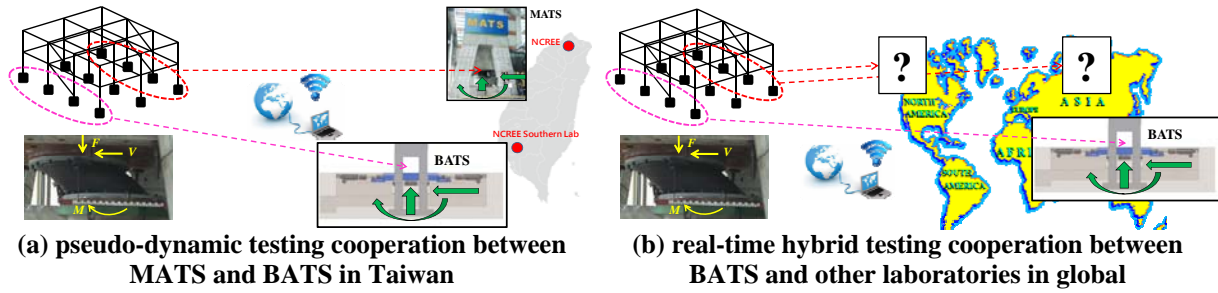


Figure 23. Realistic performance of full-scale seismic isolators.

4.4 Bilateral behavior of seismic isolators

In the past, the dynamic performance of seismic isolators was usually experimentally verified under unilateral cyclic loading and vertical compression force, which might not accurately reflect the real bilateral behavior of seismic isolators subjected to in-plane ground motion. By using the dynamic tri-axial testing facility at NCREE, the bilateral hysteretic behavior of seismic isolators, including elastomeric and metallic bearings, was experimentally investigated (Wang et al. 2017). Accordingly, a more accurate and conservative numerical model for design can be developed. Figure 24 presents the test results of a scale-down HDR bearing under figure-eight plane loading and constant vertical compression force, from which the torsional coupling effect, which results in the local shear strain increased, can be observed apparently.

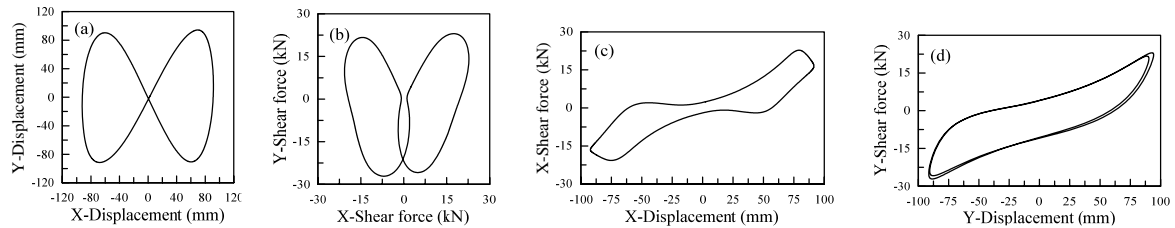


Figure 24. Test results of HDR bearings under figure-eight plane loading.

4.5 Nano-fluid smart dampers

The desired damping property of nano-fluid smart dampers can be achieved by simply changing the filled ingredient proportion. Thus, nano-fluid dampers have a much simpler mechanical design than conventional viscous dampers, which makes the manufacture easier and more cost-effective as well as makes the energy dissipation design more flexible and efficient, as shown in Figure 25(a). Besides, nano-fluid dampers can have an equivalent performance to the semi-active control but do not need any supplemental power. When applying nano-fluid dampers in a seismic isolation system, the seismic isolation performance can be easily activated with smaller damping force under minor earthquakes; meanwhile, the displacement response under major earthquakes can be suppressed by larger damping force. When applying nano-fluid dampers in bridges, leakage due to daily temperature variation can be prevented with smaller damping force; meanwhile, seismic energy can be dissipated by larger damping force. The ingredient filled in nano-fluid smart dampers is a mix of silica nanoparticles and polypropylene glycol with different proportions (Yeh et al. 2012). The rheology test results showed

that the fluid viscosity varies with the shear rate, as shown in Figure 25(b).

