Evaluation of the fatigue life and behavior characteristics of U-shaped steel dampers after extreme earthquake loading

Y. Konishi, N. Kawamura & M. Terashima
Nippon Steel Engineering, Co., Ltd., Tokyo, Japan

S. Kishiki
Osaka Institute of Technology, Osaka, Japan

S. Yamada
Tokyo Institute of Technology, Yokohama, Japan

I. Aiken & C. Black
Seismic Isolation Engineering, Inc., Emeryville, CA, USA

K. Murakami & T. Someya
Nikken Sekkei, Ltd., Tokyo, Japan

SUMMARY:
U-shaped steel dampers are widely used as energy dissipation devices for seismically-isolated structures in Japan. They have been extensively used for hospitals, residential buildings and many other types of isolated structures since the Hyogo-ken Nanbu (Kobe) Earthquake in 1995. A U-shaped damper dissipates earthquake energy through the plastic deformation of specially shaped steel elements. To establish damper fatigue limit state properties, numerous quasi-static and dynamic testing programs have been conducted. Following the M9.0 Great East Japan Earthquake a U-shaped damper from a large essential facility in Miyagi prefecture was removed from the building and subjected to a detailed testing investigation to evaluate the existing fatigue life models that have been developed for U-shaped dampers. This paper presents an overview of fatigue life testing conducted prior to the earthquake, results of the post-earthquake testing program as well as conclusions regarding residual fatigue for U-shaped dampers subjected to earthquake loading.

Keywords: U-shaped steel dampers, seismic isolation, Great East Japan Earthquake

1. INTRODUCTION

The M9.0 Great East Japan Earthquake that struck the north east coast of Japan on March 11th 2011 caused significant and long duration shaking over a very large area of Japan. Numerous seismically isolated buildings were in regions of strong shaking, including a number of buildings that included U-shaped dampers as part of the isolation system. The shaking experienced was the strongest ever seen by isolated buildings and resulted in maximum horizontal displacements of 20-25 cm in a number of cases, and in one instance a maximum movement of 41 cm.

The severity and duration of shaking presented an unusual opportunity to evaluate the residual large-deformation fatigue life of U-shaped steel dampers after actual earthquake loading. A U-shaped damper from a large essential facility in Miyagi prefecture, about 120 km from the epicentral region, was removed from the building after the earthquake and subjected to a detailed testing investigation to evaluate its remaining cyclic fatigue life. The investigation included a detailed assessment of the displacement pattern that the damper experienced in the earthquake, and uni- and multi-directional loading tests to failure, based on the assessed earthquake displacement pattern, to assess the residual fatigue life. The paper presents an overview of the investigation and testing program, along with conclusions regarding residual fatigue life, on the basis of the existing fatigue life models for U-shaped dampers and the results of the post-earthquake testing program.

2. EXPERIMENTAL TESTING

A complete U-shaped damper unit comprises four, six or eight individual U-shaped elements, or arms, which are symmetrically located between top and bottom connection plates. The configuration of the individual U arms is such that directionality effects on overall damper behavior are minimized. As part of the detailed design of the damper, the thickness and number of the U arms are design variables that allow different damper strength characteristics.

To establish damper fatigue limit state properties, numerous uni-directional, quasi-static and dynamic cyclic loading tests have been conducted on single- and multiple-U arms. Multi-directional loading tests have also been performed to verify the behavior of the dampers under generalized earthquake loading conditions.

2.1 Uni-directional Quasi-static and Dynamic Testing

An extensive testing program was conducted in Japan to study the uni-directional response of 32 full-size, U-shaped damper arms (Kishiki et al., 2008). As the response of U-shaped dampers is dependent on loading orientation, the loading protocol was designed to evaluate the fatigue life for loading in the longitudinal (0°) direction, the transverse (90°) direction, as well as loading in the cross-direction at 45° (see Figure 1). Quasi-static testing amplitudes as large as 500mm and dynamic tests ranging from +/- 30mm to +/- 250mm were conducted on three specimen sizes designated S, M and L. Table 1 lists the sizes of the U arms tested.

