**Beyond Design Performance of Viscoelastic Dampers**

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**ABSTRACT**

The actual performance and damage of viscoelastic dampers under maximum considered shaking or greater earthquakes as well as their residual performance under aftershocks was rarely discussed before. In this study, four coefficients of the fraction differential model considering ambient temperature, temperature rising, cyclic soften, and strain hardening effects were firstly characterized from performance test with shear strain levels less than 300%. Secondly, VE dampers were tested with larger shear strain levels, until 1000%, to realize their ultimate performances. In between each large shear strain level, the performance test under 300% shear strain was performed to further understand their residual performance after damage. The fraction differential model was also adopted for characterizing their post-damage behavior. The result shows that the stiffness and damping coefficient of VE dampers decrease proportionally with varying shear strain levels from 600% to 840%, and can still remain half of the original values after 840%. Thirdly, VE dampers were tested subjected to seismic response histories which can be numerically analyzed in an off-line manner. Either before or after damage, the predictions by the fraction differential model have a very good agreement with the test results

*Keywords: Viscoelastic Damper; Beyond Design Performance; Empirical Post‐damage Model; Residual Performance*

**1. INTRODUCTION**

Among the so-called velocity-type dampers, viscoelastic (VE) dampers feature their stiffness and energy dissipation capabilities generally through the shear deformation of polymer composite (termed as VE) material layers sandwiched between steel plates (Chang KC et al. 1993). Since the 1990s, researches on VE dampers for seismic application have been launched. Many performance tests on small- and full- scale VE dampers were conducted to investigate their force-deformation (or stress-strain) relationship and the effects of displacement amplitudes, excitation frequencies, ambient temperatures, temperature rises, softening, hardening, and cumulative energy absorption on their mechanical behavior (Chang KC et al. 1992; Kasai K et al. 1993; Bergman DM and Hanson RD 1993; Lai ML et al. 1995; Xu ZD et al. 2015; Wang SJ et al. 2018). With performance test verification, different methods for mathematically modeling the mechanical behavior of VE dampers (or material) were presented, such as the fractional derivative model (Gamant A 1936; Bagley RL and Torvic PJ 1983; Kasai K et al. 2001; Kasai K and Tokoro K 2002), equivalent fractional Kelvin model (Xu ZD et al. 2015), viscoelastic solid model (Gandhi F and Chopra I 1996), classical model (Chang [TS](https://ascelibrary.org/author/Chang%2C+T-S) and Singh [MP](https://ascelibrary.org/author/Singh%2C+M+P) 2009), etc.

Further studies on the inelastic seismic behavior of a structure model installed with and without VE dampers (Chang KC et al. 1996), as well as on the effect of temperature rises of VE dampers on their dynamic performance and the seismic responses of the installed structure (Chang KC et al. 1998), were conducted. It was revealed that adopting VE dampers can effectively reduce the inelastic ductility demand on the structure model under strong ground motions. Moreover, unless the structure was subjected to an extremely large earthquake, the temperature rise effect on the structural responses might not be very significant. To ensure that panel-type (or wall-type) VE dampers installed in a structure can behave in the expected form of shear deformation, installation schemes of VE dampers with and without in-plane lateral stiffeners were experimentally discussed (Chang KC et al. 1998). The experimental results showed that by using the former scheme, the undesired rotational behavior of VE dampers can be effectively avoided. Min et al. (Min KW et al. 2004) conducted vibration tests on a full-scale five-story steel frame equipped with VE dampers. The experimental results indicated that the structural response under harmonic excitation and band limited random noise can be effectively reduced because of the existence of VE dampers. Fu and Kasai (Fu Y and Kasai K 1998) compared the seismic performances of a ten-story steel structure model equipped with VE dampers and viscous dampers. It was demonstrated that VE dampers were able to reduce the seismic response of the installed structure model. Besides, with the same damping ratio, adopting VE dampers had a slightly better seismic response reduction than adopting viscous dampers. To verify the effectiveness of adopting VE dampers in reinforced concrete structures, Xu (Xu ZD 2007) tested a 1/5 scale-down three-story structure model installed with and without VE dampers. Based on the seismic reliability analysis of a hysteretic structure equipped with VE dampers performed by Guo et al. (Guo AX 2002), it was evident that adopting VE dampers can significantly enhance the reliability of the installed structure. Choi et al. (Choi H 2003) numerically verified that adopting VE dampers had a better displacement control performance for the installed structure than acceleration one.

