QUICK INSPECTION METHOD OF U-SHAPED STEEL DAMPERS BASED ON RESIDUAL DEFORMATION

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Abstract

Post-earthquake functional recovery of damaged buildings plays an important role in urban disaster prevention. Therefore, it is necessary to identify the damaged parts and determine whether it can be used continuously after earthquakes as soon as possible. Comparing with conventional structures, possible damage of seismic isolation structure always concentrated on the isolated layer, which means that seismic isolation structure is a superior structure form from the viewpoint of post-earthquake functional recovery.

U-shaped steel dampers (U-damper) have been widely accepted and implemented in seismic isolation structure as energy dissipating devices because of its stable hysteretic characteristics and sufficient fatigue capacity. In Great East Japan earthquake 2011, none fracture and seriously damaged of U-dampers in the exciting buildings has been reported, which proved U-dampers' excellent plastic deformation capacity.

A damage evaluation method based on the residual deformation of U-Dampers is discussed in this study. Series of dynamic loading test of U-dampers were conducted to quantitatively grasp the residual deformation of U-damper caused by repetition deformation. Although a typical U-damper is made up by upper and lower base plates, a selected number of single U-damper and fixing bolts, only one-directional cycle test of single U-damper were carried out here. Furthermore, experimental results of previous researches are quoted here to enlarge the date base. The residual deformation ratio-cumulative damage relationship is illustrated in this paper. Residual deformation ratio which is the ratio of the maximum height to the original one is used to evaluate the residual deformation of U-dampers. On the other hand, deformation amplitude in the test is converted to horizontal shear angle in order to avoid the effects of the U-dampers' size.

The results can be summarized as following: (1) the proposed method is available for different size of U-Dampers by the normalized deformation and form change; (2) effect of the different deviations of deformation on the form change can be negligible in the same total amplitude; (3) No significant form change generating in small amplitude, another damage evaluation method is needed in this situation.

Keywords: U-Shaped Steel Dampers, Full-scale Specimen, Dynamic Loading Test, Damage Evaluation, Image Analysis

1. Introduction

Seismic isolation is an effective structural design approach to reduce the seismic response of the upper structure from foundation by configuring a special isolated layers which has low lateral stiffness and high compressive capability. Therefore, the vast majority of earthquake-induced energy is dissipated by the isolated layer, which means seismic isolation takes advantages in the quick inspection of damaged parts and this characteristic makes it a much more dominant structural technique from the viewpoint of post-earthquake functional recovery in the comparison with traditional ones.

In previous research, device like hysteretic type [1-4] and viscous type [5] are introduced to enhance the energy dissipation capacity of seismic isolation system. For hysteretic dampers, main members of the structure remain undamaged and energy dissipation is achieved through the friction damping caused by pendulum motion or metallic material's inelastic deformation capacity. This results in higher damping and consequently decrease the displacement and forces experienced by the structure. U-damper, a kind of hysteretic type of device which fabricated from high-quality rolled steel is widely applied in japan. Beacause of the lack of restoring force capacity, U-dampers are always used in combination with rubber bearings (Fig.1). Rubber bearings are introduced in the system to provide elastic restroing forces and to support the upper structure. However U-dampers can provide considerable lateral stiffness which helps the system minimum displacement and dissapate earthquake-induced energy with the preeminent inelastic deformation capacity of its specially designed U-shaped steel elements. Furthermore, the advantage of this system is that, different configurations (Fig.1) of U-damper are able to be applied in the system to suit the different types and magnitudes of loads present at particular structure support locations. Futhermore U-dampers are quick-replaceable because they are linked to the main members as enhanced semi-rigid connections, and this is really helpfull in functional recovery of the damaged building.

The method to evaluate the cumulative damage of U-dampers and to judge whether the dampers are still rich in energy dissapation capasity after earthquake is one of most important subjects in the commercialization of U-damper. Researches about U-dampers started from early 1990s. The basic hysteretic behaviour of U-damper and the corresponding influence of the temperature and loading speed have been studied after that [6-7]. Based on Miner's rule, Kishiki *et al*. (2012) [8] developed a cumulative damage evaluation method of U-dampers subjected to one direction excitation. ENE *et al*. (2015) [9] indicated that the ultimate inelastic deformation capacity of U-damper is reduced because of the effect of torsion stresses occurring in the steel element based on huge amounts of bidirectional loading tests, and published their damage evaluation method based on analytical results of a multiple shear spring (MSS) model in 2017 [10]. All of these assessment methods are difficult to operate without computer and professional knowledge, therefore, a more convenient quick inspection method of U-damper is needed to optimize its advantages in functional recovery of damaged buildings.