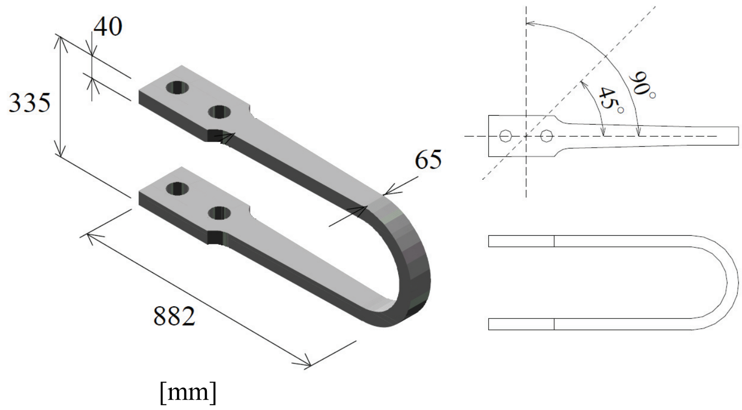


Figure 1. Typical U-shaped damper element

2.2 Large Amplitude Dynamic Testing and Generalized Earthquake Loading

In addition to the testing described above, large amplitude testing was conducted using the Seismic Response Modification Device (SRMD) testing machine at the University of California, San Diego in 2007 (Nishimoto et al., 2008). For this testing program a single size similar to the medium-sized U element (M) considered in the above testing was studied (see Table 1). A total of six individual U arms were tested; a large amplitude (± 750 mm) and a medium amplitude (± 400 mm) test was conducted in each of the three loading directions 0°, 45° and 90°. The specimens were loaded cyclically until failure.

Table 1. Specimen Sizes [mm]

Specimen	t	w	Length	h
S	28	45	611	232
M	40	65	882	335
L	55	88	1200	454
UCSD M	40	65	882	335

In addition to the testing of singe U elements, multi-directional testing of two complete U-shaped damper units comprising four arms was performed. The input displacements for the tests of the 4-arm U-shaped damper units were computed responses of a 7-story isolated building subjected to the JR Takatori 1995 Kobe Earthquake, the Koçaeli record of the 1999 Izmit Earthquake and the El Centro record of the 1940 Imperial Valley Earthquake. A photo showing one of the damper units installed in the test machine is shown in Figure 2.

Figure 2. A four-arm U-shaped damper assembly in the UC San Diego, SRMD test machine

2.3 Evaluation of Fatigue Performance

In order to evaluate the fatigue performance of the different specimens in a unified manner, test data was reduced on the basis of average shear deformation angle, γ, obtained by dividing the horizontal deformation of the U-damper, δ, by the total height of the arm, h (Fig. 3).

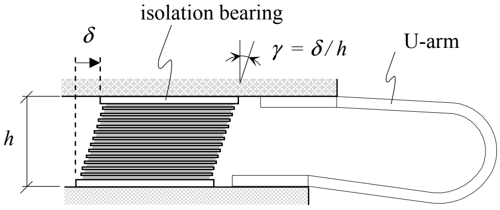


Figure 3. Definition of average shear deformation angle, γ

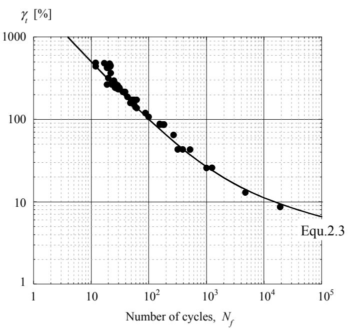
The *Manson-Coffin* relation is used to define the fatigue curve for the U-shaped damper arm. The strain amplitude in the *Manson-Coffin* relation is replaced by the amplitude of the average shear deformation angle, γ. Regression analysis is used to calibrate the *Manson-Coffin* relation in order to estimate the number of cycles to fatigue fracture, N_f, for each of the shear deformation angles, γ_t, γ_e and γ_p, which correspond to the total deformation amplitude, δ_t, elastic deformation amplitude, δ_e, and plastic deformation amplitude, δ_p, respectively. Note that, in the case of constant amplitude, fully-reversed cycles, γ_t corresponds to two times the average shear deformation angle, γ. Using this formulation, the following three equations are obtained for damper behaviour in the 0° loading direction:

$$\gamma_e = 35N_f^{-0.15} \tag{2.1}$$

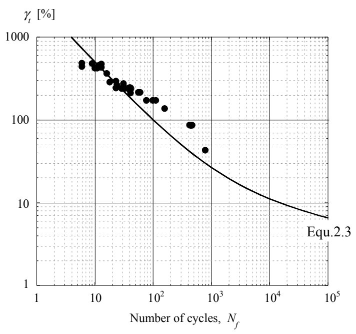
$$\gamma_p = 3620N_f^{-0.80} \tag{2.2}$$

$$\gamma_t = 35N_f^{-0.15} + 3620N_f^{-0.80} \tag{2.3}$$

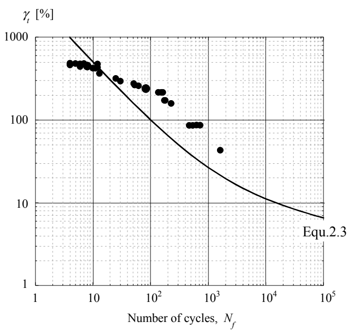
The resulting fatigue curve is shown in Fig.4 by the solid line. The black circles indicate results from the test programs described in Secs. 2.1 and 2.2 above (Kishiki et al., 2008a, Kishiki et al., 2008b). A comparison of the fatigue curve and the experimental results obtained for loading in the 0° direction (Fig. 4a) shows good agreement with observations from all previous tests. As these plots include test specimens of different sizes it is seen that the fatigue performance (the number of cycles to fatigue fracture, N_f) is largely independent of the size of the test specimen for loading in the 0° direction. It can be seen that the 0° direction fatigue curve provides a conservative prediction of fatigue life for all directions of loading.



(a) 0° loading direction



(b) 45° loading direction



(c) 90° loading direction

Figure 4. Comparison of Manson-Coffin equation and experimental results for number of cycles to fatigue failure

Next, the number of cycles to fatigue fracture is examined in the 45° and 90° directions. Figs. 4b and 4c show the comparison of the 0° direction fatigue curve with the test data for the 45° and 90° directions, respectively. The plots show that for the total shear deformation angle, γ_t, in the range of 40-400%, the number of cycles to fatigue fracture in the 0° direction is less than that in the other directions (evidenced by the fact that the experimental results lie above the fatigue curve calibrated for the 0° direction). For larger deformations, when γ_t is greater than about 400%, the number of cycles to fatigue fracture in the 45° and 90° directions is less than that in the 0° direction.

2.4 Influence of Rate of Loading on Mechanical Behaviour and Fatigue Life

A comparison of the force-deformation response obtained from quasi-static and dynamic loading tests shows that there is a small increase in damper force in the dynamic tests, however, this increase is less than 10% for all loading cases considered (Kishiki et al., 2008a). For this reason, it is concluded that the influence of rate of loading on the mechanical behavior of U-shaped dampers, including stiffness and strength, is relatively minor. In addition, a comparison of the fatigue performance of the test specimens subjected to quasi-static and dynamic loading shows that rate of loading does not have an appreciable effect on the fatigue performance (Kishiki et al., 2008a).