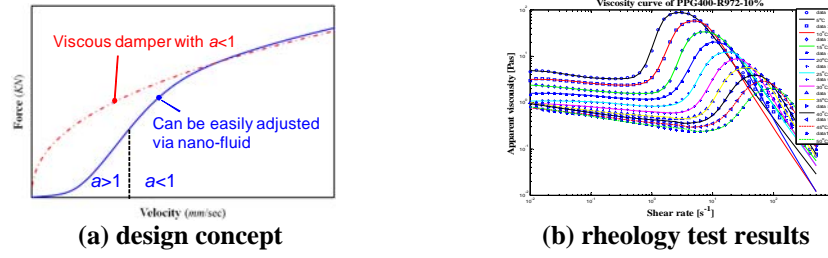


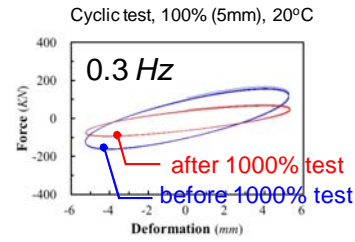
Figure 25. Nano-fluid smart dampers.

4.6 Seismic performance of full-scale VE dampers

By using the high performance energy dissipation device testing facility at NCREC, the frequency, shear strain, strain rate, and temperature dependence on the dynamic performance of full-scale VE dampers are currently being experimentally investigated, as shown in Figure 26(a). Besides, the dynamic performance and seismic response of full-scale VE dampers under maximum considered earthquake (MCE) shaking (or 1000% shear strain), together with the residual performance after experiencing maximum considered earthquake (MCE) shaking (or 1000% shear strain), are being experimentally studied, as shown in Figure 26(b). In the future, the seismic performance a RC structure model equipped with full-scale VE dampers under MCE shaking and even under near-fault ground motion will be experimentally demonstrated by using the high performance seismic simulation shaking table at NCREC.



(a) test setup



(b) test results before and after 1000% shear strain

Figure 26. Experimental study on full-scale VE dampers.

4.7 Optimum and effective design of velocity-dependent dampers

Velocity-dependent dampers have been widely applied in structural seismic design and retrofit in Taiwan. Nowadays, how to design a minimum of dampers by optimizing the damper placement and coefficient distribution to achieve the same desired damping ratio becomes a very important issue (Hwang et al. 2013), either in Taiwan or the whole world. In addition, recently, to obtain better space use and architectural lighting, a few installation schemes different from the typical ones has been adopted in Taiwan, as shown in Figure 27. In these cases, since velocity-dependent dampers are connected to beams or girders through a force-transferring component, rather than directly connected to beam-column joints, the flexibility of beams or girders as well as the out-of-plane movement of dampers might significantly affect the desired energy dissipation performance. These issues have been numerically and experimentally discussed in Taiwan (Lin et al. 2016).



Figure 27. Installation of dampers different from typical schemes in Taiwan.

4.8 Sloped rolling-type seismic isolators

In the past decade, NCREC has theoretically and experimentally studied the dynamic behavior and seismic performance of the sloped rolling-type seismic isolator. To have a more conservative design, i.e. taking the effect of vertical excitation on the horizontal acceleration control performance into account, a generalized numerical model has also been proposed (Wang et al. 2017). To facilitate the practical design for engineers, empirical equations for displacement prediction of the sloped rolling-type seismic isolator are being investigated in a statistical manner, as presented in Figure 28.

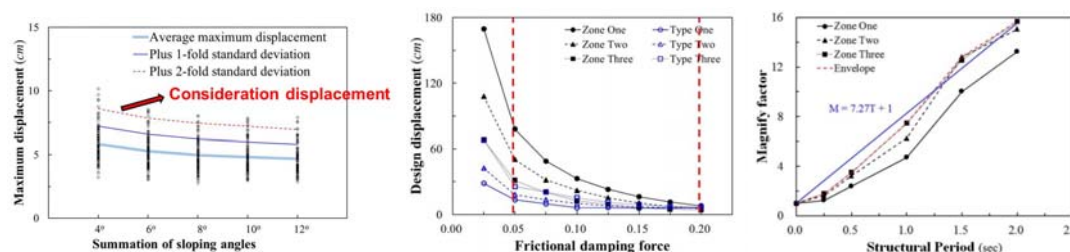


Figure 28. Statistical study on displacement responses of sloped rolling-type seismic isolators.

5 CONCLUSIONS

Passive control technology has been widely implemented in new and retrofitted buildings and infrastructures in Taiwan after the 1999 Chi-Chi earthquake. To date, the numbers of building projects adopting seismic isolation devices and velocity-dependent dampers are more than 120 and 400, respectively. Recently, seismic isolation technology has also been applied to protect critical equipment or facilities in many organizations and industries in Taiwan. In 2017, NCREC will have the Tainan laboratory which possesses several new and advanced testing facilities. With the existing and new testing facilities, more and more domestic and international collaborative research activities relevant to structural control technology will be launched.