Damage assessment of damaged members based on visible damage such as residual deformation and crack trends to be the mainstream of urban disaster prevention. Previous researches indicated that cyclic loading induced residual deformation of U-dampers (Fig.2) always concentrate on the middle of their parallel arms [6]. A quick inspection method of U-dampers based on residual deformation (shape change) will be discussed in present study. Although huge amounts of cyclic loading tests had been conducted in previous researches, no information about the detail of dampers' residual deformation had been recorded. Therefore, the first step towards acquiring sufficient knowledge in this direction is to conduct loading test using one-direction excitation and to establish residual deformation-cumulative damage relationship of the dampers.

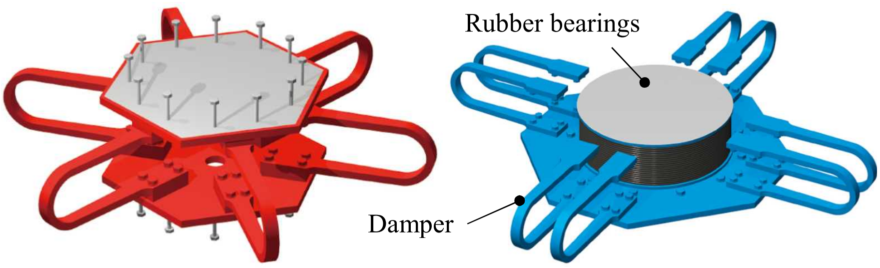


Fig. 1 – Various configurations of U-dampers [11].

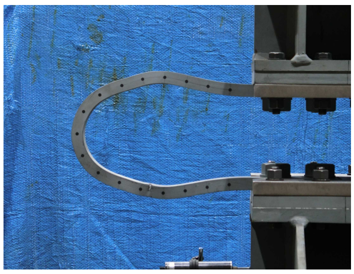


Fig. 2 – Shape change.

2. Cyclic loading test with one-direction excitation

The energy dissipation capacity of U-damper is achieved by the yielding of U-shaped steel elements, which is caused by a combination of bending and local torsion. How these complicated behaviors influence damper's residual deformation-cumulative damage relationship will be discussed in further study, only one-directional cyclic loading tests of single U-damper were conducted in the initial stage of this research. Furthermore, U-dampers are usually integrated with rubber bearings or placed under elements that don't transmit vertical force, which means they are not designed for supporting the upper structure. Therefore, no vertical loads were applied in tests.

2.1 Outline of specimen

Specimens in present study are full-scale U-dampers which are same in size. U-damper is fabricated from high-quality rolled steel SN490B. The U shape is fabricated by cold bending and heat treatment is given to enhance the mechanical property of the dampers. Representative dimensions of specimens are shown in Fig.3 and table 1. In order to indicate the influence caused by the difference of U-damper's size, test result of the U-dampers in different size [12] are quoted here to enlarge the date base, and the dimension of them is listed in Table.1 as well. To be a supplementary explanation, from specimens in this experiment to that of previous research, apart from the scale (which ranges from 1.00 to approximately 1.40), the manufacture process, material specifications and proportions of geometric characteristics keep the same.

Table 1 – Chemical composition of cement samples

	Dimension				
	h_o	w_1	w_2	l	t
Present research	232	60	45	416	28
Previous Research [5]	335	87	65	602	40