Apart from new buildings, the adoption of VE dampers to seismically retrofit existing buildings attracted immense attention and has also been studied. Foutch et al. (Foutch DA et al. 1993) experimentally verified the effectiveness of adopting VE dampers for seismic retrofit of non-ductile reinforced concrete structures. A 1/3 scale-down damaged reinforced concrete structure model retrofitted by using VE dampers was experimentally and analytically studied (Shen KL et al. 1996). Crosby et al. (Crosby P et al. 1994) presented a practical case of applying VE dampers to a thirteen-story steel structure. All the experimental and numerical results showed that the retrofit strategy was effective in reducing the seismic response of the installed structure model due to the good energy absorption performance of VE dampers. It was worth noting that the adoption of VE dampers can effectively protect non-ductile reinforced concrete structures from brittle failure during earthquakes.

Apparently, most past researches relevant to VE dampers aimed at their design (or pre-damage) performance. Once the shear deformation of the installed VE dampers exceeds their nominal design range and thus cause damage to the dampers, if any, it might not be an economical and conservative design respectively when the viscoelasticaly damped structure is a supplemental damping design and a retrofit design. That is, without considering the contribution of damaged VE dampers, if any, the new building designed with VE dampers as supplemental damping, at most, is an uneconomical design but the structural safety is still guaranteed. However, for existing buildings retrofitted by VE dampers, damage to VE dampers may cause the design not conservative and, most importantly, the structural safety will not be guaranteed. Therefore, in this study, the beyond design and residual performances of the full-scale VE dampers after suffering damage are experimentally clarified and discussed. With considering appropriate reduction factors, the Kelvin-Voigt model is adopted to conservatively approximate the beyond design and residual performances of the full-scale VE dampers after damage occurs.

**2. EXPERIMENTAL STUDY**

***2.1 Test Specimens***

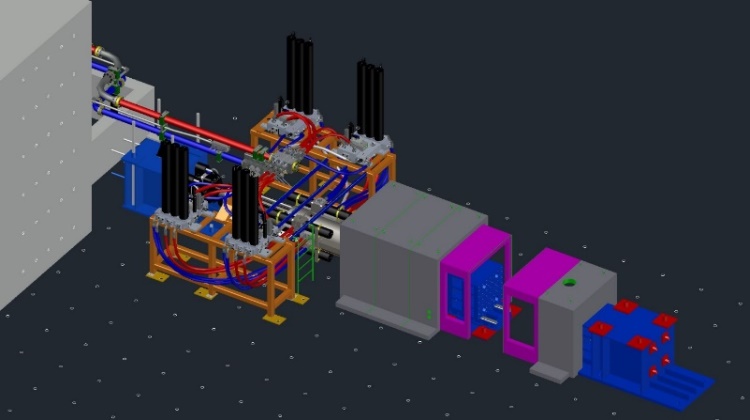
The two identical full-scale VE dampers in configuration and material are chosen as the test specimens in this study, denoted as Specimens A and B hereafter and as presented in Figure 1. Both were manufactured by the Nippon Steel Engineering Co., Ltd., and their design (or pre-damage) performance under maximum shear strains (*γ*max) not greater than 300 % have been tested in Wang et al.’s research (Wang SJ et al. 2018). Each damper specimen comprises four VE material layers (Type ISD111) of thickness 5 mm and area of 2500 cm2. The four VE material layers are designed in parallel and sandwiched between five steel plates. The nominal shear force capacity of each damper is 500 kN.

