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# Prediction Method of Low Cycle Fatigue Capacitates of Steel Seismic Passive Control Devices under Random Plastic Deformation

Takumi Ito, Keita Saito, Akinobu Kano, Dong Hang Wu, Takashi Nagumo, Haruhiko Hirata

***Abstract*— A vibration control device for buildings referred to as “scaling-frame structures” is proposed. The plastic deformation is excited, so that the ductile fracture occurs owing to low cycle fatigue. In this study, the low cycle fatigue characteristics and capacities are investigated experimentally, and the evaluation method of cumulative ductility is used until fracture. The cumulative ductility of the steel member is summarized in the “Similitude Law of Prefracture Hysteresis”. Based on cyclic loading tests, the effect of the ductility amplitude is expressed mathematically. Furthermore, the “Linear Damage Rule” is applied, thus allowing accurate prediction of the cumulative ductility during the occurrence of random plastic deformations.***

***Index Terms*—seismic passive control system, low cycle fatigue capacity, experimental loading test.**

## I. INTRODUCTION

In countries where earthquakes occur frequently, seismic disasters have been reported. Thus various types of vibration control systems have been developed for use for building structures, and have been extensively recognized as an effective system against seismic excitations [1]. In our previous study, the vibration control device referred to as the “scaling-frame (SF) structures” has been introduced as shown in Fig.1, and it has been already adopted on low-rise wooden houses as shown in Fig.2 and middle-rise steel frame structures [2], [3]. Experimental studies have been performed by authors to investigate the resistant mechanism and seismic mitigation effects of SF structures [4]. Furthermore, an analytical method and a design procedure for SF structures have been established.

Generally, the plastic deformation of the vibration control device is excited, that leads to the ductile fracture owing to low cycle fatigue. To prevent the collapse of buildings, it is desirable that the low cycle fatigue characteristics and capacities are clarified, and the evaluation method of cumulative ductility until the occurrence of fracture is prepared. In general, it is clarified that the difference of cumulative ductility of steel members is quite large between small and large ductility amplitudes. This is summarized in the “Similitude Law of Prefracture Hysteresis”.

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Furthermore, when the random deformation amplitudes, such as those associated with seismic responses, are input to the vibration control structure, the “Linear Damage Rule” is applied for the prediction of the fracture, which rule is frequently used to estimate fatigue life. Additionally, some studies have already been published in relation to estimation method. In this study, the plastic cyclic loading tests are conducted to investigate the applicability of the estimation method for fractures.

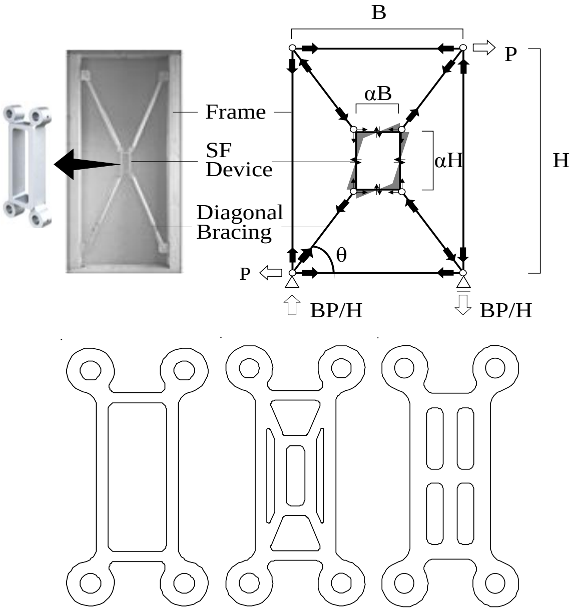

**Fig.1 Conceptual diagram of SF structures and various type of SFD**

**Fig. 2 Example of SF Structures**

## II. GENERAL DESCRIPTION OF SF STRUCTURE

### *A. Configuration of SF Structures*

SF structures consist of beam-column frames, diagonal bracings, and SF devices (SFD) as shown in Fig.1 [2] [3], and vibration energy is absorbed owing to the plastic behavior of the diagonal deformation of SFD. SFD is made of steel or aluminum, and it has some advantages such as workability, productivity, and containment.