6 REFERENCES

- Chang, K.C., Chuang, W.C., Wang, S.J., & Hwang, J.S. 2015. From seismic isolation to building mass damper - an experimental and analytical study. *Proc. of the Structural Engineering Frontier Conference (SEFC 2015)*, Yokohama, Japan.
- Chang, K.C., Hwang, J.S., Wang, S.J., & Lin, W.C. 2015. Progress of seismic isolation and energy dissipation in Taiwan – application, research and design. *Proc. of the 14th World Conference on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures (14WCSI)*, San Diego, U.S.A.
- Earthquake Protection System, Inc. (EPS). 1985. *Friction Pendulum™ Bearings*, Vallejo, California.
- Hamidi, M. & El Naggar, M.H. 2007. On the performance of SCF in seismic isolation of the interior equipment of buildings. *Earthquake Engineering and Structural Dynamics*, Vol 36(11): 1581-1604.
- Huang, Y.N. & Liu, C.R. 2016. Impact of near-fault ground motions on the efficiency of viscous-damping systems. *Proc. of the ASME 2016 Pressure Vessels and Piping Conference*, Vancouver, Canada.
- Hwang, J.S., Huang, Y.N., Hung, Y.H., & Huang, J.C. 2004. Applicability of seismic protective systems to structures with vibration sensitive equipment. *Journal of Structural Engineering*, Vol 130(11): 1676-1684.
- Hwang, J.S., Huang, Y.N., Yi, S.L., & Ho, S.Y. 2008. Design formulations for supplemental viscous dampers to building structures. *Journal of Structural Engineering*, Vol 134(1): 22-31.
- Hwang, J.S., Lin, W.C., & Wu, N.J. 2013. Comparison of distribution methods for damping coefficients to buildings. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, Vol 9(1): 28-41.
- Lin, W.C., Wang, S.J., Hwang, J.S., & Chiang, C.T. 2016. Evaluation of current installation schemes for viscous dampers in Taiwan. *Proc. of the 13th National Conference on Structural Engineering and 3rd National Conference on Earthquake Engineering*, Taoyuan, Taiwan.
- Liou, S.K. 2010. Seismic isolation design and quality control of elastomeric bearings: A case study of Lan-Hai Project (38 stories/133m). *Proc. of the Conference on Design and Construction of Seismically Isolated*

Buildings, Taipei, Taiwan. (in Chinese).

- Wang, S.J., Chang K.C., Hwang, J.S., Hsiao, J.Y., Lee, B.H., & Hung, Y.C. 2012. Dynamic behavior of a building structure tested with base and mid-story isolation systems. *Engineering Structures*, Vol 42: 420-433.
- Wang, S.J., Hwang, J.S., Chang, K.C., Lin, M.H., & Lee, B.H. 2013. Analytical and experimental studies on mid-story isolated buildings with modal coupling effect. *Earthquake Engineering and Structural Dynamics*, Vol 42(2): 201-219.
- Wang, S.J., Hwang, J.S., Chang, K.C., Shiau, C.Y., Lin, W.C., Tsai, M.S., Hong, J.X., & Yang, Y.H. 2014. Sloped multi-roller isolation devices for seismic protection of equipment and facilities. *Earthquake Engineering and Structural Dynamics*, Vol 43(10): 1443-1461.
- Wang, S.J., Lin, W.C., Hwang, J.S., & Huang, B.W. 2017. Hysteretic behavior of high-damping rubber bearings under non-proportional plane loading. *Proc. of the 16th World Conference on Earthquake Engineering (16WCEE)*, Santiago, Chile.
- Wang, S.J., Yu, C.H., Lin, W.C., Hwang, J.S., & Chang, K.C. 2017. A generalized analytical model for sloped rolling-type isolation bearings. *Engineering Structures*, doi: 10.1016/j.engstruct.2016.12.027.
- Yao, C.H., Kan, S.Y., Yin, Y.L., Huang, W.X., & Liang, C.C. 2012. A case study of a residential building with base isolation system in seismic zone II of Taipei City. *Proc. of the 11th National Conference on Structural Engineering and 1st National Conference on Earthquake Engineering*, Taichung, Taiwan. (in Chinese).