***2.2 Test Specimens***

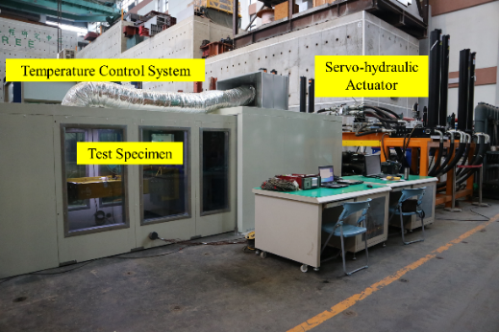
By using the high-performance damper testing facility at the Taipei Laboratory of the National Center for Research on Earthquake Engineering (NCREE) (Wang SJ et al. 2017), as shown in Figure 2(a), the VE damper specimens were dynamically tested subjected to uniaxial reversal loading, as shown in Figure 2(b). As presented in Figure 2(a), the testing facility consists of three steel reaction components, a temperature control system, and a high-speed servo-hydraulic actuator that possesses a maximum stroke capacity of ±600 mm and a maximum force capacity of ±2MN. The maximum velocity capacity is ±1 m/s when the force reaches ±1 MN. Pre-stressed steel bars are employed to mount the three reaction components on the strong floor as well as assemble the actuator, reaction components, and any necessary fixtures. The reaction component connected to the actuator piston end is designed with a linear guide system, thus guaranteeing a nearly perfect uniaxial movement control with very limited friction force. Test specimens are installed horizontally at the space between the two reaction components, which can be adequately adjusted in compliance with different size requirements. With the temperature control system, the ambient and operating temperatures of the specimens varying from 5°C to 50°C can be controlled and monitored in the chamber.



Figure 1. VE damper specimens



(a) High-performance damper testing facility

**Uniaxial Reversal Loading**

(b) Installation of test specimens

Figure 2. Test setup

***2.3 Measurement Sensors***

In addition to the built-in displacement transducer and load cell of the high-speed servo-hydraulic actuator for recording the test results, an additional linear variable differential transformer (LVDT) was installed on the VE damper specimens for measuring their pure shear deformation (i.e. excluding any deformation induced by other components, connections, fixtures, and etc. as well as any gaps) during the tests.

***2.4 Test Protocols***

In Wang et al.’s research (Wang et al. 2018), the design (or pre-damage) performance of the same VE damper specimens as those used in this study has been experimentally and analytically investigated. The previous test results under sinusoidal reversal loading, which are termed as the pre-damage (or design performance) test results hereafter, will be compared in this study as a counterpart. It was indicated that the specimens did not have any damage when subjected to sinusoidal reversal loading with maximum shear strains not greater than 300%, which conservatively implies that the nominal design range of the specimens should be larger than 300% shear strain. Therefore, the same sinusoidal reversal loading protocol but with larger shear strains is adopted in this study. To experimentally understand the approximate pre-damage range as well as the ultimate and beyond design performances of the specimens, various maximum shear strains greater than 300 % applied to Specimen A in this study, i.e. in sequence, from 480 % to 960 % with an increment of 120 %, are determined in an arbitrary manner. After testing with every shear strain, the tests under maximum shear strains of 60 % and 200 %, which are identical to those adopted in Wang et al.’s research (Wang et al. 2018) and are termed as the residual performance tests hereafter, were conducted on Specimen A. Through testing the same specimen before and after suffering damage, if any, its residual performance can be compared in a fair manner. To preclude the influences of previously experienced deformation and damage, if any, on the beyond and residual performance assessments of the specimens, only one maximum shear strain, i.e. 1000 %, was directly loaded to Specimen B. Afterward, likewise, the tests under maximum shear strains of 60 % and 200 %, which are also termed as the residual performance tests hereafter, were conducted on Specimen B. For each test condition in this study, an excitation frequency of 0.3Hz, an ambient temperature of 20 °C, and a cycle number of six are adopted, which are identical to those adopted in Wang et al.’s research (Wang et al. 2018). Note that for adequately cooling the specimens, there is a resting time period between performing each test condition. The test program in this study is detailed in Table 1. Based on the test results, some empirical post-damage models for appropriately and conservatively assessing the beyond design and residual performances of the VE damper specimens after suffering damage can be provided.

Table 1. Captions of tables; first letter capitalized, period at end, and centrally aligned.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Specimen | | A | | B | |
| Sinusoidal reversal loading | Excitation frequency (Hz) | 0.3 | | | |
| Maximum shear strain (%) | 480, 600, 720, 840, 960 | 60, 200  (after each shear strain level) | 1000 | 60, 200  (after 1000% shear strain) |
| Ambient temperature (°C) | 20 (±2°C tolerance) | | | |
| Number of cycles | 6 | | | |