3. EVALUATION PERFORMANCE OF U-SHAPED DAMPERS UNDER SEVERE EARTHQUAKE LOADING

3.1 Seismically-Isolated Buildings in the Great East Japan Earthquake

More than 100 seismically-isolated buildings are located in the Miyagi, Iwate and Fukushima prefectures, the region that experienced the strongest levels of shaking in the M9.0 Great East Japan Earthquake of March 11, 2011. Based on first-hand observations by some of the authors, instrument and other displacement records and information, it is believed that several dozen buildings experienced shaking that caused maximum displacements in the range of 20-30 cm. A number of these buildings used seismic isolation systems comprising rubber bearings and U-shaped steel dampers. The largest movement of an isolated building in the earthquake was 41 cm, and this also occurred in a building with U-shaped dampers. Because of the significant movement of many isolated buildings, and the extremely long duration of shaking that occurred in the main shock and the subsequent very large number of significant aftershocks, there has been particular interest in the continued integrity of isolation devices, and particularly the residual capacity of devices that have explicit fatigue life capacity, such as yielding steel elements. A unique opportunity became available to remove a U-shaped steel damper unit from an isolated hospital building that experienced a maximum movement in the earthquake of approximately 25 cm, and to perform investigations and testing to evaluate the residual fatigue life of the damper. This investigation, the testing performed and the results obtained are described in the remainder of this section and Sec. 4 below (JSSI, 2012).

One 8-arm U-shaped damper unit was removed from the hospital building mentioned above and subjected to testing to evaluate its residual fatigue capacity. A damper schematic and a photo showing the damper prior to removal are shown in Figure 5 below.

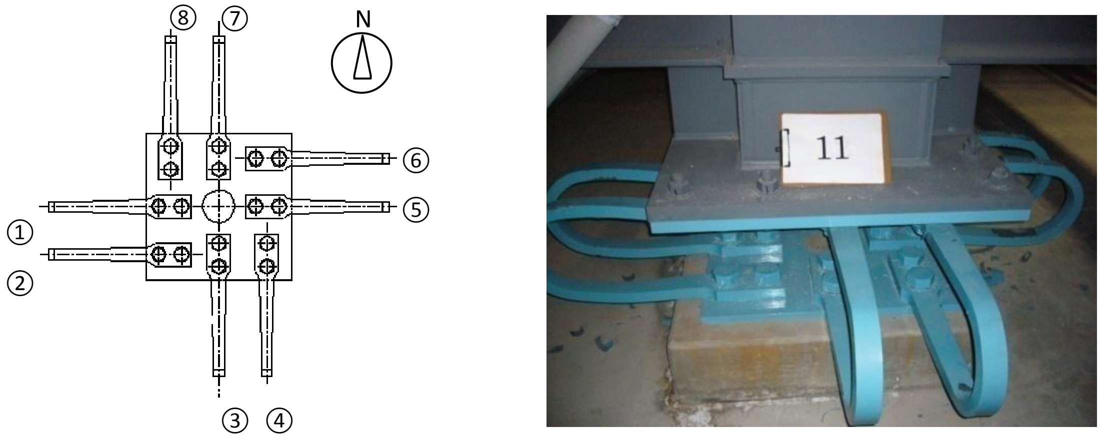


Figure 5. Schematic and photo of 8-arm U-shaped damper unit removed for testing

Before testing, it was necessary to evaluate the loading imposed on the damper during the earthquake and estimate the corresponding fatigue demand, as well as, determine the most appropriate loading to be applied to estimate the residual fatigue capacity. This process is described in the following sections.

3.2 Measured Displacement and Orbit Evaluation Method

A scratch plate device is a low-cost and effective method of recording the displacement orbit response of a seismically-isolated structure. A scratch plate device comprises a stiff arm rigidly attached to the superstructure and positioned directly above a flat metallic or plastic surface fixed to the foundation. A sharp stylus at the end of the arm contacts the surface of the recording plate with sufficient pressure such that a scratch or score is made on the recording plate when there is relative movement between the building superstructure and the foundation. The hospital building has four scratch plates, one at each corner of the structure (Figure 6). The largest excursions of displacement response recorded by one of four the scratch plate devices are shown in Figure 7.