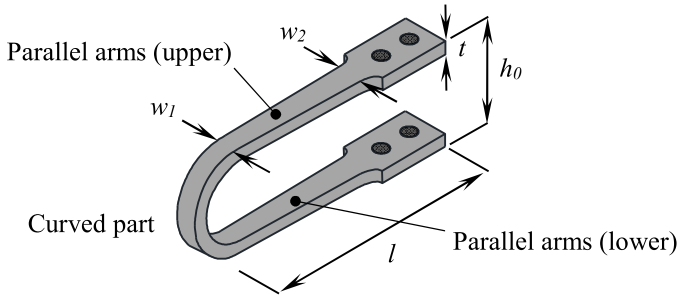


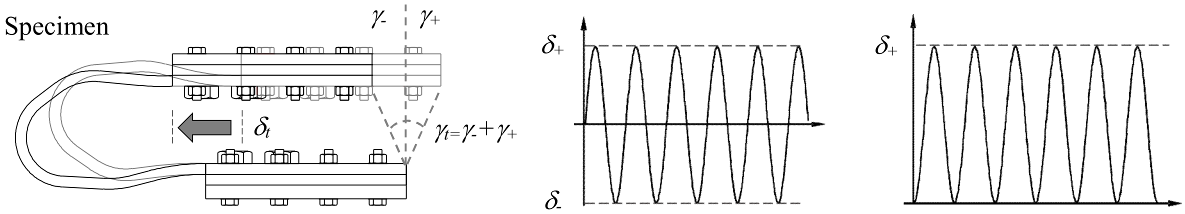
Fig. 3 – Dimension of specimen.

2.2 Test Program and loading equipment

Deformation amplitude of loading histories and amplitude deviation are the variables in the loading tests. In order to establish the residual deformation-cumulative damage relationship for U-dampers in different size by same index, U-damper's peak-to-peak deformation amplitude δ_t is converted to horizontal shear angle γ_t. The definition of γ_t is shown in Fig.4 (a) and Eq.1, which is the proportion of U-damper's peak-to-peak deformation amplitude δ_t to original height of specimen h_0.

$$\gamma_t = \frac{\delta_t}{h_0} \times 100\% \quad (1)$$

As shown in Table 2, five specimens in total were tested in this study. All specimens were loaded dynamically (sine wave) at room temperature at a loading speed of 4mm/s in average. Variable for specimen No. 1, 2, 3, 5 is horizontal shear angle γ_t (γ_t=25, 55, 70, and 110%). Although specimen No.3 and No.4 are same in horizontal shear angle γ_t (γ_t=55%), they are different in amplitude deviation and distinguished into No offset γ_t=55% (Fig.4 (b)) and offset γ_t=55% (Fig.4 (c)). No offset γ_t=55% means γ_-=γ_+=22.5% are given in both positive and negative sides, in contrast, offset γ_t=55% means amplitude γ_+=55% is only given in positive side.



(a). Definition of γ_t and δ_t (b). No offset (c). Offset

Fig. 4 – Experimental varibles

Table 2 – Specimen list and fatigue life.

	No.	γ_t	amplitude（mm)	Amplitude deviation	Fatigue life (cycle)
Present research	1	110%	±127.6	No offset	128
	2	70%	±81.2	No offset	312
	3	55%	±62.4	No offset	418
	4	55%	+127.6	offset	302
	5	25%	±2.9	No offset	1381
Previous Research	1	40%	±67	No offset	617
	2	70%	±118	No offset	267
	3	150%	±251	No offset	64
	4	300%	±502	No offset	25

Set-up of these tests are shown in Fig.5. Specimens are tested under horizontal loading in 0 degree with respect to the symmetry axis of U-damper. The lower arm of specimen is connected to reaction jig fixed on reaction beam through several base plates to get reaction force. The upper arm is connected to loading unit through base plates and loading jig, while loading unit is installed on parallel rails of reaction beam and connected to actuator (2000kN) by PC bar. Therefore, horizontal cyclic deforming force under sinusoidal displacement is able to be applied to the specimens by actuator until specimens' fracture.

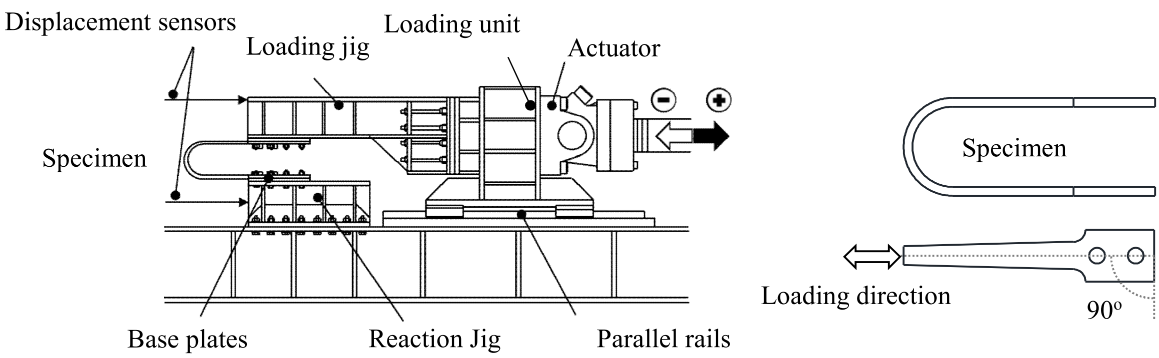


Figure. 5 – Set-up.