***2.5 Test Results and Discussion***

The design (or pre-damage) performance of Specimens A and B tested before (Wang et al. 2018) under a maximum shear strain of 60% with excitation frequencies of 0.3 Hz and 1 Hz as well as at ambient temperatures of 10°C, 20°C, and 30°C is shown in Figure 3. The calculated characteristics of Specimen A, including the average shear storage stiffness *Kd,avg*, damping coefficient *Cd,avg*, and maximum shear force response *Fmax.avg* considering the test data of the intermediate five complete cycles (i.e. excluding the beginning half and ending half cycles) as calculated respectively in Equations 1 to 3 (FEMA273 1997), as well as the maximum shear force response *Fmax,beginning* obtained from the beginning half cycle, are tabulated in Table 2 for better comparison. In general, it can be concluded that (1) with the same displacement amplitude and ambient temperature, the higher the excitation frequency (or strain rate) is, the larger the shear storage stiffness and the smaller the damping coefficient are obtained; (2) with the same displacement amplitude and excitation frequency, the higher the ambient temperature is, the smaller the shear storage stiffness and damping coefficient are obtained; (3) the shear storage stiffness and damping coefficient are decreased with increasing the shear strain, i.e. the so-called softening phenomenon; and (4) the shear force amplification at the beginning half cycle becomes more significant when the test strain rate is higher, i.e. the so-called hardening behavior.

Table 2. Experimental design performance of Specimen A (Wang et al. 2018)

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Maximum shear strain (%) | 60 | | | | | | 200 | |
| Excitation frequency (Hz) | 0.3 | | | 1 | | | 0.3 | 1 |
| Ambient temperature (°C) | 10 | 20 | 30 | 10 | 20 | 30 | 20 | 20 |
| (kN/mm) | 47.81 | 25.15 | 15.72 | 80.83 | 39.55 | 22.23 | 19.27 | 30.78 |
| (kN-s/mm) | 28.31 | 12.11 | 5.79 | 16.52 | 6.88 | 3.24 | 9.49 | 5.17 |
| (kN) | 222.90 | 107.86 | 61.64 | 397.92 | 184.32 | 97.92 | 275.26 | 457.60 |
| (kN) | 199.44 | 98.79 | 57.94 | 387.72 | 175.74 | 93.29 | 316.95 | 621.30 |

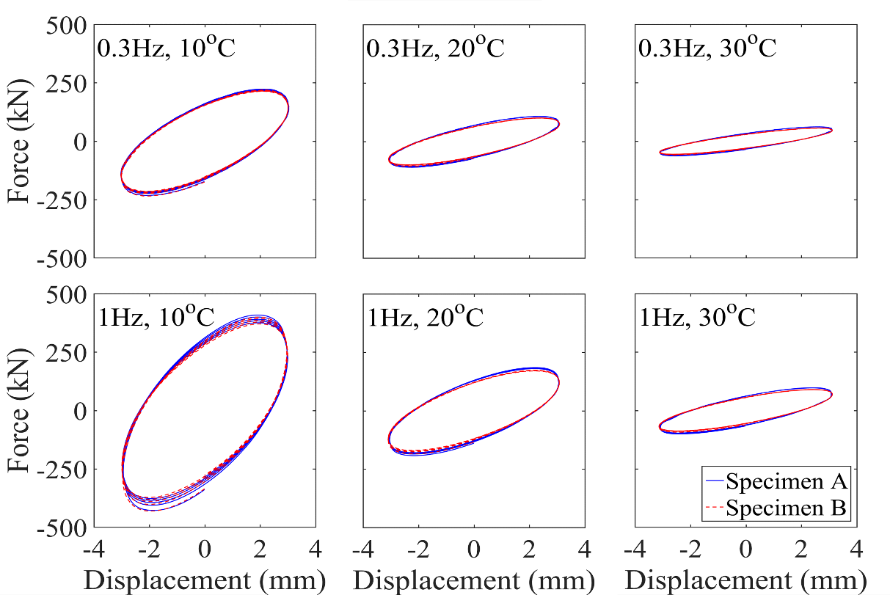


Figure 3. Experimental design performance of Specimens A and B under 60% shear strain [7]

 (1)

 (2)

 (3)

where and  are the positive maximum and negative minimum shear deformation at the *i*th cycle (excluding the beginning half and ending half cycles) of loading, respectively;  and  are the shear forces at  and , respectively;  is the calculated enclosed hysteresis loop area at the ith cycle of loading;  is the angular frequency of sinusoidal reversal loading; and  and  are the positive maximum and negative minimum shear forces at the *i*th cycle of loading.