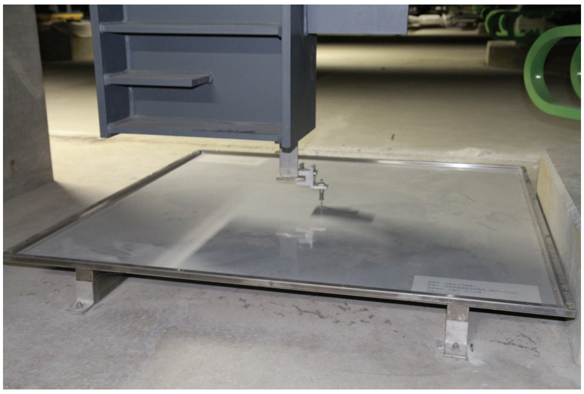


Figure 6. Photo of a displacement orbit scratch plate

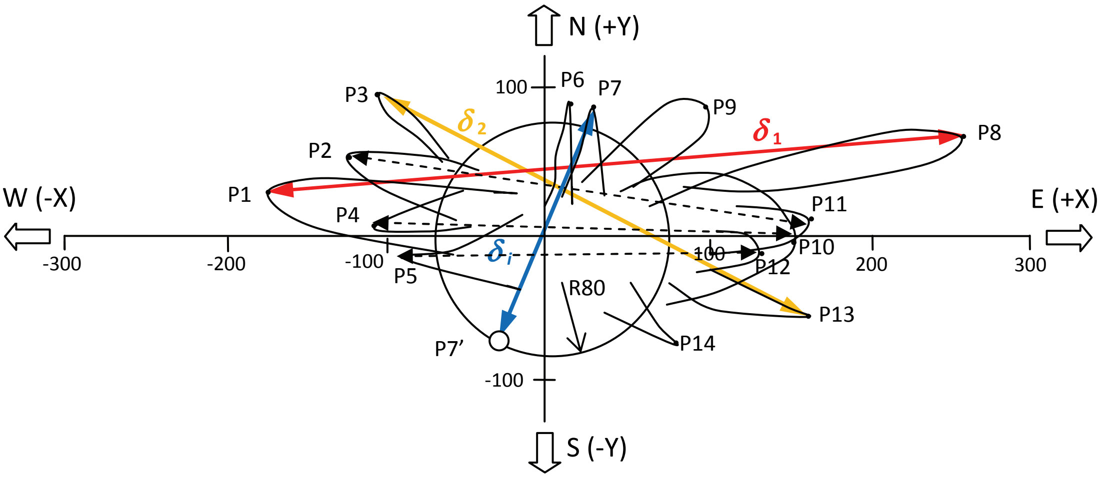


Figure 7. Evaluation of earthquake displacement orbit record

In previous fatigue studies, the deformation of the U-shaped damper has been evaluated as an offset amplitude and to do so information concerning the displacement history is necessary. This information, however, cannot be readily obtained from an irregular earthquake displacement orbit. Due to the extremely long duration of the Great East Japan Earthquake event and the numerous large aftershocks that followed, the large number of smaller deformation excursions less than about 80 mm were not distinguishable on the scratch plate. Considering these issues, the displacement orbit records were evaluated on the basis of the following assumptions:

(1) As the main direction of the deformation was East-West, the distance between peak points on the West and East sides is measured in sequence from peak points that are displaced maximally with respect to each other, and the resulting values are deemed to be the amplitude. Thus, the distance between points P8 and P1 in Fig. 7 is the maximum amplitude, δ_1, and the distance between P13 and P3 is the next largest amplitude, δ_2. These amplitudes are followed by the distance between P11 and P2, and the distance between P10 and P5, and so on.
(2) Since there are a greater number of peaks observed on the East side compared to the West side, peaks other than P8, P13, P11 and P10 on the East side of the orbit do not have corresponding peak points on the West side. It is therefore assumed that the corresponding peak on the West side is 80 mm for each additional East side peak. Taking P7 as an example, it is assumed that a peak value, P7', exists at the 80 mm radius at a point symmetrically opposite to P7 through the point of origin, and therefore the amplitude δ_i is deemed to be the distance between P7 and P7'.