### *B. Theoretical Expression of Rigidity and Strength*

Herein, the mechanical and geometrical properties of SF structures are explained. Based on the definition of the SF structure, the relation between the out-frame size and SFD is defined as the "reduction rate α" as shown in Fig.1. Fig.3 shows the resistant mechanism of SFD. From this model, the rigidity $K_0$ and yield strength $P_y$ of the SF structure are obtained theoretically using α as follows:

$$K_0 = \frac{12 E_{SF} I_{SF}}{\alpha^3 H^2 (B+H)} \tag{1}$$

$$P_y = \frac{4\sigma_y Z_{SF}}{\alpha H} \tag{2}$$

Where, $E$: the Young's modulus of the SFD, $I_{SF}$: the moment of inertia of area of the SFD, $Z_{SF}$: the elastic modulus of SFD, $B$: the length of the beam, $H$: the length of the column, $L$: the diagonal length of the beam-column frame, $f_b$: the allowable bending stress of the SFD.

From the above equations, it can be said that rigidity is inversely proportional to the cube of reduction rate α, and the strength is inversely proportional to the reduction rate α. In other words, the smaller the reduction rate of SFD is, the larger rigidity and strength can be obtained, and the high energy absorption can be expected.

### *C. Relationship of Strain of SFD and Story Drift of Frame*

Based on Eqs. (1) and (2), the following relationship between the strain of SFD $\varepsilon$ and story drift angle of frame $R$ can be obtained as,

$$\varepsilon = \frac{3 \cdot b}{2 \cdot \alpha^2 \cdot (B+H)} R \tag{3}$$

$b$: the width of the section of SFD

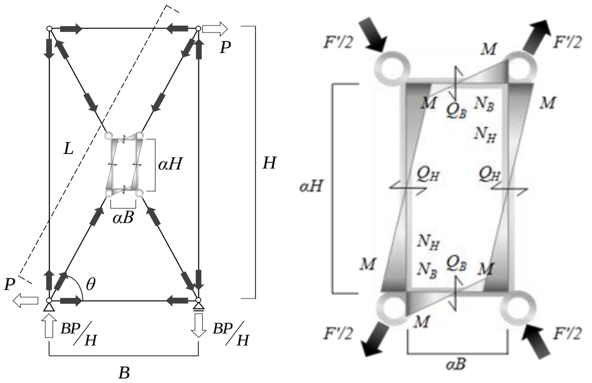

**Fig. 3: Conceptual diagram of SF structures and various type of SFD**

Additionally, if the relation of stress – strain curve during the inelastic range is assumed to be linear, the relationship of the strain and story drift angle can be obtained as follows,

$$\varepsilon = \varepsilon_y + (\varepsilon_p - \varepsilon_y) \cdot \frac{(R - R_y)}{(R_p - R_y)} \tag{4}$$

$R_y$: the story drift angle at yielding of SFD,

$$R_y = \frac{\alpha^2 \, \varepsilon_y \, Z_{SF} \, B^2 (B+H)}{3 \, I_{SF} \, L^2 \cos^2\theta}$$

$R_p$: the story drift angle at the plastic state of SFD, and $R_p = \mu_p R_y$ (where, $\mu_p = \varepsilon_p / \varepsilon_y$)

## III. THEORETICAL DESCRIPTION OF ESTIMATION METHOD OF FRACTURES

### *A. Relation of Plastic Amplitude and Fatigue Life*

The relationships of the modified number of cycles at fracture are governed only by the plastic amplitude. This relationship between the cycle and amplitude can be expressed by a specific formula, which is not influenced by the materials, shape, connections, etc. The Mancon - Coffin formula [5] is extensively adopted to formulate this relationship in accordance to,

$$\Delta\varepsilon_p \cdot N^{k_1} = C \tag{5}$$

Where, $\Delta\varepsilon_p$: the plastic amplitude, $N_f$: the number of cycle at fracture, $k_1$, $C$: constants.