The experimental force-displacement relation of Specimen A under 480 % to 960 % shear strain and the appearance photos after the tests are shown in Figure 4, and that of Specimen B under 1000 % shear strain and the appearance photo after the test are shown in Figure 5.

|  |  |
| --- | --- |
| 480%_0 | 600%_0 |
| (a) under 480% shear strain | (b) under 600% shear strain |
| 720%_0 | 840%_0 |
| (c) under 720% shear strain | (d) under 840% shear strain |
| 960%_0 |  |
| (e) under 960% shear strain | (f) appearance after tests |

Figure 4. Experimental design and beyond design performances and appearance of Specimen A

|  |  |
| --- | --- |
| 1000%_0 |  |
| (a) under 1000% shear strain | (b) appearance after tests |

Figure 5. Experimental beyond design performance and appearance of Specimen B under 1000% shear strain

As observed from Figure 4, the *Fmax,beginning* of Specimen A at the beginning half cycle, 1488.33 kN, occurs at 613 % shear strain. At almost the same shear strain level during the test, it was visually observed that the VE material layers had apparent damage in a tear failure mode. Accordingly, it is indicated that the test results of Specimen A under 480 % and 600 % shear strain in this study can also be termed as the pre-damage (or design performance) test results. According to analysis results, after Specimen A has apparent tear damage, the experimental mechanical properties *Kd,avg*, *Cd,avg*, and *Fmax.avg* are greatly decreased under 720 % shear strain compared with those under 600 % shear strain but have no further obvious reduction under higher shear strain (i.e. 840 % and 960 %). It is because the damaged VE material is in a paste-like state, in which there still exist a certain degree of bonding and friction forces between separate molecules. In addition, before damage occurs, the larger the shear strain is (or more precisely, the higher the strain rate is), the more significant shear force amplification at the beginning half cycle is obtained. The *Fmax,beginning* is almost triple as large as the nominal shear force capacity of the VE damper specimens, i.e. 500 kN. After damage occurs, the shear force at the beginning half cycle will never exceed the maximum experienced value but is still much larger than the nominal shear force capacity.

As observed from Figure 5, the *Fmax,beginning* of Specimen B at the beginning half cycle, 1610.22 kN, occurs at 622 % shear strain. At almost the same shear strain level during the test, it was visually observed that the VE material layers had apparent damage in a tear failure mode. Therefore, based on the test results of the two specimens, it is rationally concluded that the specimens can remain the expected design performance and almost intact without severe damage until the shear strain exceeds 600 % approximately. This conclusion can be further verified by comparing the experimental performances before and after the tests with 600 % shear strain with the analytical predictions. According to the almost identical test observation from the two specimens, it is implied that the influence of previously but not continuously experienced deformation on their damage occurrence moment is of insignificance.

The experimental force-displacement relation of Specimens A and B under 60 % and 200 % shear strain after the tests with maximum shear strains larger than 300% is shown in Figure 6. By comparing Figure 8 with Figure 5, it is evident that the residual shear storage stiffness and damping coefficient of the specimens after suffering damage become smaller than those before suffering damage. Nevertheless, compared with the residual performance of Specimen A under 720 % shear strain, the residual performances of Specimen A under 840 % and 960 % shear strain as well as Specimen B under 1000 % shear strain have no further obvious reduction. Similarly, it is because the damaged VE material is in a paste-like state, in which there still exist a certain degree of bonding and friction forces between separate molecules. By comparing the residual performance of Specimen A after the test with 960% shear strain with that of Specimen B after the test with 1000% shear strain, it can be seen that the influences of previously but not continuously experienced deformation and damage on the residual performance of the VE damper specimens are not significant. Hereafter, the beyond design performance test results under maximum shear strains of 720 %, 840 %, 960 %, and 1000 %, as well as the residual performance test results under maximum shear strains of 60 % and 200 % after each shear strain level aforementioned, are termed as the post-damage test results. The rest are termed as the pre-damage (or design performance) test results

|  |  |  |  |
| --- | --- | --- | --- |
| after480%_0 | after480%_0 | C:\Users\ncree20171121\AppData\Local\Microsoft\Windows\INetCache\Content.Word\after600%_0.3_0.3.bmp | C:\Users\ncree20171121\Desktop\ve_paperplot\figure7\after600%_0.3_1.bmp |
| (a) Specimen A after 480% shear strain | | (b) Specimen A after 600% shear strain | |
| after720%_0 | after720%_0 | after840%_0 | after840%_0 |
| (c) Specimen A after 720% shear strain | | (d) Specimen A after 840% shear strain | |
| after960%_0 | after960%_0 | after1000%_0 | after1000%_0 |
| (e) Specimen A after 960% shear strain | | (f) Specimen B after 1000% shear strain | |