2.3 Measuring plan

Force-deformation relationships of specimens were recorded in loading tests. Horizontal force in system were measured by a load cell installed in loading unit. Deformation of specimens was obtained through the real-time displacement recorded by the displacement sensors shown in Fig.5.

Image analysis was used to estimate the residual deformation of U-dampers. Digital camera which was fixed almost 2 meters away from specimen recorded the U-dampers' shape change at the timing of γ_t=0% and positive/negative peak deformation. Based on the fatigue behaviour illustrated in Kishiki *et al.* (2008) [7], photo was taken at 1% each until 20% of the predicted loading cycles till fracture, thereafter 10% each till fracture. In order to verify the precision of Image analysis, measurements of specimen's residual deformation (distance between measurement points P_4 and P_{14} in Fig.6) were performed through metal scale at 10% each of the predicted loading cycles till fracture. Residual deformation of specimens were converted to index ξ to eliminate the influence of U-dampers' size. The definition of residual deformation ratio ξ is shown in Eq.2. Here, h_t represents the U-dampers' residual deformation at any timing, h_0 means U-dampers' original height (refer to Fig.7).

$$\xi = \frac{h_t}{h_o} \tag{2}$$

17 measurement points in total with diameter of 7mm were drawn on specimens before loading test (Fig.6). Thereafter based on the photos taken during loading test, image analysis software "Dipp-Motion V" [13] was used to complete the action tracking of each measurement point in the coordinates with the origin located at P_{18}. In addition, at the timing of γ_t=0%, loading tests were stopped temporarily to make sure that the shape change of specimen can be accurately recorded, however, error less than 4mm still occurs in the comparison with metal scale measured results.

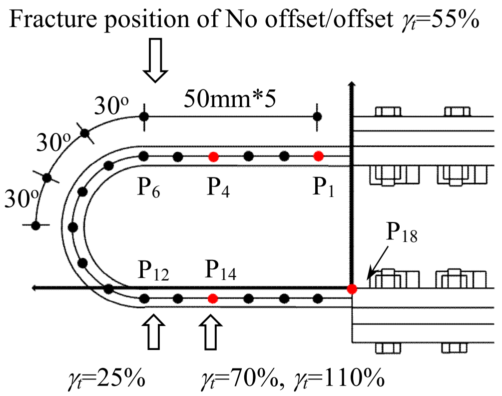


Figure. 6 – Fracture point and measurement point

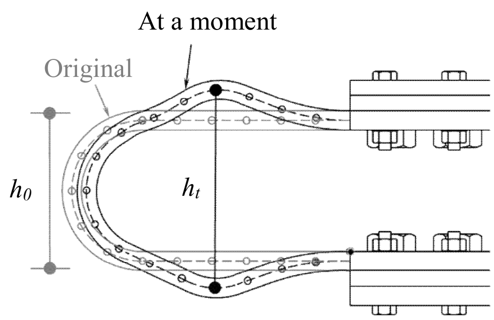


Figure. 7 – Residual deformation h_t.

Furthermore, cumulative damage of U-damper (D) is defined as the ratio of cycle number at any timing (n_i) to the loading cycles till fracture (n_f) (refer to Eq.3).

$$D = \frac{n_i}{n_f} \tag{3}$$

3. Experimental result and consideration

Hysteresis behaviour, fatigue behaviour and shape change of specimens will be checked in this section.