3.3 Estimation of Fatigue Damage from Earthquake Loading

The fatigue damage of a U-shaped damper subjected to an excitation force of variable amplitude is evaluated using *Miner's rule*, also known as the *Palmgren-Miner linear damage hypothesis*, a method often used to evaluate the low-cyclic fatigue of steel. According to this rule, the cumulative damage ratio, D, is given by:

$$D = \Sigma(n_i / N_{fi}) \tag{4.1}$$

where,

n_i: number of cycles for the i^{th} amplitude
N_{fi}: number of cycles to fatigue fracture for the i^{th} amplitude

In the above equation, the number of cycles to fatigue fracture, N_{fi}, is calculated for a given amplitude using the *Manson-Coffin* relation (Eqn. 2.3). When the index D reaches a value of 1.0, it has reached its theoretical fatigue limit. The residual fatigue life of the U-shaped damper is then given by the value *1-D*.

Eqn. 4.1 is used to calculate the cumulative damage ratio, D, using the methodology outlined in Section 3.2 to identify the orbit cycle amplitudes. The results for all four scratch plate devices under the building are given in Table 2. It is seen that the cumulative damage ratios are between 4.5% and 5.2% for the four scratch plate records, with an average of 4.9%, and the average residual fatigue life is 95.1%.

Table 2. Cumulative Damage Ratio and Residual Fatigue Life

Scratch Plate Orbit	Maximum Peak-to-Peak Deformation, L	Cumulative Damage Ratio, *D*	Residual Fatigue Life, *1-D*
1	424 mm	0.052	0.948
2	426 mm	0.045	0.955
3	427 mm	0.050	0.950
4	428 mm	0.048	0.952
Average	426 mm	0.049	0.951

4. EXPERIMENTAL DETERMINATION OF RESIDUAL FATIGUE LIFE AFTER SEVERE EARTHQUAKE LOADING

4.1 Test Specimens

The eight U-shaped arms of the damper unit removed from the hospital were divided into four test specimens, each with two U arms. Comparing the original damper orientation in Figure 5 to the orbit in Figure 7, it is seen that deformation in the East-West, or X, direction was predominant. Consequently, the U arms labeled ①, ②, ⑤ and ⑥ in Figure 5 experienced deformation predominantly in their in-plane direction while the U arms ③, ④, ⑦ and ⑧ experienced deformation predominately in their out-of-plane direction. Since strain accumulation depends on the orientation of the U arm to the direction of loading, the test specimens were configured and oriented in such a way that the applied load would be in the same direction that the individual U arms experienced in the earthquake. With this configuration, additional imposed strain will be further concentrated in the locations previously loaded by the earthquake movement and thus the fatigue test would be the most severe. Figure 8 shows the four test specimens and the individual U arms from the original damper unit removed from the hospital building.