Figure 6. Experimental residual performance of Specimens A and B

**3. PRE-DAMAGE ANALYTICAL MODEL**

The pre-damage analytical model based on the fractional derivative approach for characterizing the frequency-, temperature-, softening-, and hardening- dependent behavior of the intact VE damper specimens, as well as its identified coefficients, constants, slopes, and function from the test results under maximum shear strains not greater than 300% by using the least square method, has been thoroughly discussed in Wang et al.’s research (Wang et al. 2018). The theoretical details about the model can be obtained by referring to Kasai et al.’s (Kasai K et al. 1993 and 2001) and Wang et al.’s (Wang et al. 2018) researches.

**4. COMPARISON BETWEEN TEST RESULTS AND PREDICTIONS**

***4.1 Design Performance before Suffering Damage***

In this study, the same coefficients, constants, slopes, and function as those obtained in Wang et al.’s research (Wang et al. 2018), are adopted in the pre-damage analytical model for predicting the pre-damage (or design) performance of the VE damper specimens under 60 % and 200 % shear strain after the tests with 480 % and 600 % shear strain. The comparison between experimental force-displacement relation and prediction by the pre-damage analytical model for Specimen A is presented in Figure 10. To quantitatively evaluate the prediction accuracy, the coefficient of determination for force histories, , and an author-defined energy dissipation ratio, *EDR*, are correspondingly calculated as per Equations 4 and 5 and are also provided in the figure. Note that the values of and *EDR* closer to unity indicate that the prediction by the analytical model is more accurate. As observed form Figure 10, apparently, adopting the pre-damage analytical model could provide an excellent match of the pre-damage (or design performance) test results of Specimen A. Besides, it is analytically verified that the specimens are almost intact without severe damage after the tests with 480 % and 600 % shear strain.

|  |  |
| --- | --- |
| 20_0 | 20_0 |
| (a) under 60% shear strain after testing with 480% shear strain | (b) under 200% shear strain after testing with 480% shear strain |
| 20_0 | 20_0 |
| (c) under 60% shear strain after testing with 600% shear strain | (d) under 200% shear strain after testing with 600% shear strain |

Figure 7. Comparison between pre-damage experimental results and analytical predictions for Specimen A

 (4)

 (5)

where  and  are the predicted and experimental shear forces, respectively; the subscript *i* represents the data point at time ; the subscript *mean* represents the mean value of total data points during six cycles; *m* represents the total number of data points; and  and  are the predicted and experimental enclosed hysteresis loop areas, respectively.

***4.2 Beyond Design Performance after Suffering Damage***

In engineering practice, if the installed VE dampers have damage during an earthquake, the priority concern is whether the damaged damped structure can still survive safely in the continuously greater shaking or following aftershocks, rather than whether it can resist another earthquake event long time later. Afterward, the damaged damped structure should be retrofitted by replacing dampers or adopting other effective approaches, or should even be rebuilt. Under the circumstance, a conservative prediction that can approximately capture the damaged behavior of VE dampers through an efficient assessment process, rather than a very accurate prediction by using a very complicated approach, might have more engineering sense. Therefore, rather than adopting an exact post-damage analytical model, the Kelvin-Voigt model with reasonable and conservative reduction, which is called the empirical post-damage model hereafter, is recommended in this study to characterize the beyond design performances of the VE damper specimens after suffering damage.

On the other hand, only considering the intermediate five-cycle test data, the experimental beyond design performance of the damaged VE damper specimens under 720%, 840%, 960%, and 1000% shear strain is compared with the prediction by the pre-damage analytical model, as shown in Figure 8. For better and quantitative comparison, the reduction ratios of experimental mechanical properties and to the mechanical properties calculated from the pre-damage analytical results under maximum shear strains larger than 300% (i.e. 480%, 600%, 720%, 840%, 960%, and 1000%) are presented in Figure 9. Adopting the pre-damage analytical model, of course, will significantly overestimate the beyond design performance and mechanical properties of the damaged specimens. The comparison results shown in Figure 9 reveal that once the specimens have tear damage under maximum shear strains greater than 600%, their reduced shear storage stiffness and damping coefficient can remain steady and might be estimated through the originals multiplied by a constant reduction factor. the values of 0.15 and 0.42 can be regarded as sufficiently proper and conservative reduction factors for respectively estimating the reduced shear storage stiffness and damping coefficient of the damaged specimens under maximum shear strains greater than 600%. Accordingly, the beyond design hysteretic behavior of the damaged specimens can be simply and practically predicted by the Kelvin-Voigt model consisting of a spring with the reduced shear storage stiffness *Kd,reduced* and a dashpot with the reduced damping coefficient *Cd,reduced* connected in parallel as respectively given in Equations 6 and 7.