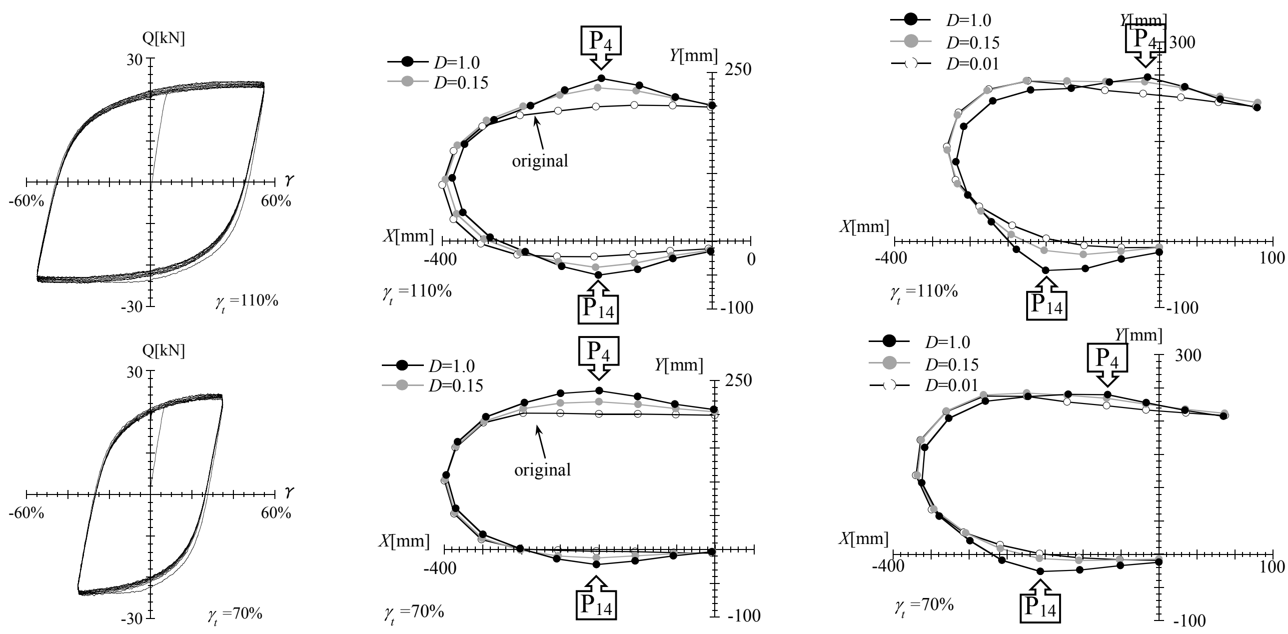
3.1 Force-deformation relationship

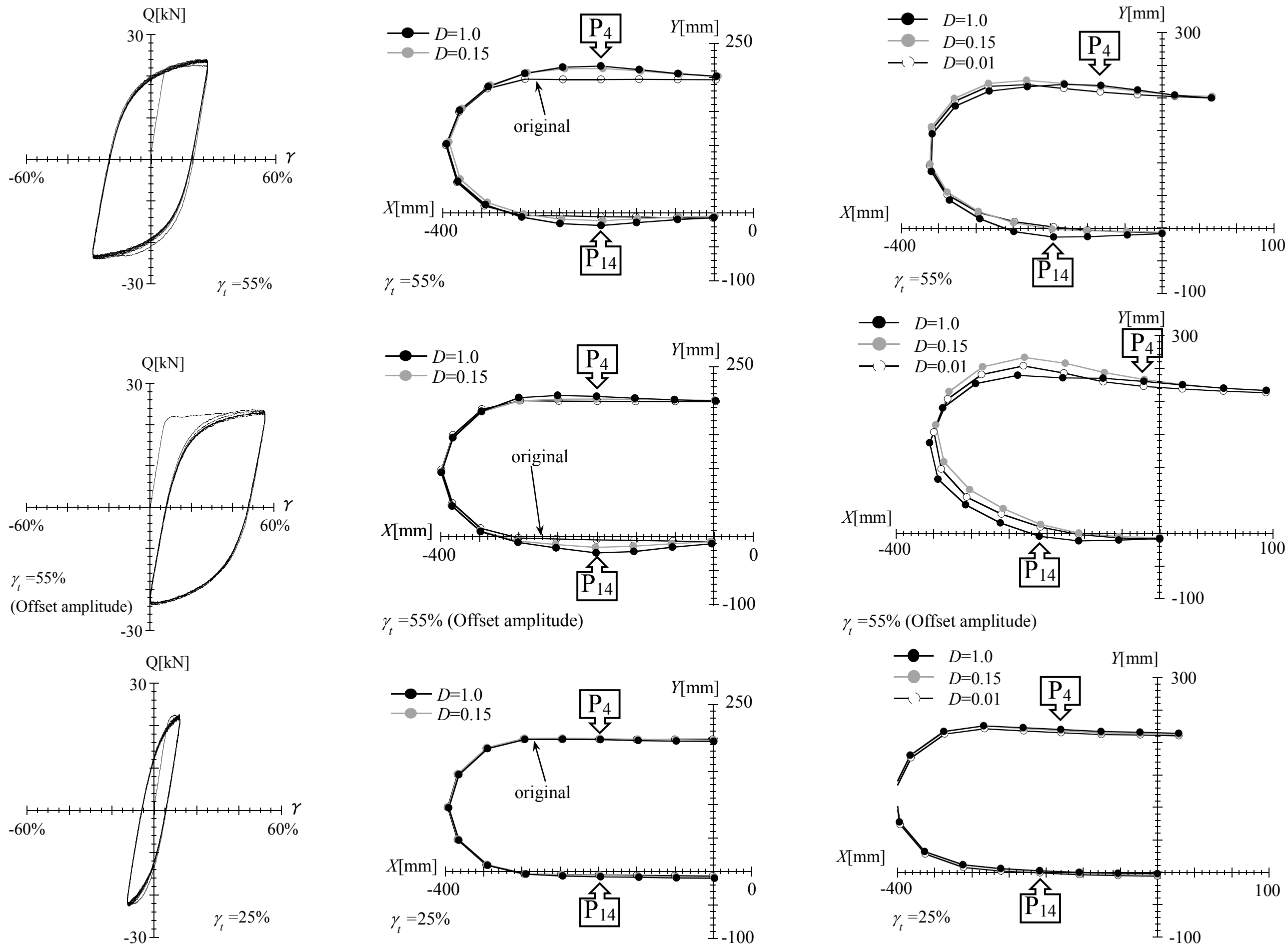
U-dampers are composed of metallic material with high ductility. Dampers' full and stable hysteresis loops (Fig. 8(a)) indicate their preeminent energy dissipation capacity. The ductile fracturing for each specimen was confirmed at the end of loading test when the force in the specimen decreased rapidly and showed a negative high-order stiffness. Fig.6 indicates the fracture point of all specimens. For Specimen γ_t=25% and 55%, fracture occurs at the root of U-damper's curved part corresponding to measurement points P6 and P12. In contrast, specimens with larger horizontal shear angle (γ_t=70% and 110%) approximately fracture at the middle of U-damper's parallel arms (between measurement points P13 and P14). This is almost consistent with the experimental results of Kishiki *et al*. (2008) [7]. It is worth mentioning that specimen no offset and offset γ_t=55% fractured at the same location and the outline of their force-deformation relationships shows high consistency with each other, which means the hysteretic behaviour of U-damper is not strongly affected by the amplitude deviation of cyclic loading.