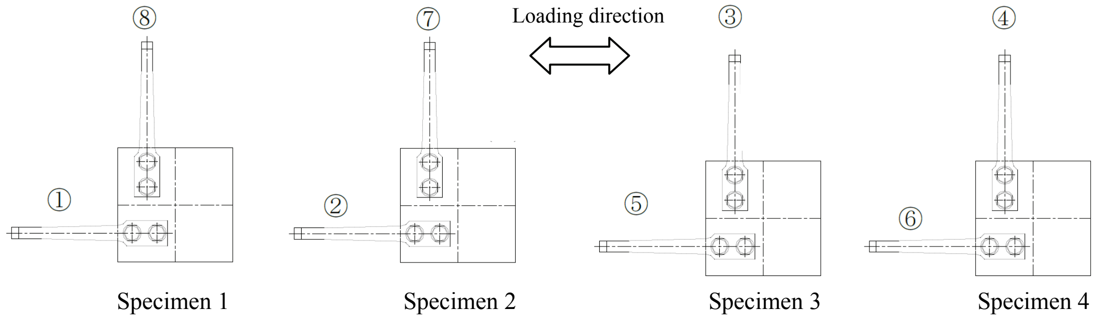


Figure 8. U-shaped damper specimens for residual fatigue life tests

4.2 Results of Residual Fatigue Testing

In order to determine the residual fatigue life experimentally, the four specimens were subjected to repeated uni-directional cycles to failure. Two loading amplitudes were used for testing. The first amplitude, used for Specimens 1, 2 and 3, was chosen to be the average maximum peak-to-peak deformation observed in the recorded earthquake orbits. In Table 2, the average maximum peak-to-peak deformation is found to be 426 mm. This value corresponds to a testing amplitude of +/- 213 mm, or γ_t = 127%. The second testing amplitude, used for Specimen 4, was chosen to be the allowable maximum design deformation of 490 mm, which corresponds to γ_t = 292%. Table 3 lists the loading amplitude and the number of cycles until fracture for each test specimen. For Specimens 1, 2 and 3, it is seen that the number of cycles needed to fracture the U arms oriented in the 0° direction ranged from 70 to 77, with an average of 74. For all three of the specimens, 300 cycles were applied in the 90° direction without fracture. For the larger amplitude imposed on Specimen 4, only 25 cycles in the 0° direction, and 41 cycles in the 90° direction, were required to fracture the specimen.

Table 3. Number of Cycles to Failure

Specimen	Testing Amplitude	Cycles to Fracture, 0°	Cycles to Fracture, 90°
1	+/- 213 mm (γ_t = 127%)	76	300*
2		70	300*
3		77	300*
4	+/- 490 mm (γ_t = 292%)	25	41

* test stopped without specimen fracture

4.3 Comparison of Computed and Measured Residual Fatigue Life

As described in Section 2.3, results from previous testing have been used to establish an expression to estimate the fatigue life for a given horizontal displacement amplitude. The *Manson-Coffin* relation given by Eqn. 2.3 estimates a total of 80 cycles to fatigue failure for a displacement amplitude of γ_t = 127% and 25 cycles for a displacement amplitude of γ_t = 292%. These estimates are illustrated in Figure 9. Table 4 below compares the residual fatigue life determined from experimental testing to the estimated residual fatigue life calculated by multiplying the *Manson-Coffin* estimates of 80 and 25 cycles, by the value 0.951, the residual fatigue life value from Table 2.

Table 4. Comparison of Estimated and Experimental Cycles to Failure

Specimen	Testing Amplitude	Tested Cycles to Fracture	Estimated Cycles to Fracture
1	+/- 213 mm (γ_t = 127%)	76	76
2		70	76
3		77	76
4	+/- 490 mm (γ_t = 292%)	25	24