|  |  |  |  |
| --- | --- | --- | --- |
| 20_0.3_720 | 20_0.3_840 | 20_0.3_960 | 20_0.3_1000 |
| (a) Specimen A under 720% shear strain | (b) Specimen A under 840% shear strain | (c) Specimen A under 960% shear strain | (d) Specimen B under 1000% shear strain |

Figure 8. Comparison between beyond design performance test results and pre-damage predictions for Specimens A and B after suffering damage

|  |  |
| --- | --- |
|  |  |
| (a) Shear storage stiffness | (b) Damping coefficients |

Figure 9. Reduction of beyond design performances after tests with shear strains larger than 600%

 (6)

 (7)

where *κ*1 and *κ*2 are the reduction factors for estimating the residual (or reduced) shear storage stiffness and damping coefficient of damaged VE dampers.

The experimental beyond design performance of the damaged specimens only considering the intermediate five-cycle test data in comparison with the prediction by the empirical post-damage model is shown in Figure 10. The values of  and *EDR* are also provided in the figure for better understanding. It is found that the prediction by simply considering reduction factors in the Kelvin-Voigt model is still satisfactory in accuracy and conservative sufficiently. Although this empirical approach, as emphasized before, has more engineering sense in practice, an exact post-damage analytical model for predicting the beyond design performance of damaged VE dampers is still required to be investigated in the future, if the effect of the shear force amplification at the beginning half cycle on the overall structural seismic performance is not negligible.

|  |  |  |  |
| --- | --- | --- | --- |
| C:\Users\ncree20171121\Desktop\ve_paperplot\figure13\20_0.3_720_2.bmp | 20_0 | 20_0 | 20_0 |
| (a) Specimen A under 720% shear strain | (b) Specimen A under 840% shear strain | (c) Specimen A under 960% shear strain | (d) Specimen B under 1000% shear strain |

Figure 10. Comparison between beyond design performance test results and empirical post-damage predictions for Specimens A and B after suffering damage

**5. CONCLUSIONS**

In this research, the beyond design and residual performances of the full-scale VE dampers after suffering damage are experimentally investigated. It was rarely discussed in past relevant researches and practical applications. Some conclusions are made as follows.

1. The test results indicate that the VE damper specimens can remain the expected design performance and almost intact without severe damage before subjected to 600% shear strain approximately. When the specimens have tear damage, their beyond design and residual performances, in terms of the storage stiffness and damping coefficient, will be decreased significantly compared with the originals but can almost remain steady under higher shear strains. In addition, the influences of previously but not continuously experienced deformation on the damage occurrence moment of the specimens, as well as those of previously experienced deformation and damage on the residual performance of the damaged specimens, are less significant.

2. The test results show that before the VE damper specimens have tear damage, the higher the shear strain rate is, the more significant shear force amplification at the beginning half cycle is obtained. After suffering tear damage, the shear force at the beginning half cycle will never exceed the maximum experienced but is still much larger than the nominal shear force capacity. This hardening phenomenon should be considered very seriously for the detailed design of connected members and structures even if it might not affect the overall structural seismic performance very much.

3. To have more engineering sense in practice, an empirical post-damage model in which reasonable and conservative reduction factors are incorporated into the Kelvin-Voigt model is proposed to assess the experimental residual and beyond design performances of the damaged VE damper specimens. Except for the shear force amplification at the beginning half cycle, which will be further studied by using an exact post-damage analytical model in the future, it is demonstrated that the predictions by the empirical post-damage model are still satisfactory in accuracy and conservative sufficiently.

4. VE dampers made by different manufactures may have quite different mechanical properties. Therefore, the test performances discussed and the empirical models proposed in this paper are valid only for the tested VE dampers (Type ISD111) manufactured by the Nippon Steel & Sumitomo Metal Corporation.

**6. ACKNOWLEDGEMENTS**

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