3.2 Deformation behaviour

No significant shape change emerged on the parallel arms of specimen γ_t=25%, while for the other specimens, cyclic bending induced ductile cracks initiated on both parallel arms of the dampers, and was concentrated mainly on the middle of parallel arms (between measurement points P4 and P14). It can also be confirmed that the residual deformation h_t increased with the growth of cumulative damage D at the timing of γ_t=0% (Fig.8 (b)) in cyclic loading test. Similar to the case of γ_t=0%, when reached the peak deformation in positive side (Fig.8 (c)) h_t increased in the same way. Displacement of isolation seismic system is considered to return to 0 after earthquake, which means h_t of U-dampers installed in the system grows up in the way shown in Fig.8 (b). Therefore, it is reasonable to use the distance between measurement points P4 and P14 to describe the shape change and evaluate the cumulative damage of dampers.

To be a supplementary explanation, for specimens with small horizontal shear angle γ_t, softening of metallic material caused by Bauschinger effect trends to be much more remarkable from cycle No.2. This results in a significant decrease of material's yielding strength, which means damper is not been significantly influenced by non-linear behaviour and less cyclic bending induced ductile cracks emerges when γ_t is smaller than 55% in present study. This is considered to be the reason why specimens with small γ_t fractured at the root of curved part rather than the middle of parallel arms and why no significant shape change emerged on the parallel arms of specimen γ_t=25%.





(a). Force-deformation relationship (b). Shape change (γ_t=0%) (c). Shape change (peak deformation)

Figure. 8 – Force-deformation relationship and shape change.