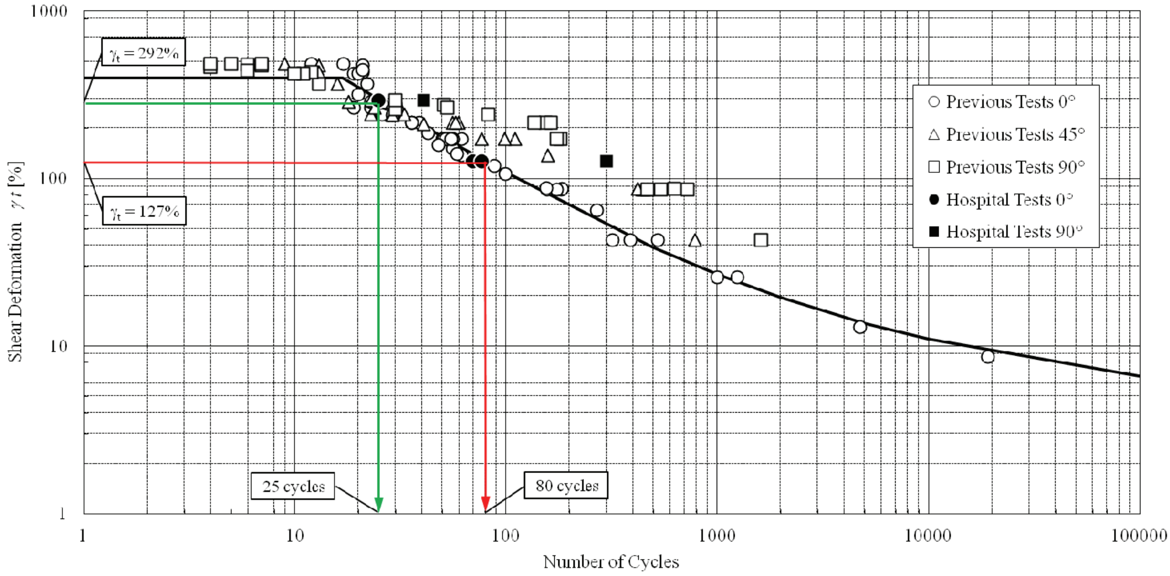


Figure 9. Estimate of Fatigue Life for Experimental Input Amplitudes Considered in Testing

5. CONCLUSIONS

U-shaped steel dampers have been used extensively in seismically-isolated hospitals, emergency facilities, residential and many other types of buildings in Japan. To evaluate the fatigue performance of U-shaped dampers and the influence of rate of loading on fatigue life properties, quasi-static and dynamic loading tests have been performed on a large number of full-scale U arms of different sizes. From these tests it has been found that:

1) The average shear deformation angle, γ, which is derived from the horizontal deformation, δ, of a U-shaped damper divided by the overall height, h, of the U arms is an effective parameter to evaluate fatigue performance for U arms of various different sizes.

2) Fatigue performance is accurately predicted by the *Manson-Coffin* relation fit to 0° loading direction test data.

3) For total shear deformation angles, γ_t, less than 400%, the 0° direction estimate also provides a conservative estimate of the number of cycles to fracture for the 45° and 90° directions.

4) At higher rates of loading, U-dampers exhibit higher force and initial stiffness, but the increase over quasi-static properties is not more than 10 percent, and thus, the influence of rate of loading on mechanical properties is minor.

5) Rate of loading does not significantly affect the fatigue performance of U-shaped dampers. On the basis of comparison of quasi-static and dynamic test results, for maximum shear deformation angle rates of loading less than 200 % / sec., the fatigue performance of dynamically loaded U-shaped dampers is accurately given by fatigue fracture predictions based on quasi-static test data.

The M9.0 Great East Japan Earthquake caused significant shaking of many seismically-isolated buildings and presented a unique opportunity to evaluate the residual fatigue life of U-shaped dampers from an isolated hospital building after it had experienced significant earthquake movements. A U-shaped damper was removed from the building and subjected to various cyclic fatigue tests to failure. From the post-earthquake evaluation tests it was found that:

6) The residual fatigue life determined from testing of the U arms of the earthquake loaded damper was found to agree well with fatigue damage ratio predicted from evaluation of the earthquake displacement orbit record, confirming the accuracy of the existing fatigue damage estimation method for the displacement orbit from the isolated hospital building response in the Great East Japan Earthquake. More work is required to confirm the accuracy of the fatigue damage estimation method for other types of earthquake response records.

7) The post-earthquake evaluation of the U-shaped dampers concluded that the earthquake loading had induced a damage ratio of approximately 0.05, and thus that about 95% of the damper fatigue life remained after the earthquake.

8) More research is needed to confirm a practical and general method for the evaluation of residual damper fatigue life after earthquake loading.

9) The earthquake loading, and the associated U-shaped damper performance and residual fatigue life, were all found to be consistent with existing design and performance requirements. As a result of the post-earthquake fatigue investigation, it has been concluded that the U-shaped dampers have ample residual fatigue life and do not require replacement.

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