3.3 Fatigue characteristics

Fatigue behaviour can't be ignored in the application of U-damper. Horizontal shear angle γ_t is used for fatigue behaviour assessment in present study to eliminate the influence caused by the difference of dampers' size. Refer to the investigation of U-dampers' fatigue behaviour in Kishiki *et al.* (2008) [7], replacing the strain amplitude in Manson-Coffin law with γ_t (Eq.4), the relationship between horizontal shear angle γ_t and loading cycles till fracture n_f of single U-damper are plotted in Fig.9. Test result in present study responds to Eq.4 very well and the fatigue behaviour of specimens are all conservatively estimated by Eq.4. γ_t is proved to be an available index in fatigue behaviour assessment of U-damper.

$$\gamma_t = 35n_f^{-0.15} + 3620n_f^{-0.80} \tag{4}$$

It is worth noting that, although the loading cycles till fracture n_f of specimen offset γ_t=55% (302 cycle) is almost 70% of that of no offset γ_t=55% (418 cycles), both of them are still able to be estimated by Eq.4. Therefore, it is considered to be reasonable to neglect the effect caused by amplitude deviation in assessment of U-dampers' fatigue behaviour.

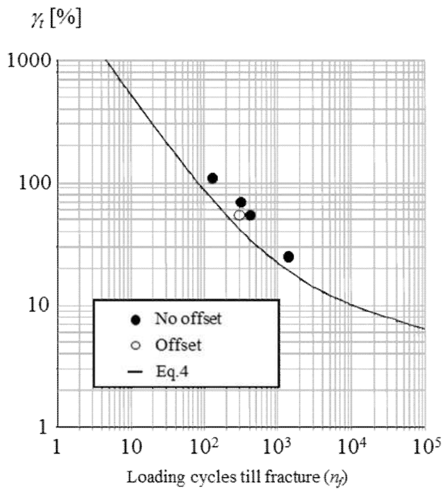
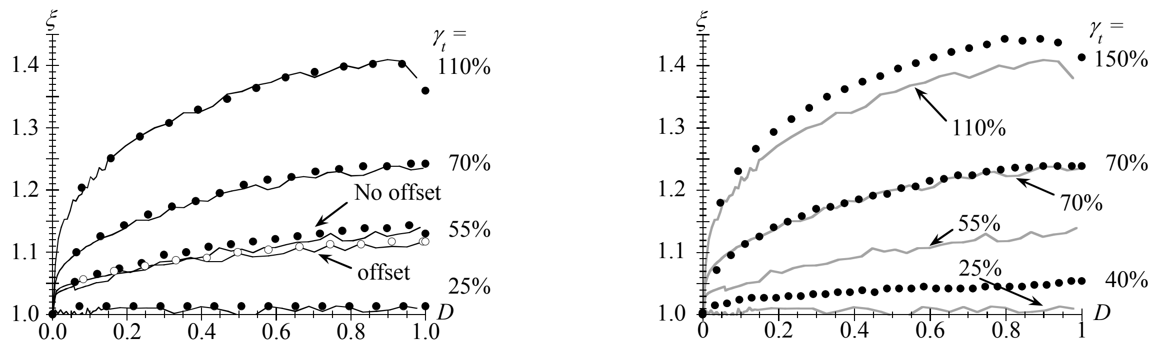


Figure. 9 – Fatigue behaviour of U-damper.

3.4 Residual deformation ratio-cumulative damage relationship

Specimens' residual deformation ratio-cumulative damage relationships (ξ-D) are shown in Fig.10 (a). Here, measurement result of metal scale (spot) is completely consistent with the result of image analysis (black line). Image analysis is able to trace the shape change of U-damper accurately.



(a) (b)

Figure. 10 – Residual deformation ratio-cumulative damage (ξ-D) relationship

The residual deformation increases rapidly till cumulative damage D reaches 0.1, and the increase of the residual deformation in each γ_t reminds nearly stable from D=0.2 until the end of loading test. This tendency is most remarkable in the case of specimen γ_t=110%. It is easy to observe that residual deformation increase with the growth of cumulative damage, and the shape change becomes much more obvious with the increase of horizontal shear angle γ_t. As above-mentioned, for specimen which is large in horizontal shear angle γ_t, shape change is obvious and visible to the naked eye (For specimen γ_t=110%, h_t reached 296 mm at the end of cyclic loading test), in contrast, for specimens with small γ_t (γ_t=25%), no obvious shape change occurs till its' fracture. Therefore, in the case of small horizontal shear angle (less than 25% in present study), residual deformation ratio ξ is not an effective index in the evaluation of cumulative damage. Another evaluation method is required for this situation.

Specimen no offset and offset γ_t=55% share almost the same residual deformation ratio-cumulative damage relationship. Apart from this, as above-mentioned, the outline of their hysteresis loops and their fracture point are similar with each other. To summarize, amplitude deviation is negligible in cumulative damage evaluation of U-damper.

The comparison with the test results of reference [12] is shown in Fig.10 (b). Test results of this experiment are shown by gray line, and test results of previous research are shown by spot. Shape change of specimen γ_t=150% from previous research is much more obvious than that of specimen γ_t=110% from this experiment. Similarly, ξ-D relationship of specimen γ_t=40% from previous research emerges between that of specimen γ_t=25% and specimen γ_t=55% from present study. Totally speaking, the results of this experiment and reference [12] are mutually complementing each other. On the other hand, for ξ-D relationships of specimens which are same in horizontal shear angle (γ_t=70%), although the two specimens are different in size, ξ-D relationships are completely consistent with each other. It means that horizontal shear angle γ_t is an effective index in cumulative damage evaluation for U-dampers in different size.

3.5 Residual deformation ratio-horizontal shear angle (ξ-γ_t) relationship

Based on the above-mentioned investigation, a primitive form of U-dampers' quick inspection method is proposed in this section. For a specific cumulative damage D, the relationship between horizontal shear angle γ_t and residual deformation ratio ξ can be organized as Fig.11. γ_t of U-dampers can be obtained easily from the displacement orbit recorded by scratch plate device [14] ((a) in Fig.11), and ξ of U-dampers can be obtained in short time by measuring the residual deformation which emerges between U-dampers' parallel arms after earthquake ((b) in Fig. 11). At last, cumulative damage of this damper can be estimated from the intersection of (a) and (b) in Fig.11 (about 0.1 in this case).

Although both of the ξ-D relationships of present and previous studies were used in the establishment of ξ-γ_t relationships in Fig.11, image analysis was not applied in reference [12], and the ξ-D relationships of the specimens in reference [12] were established by connecting the metal scale measured results (spot in Fig.10 (b)) into line (no records left when D is less than 0.05). However, As mentioned in section 4.1, residual deformation increases rapidly till D reaches 0.1, which means records in reference [12] were too short to reflect the real shape change of dampers in the initial stage of cyclic loading test. This is the reason why there are no ξ-γ_t relationships for D less than 0.05 in Fig.11.

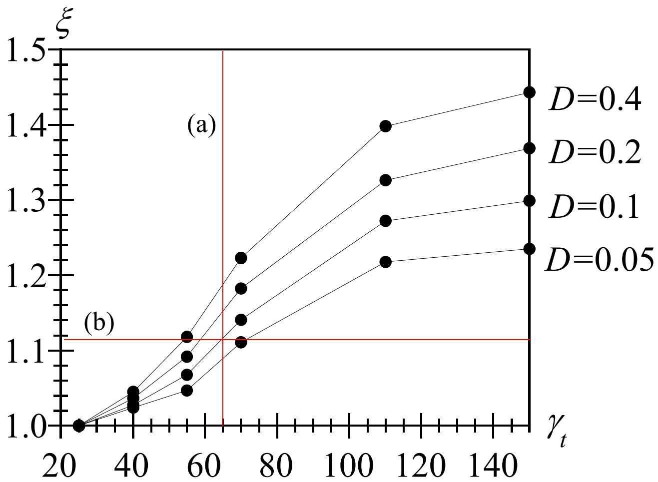


Fig. 11 – Horizontal shear angle-shape change rate (ξ-γ_t) relationship.

4. Conclusions

U-shaped steel damper is widely accepted and implemented in seismic isolation system as energy dissipating device. Series of full-scale experiments were carried out to quantitatively grasp the residual deformation of U-damper caused by cyclic loading in present study. The residual deformation ratio-cumulative damage relationship of U-damper is illustrated, and a quick inspection method of U-damper based on shape change is discussed as well. The results obtained from this experiment are summarized below.

[1] Results of cyclic loading tests verify that cumulative damage of U-dampers is related to their residual deformation. Indexes investigated in present study (horizontal shear angle γ_t and residual deformation ratio ξ) are effective in cumulative damage evaluation of U-damper.

[2] When U-dampers are same in horizontal shear angle γ_t, difference in amplitude deviation is negligible in cumulative damage evaluation.

[3] Cumulative damage of U-dampers in different size can be evaluated through the same residual deformation ratio-cumulative damage (ξ-D) relationship as long as they are same in horizontal shear angle γ_t.

[4] No obvious shape change emerges on the parallel arms of U-dampers when horizontal shear angle γ_t is too small (less than 25% in present study). Another evaluation method is need in this situation.

5. Acknowledgements

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