Based on Eqs. (4) and (5), the relationship of the modified number of cycles at the fracture of SFD and story drift angle of frame can be expressed as follows,

$$N_f = \sqrt[k_1]{\frac{C(R_p - R_y)}{\varepsilon_p (R - R_y) + \varepsilon_y (R_p - R)}} \tag{6}$$

### *B. Estimation Method of Fatigue Life by Linear Damage Rule*

To estimate the fatigue life under random cyclic amplitudes, the "Linear Damage Rule" [6], [7] is frequently used. According to this rule, the damage is cumulated owing to reverse stress. Additionally in reference [8], it is verified that the Linear Damage Rule is valid for steel members if the stress amplitude is replaced by the ductility amplitude, and if the number of cycles is replaced by modified number. This is described as follows, "If a ductility amplitude is applied at a condition where fracture would occur if $N_f$ cycles are applied, the percentage of life used up is $1/N_f$", and this is formulated as follows,

$$D = \sum \frac{1}{N} \tag{7}$$

When the cumulative damage amounts to unity, this demarcates the end of the fatigue life.

### *C. Estimation Method of Fatigue Life by Non-linear Damage Rule*

Generally, the use of passive control devices on the seismic damping frames sometimes leads to a mismatch between the center of the vibration under seismic response and the original position of the frame. This means that residual deformation is generated after the seismic inelastic response. In these cases, the prediction method that is based on Miner's rule, underestimates fatigue life. Correspondingly in reference [9], use of an estimation method that considering the history of the amplitude is suggested.

First, the plastic amplitude range, plastic amplitude average and cumulative plastic amplitude under random loading are defined as follows (see Fig.5),

Plastic amplitude range: $\xi_i = |\mu_i - \mu_{i-1}|$ (8)

Plastic amplitude average: $\zeta_i = \dfrac{\mu_i + \mu_{i-1}}{2}$ (9)

Cumulative plastic amplitude: $\eta_N = \sum_{i=1}^{N} \xi_i$ (10)

When the materials or members are broken after $N_f$ cycles are subjected to constant plastic amplitudes, the cumulative ductility at fracture is given as follows,

$$\eta_F = \sum_{i=1}^{N_F} \xi_i \qquad (11)$$

If both sides of Eq. (11) are divided by $\eta_F$, the following equation is obtained.

$$1 = \sum_{i=1}^{N_F} \frac{\xi_i}{\eta_F} \qquad (12)$$

Furthermore, the sum of plastic amplitudes during each cycle are defined as follows,

$$D = \sum_{i=1}^{N} \frac{\xi_i}{\eta_{F,i}} \qquad (13)$$

Furthermore, considering the reference [10], the following formulation is given.

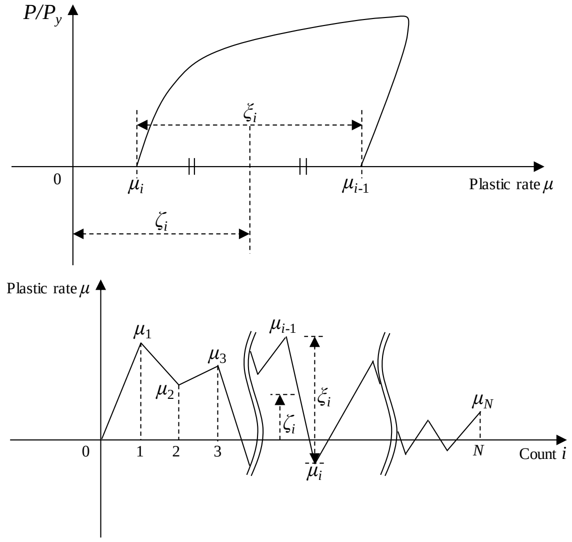

Fig. 5: Definition of parameters related to plastic behavior

$$\eta_{F.i} = 2^{k_2-1} A^k (1 - \frac{|\varsigma_i|}{A})^{k_2} \xi^{-k_2+1} + |\varsigma_i| \qquad (13)$$

Where, $A$ and $k_2$ are constants.

When the cumulative damage amounts to unity, this demarcates the end of fatigue life.

## IV. OUTLINE OF EXPERIMENTAL STUDY

### *A. General Description of Loading Test Study*

To investigate the fracture characteristics of SFD and the effectiveness of the estimation method of fatigue cycle, the horizontal static loading tests are conducted herein. First, the relation of the number of cycles and plastic amplitude (S-N curve) of the SF structure is obtained experimentally. Furthermore, to investigate the applicability of the estimation method based on the S-N curve and cumulative damage rules, the loading tests with random amplitude history are then conducted.

### *B. Configuration of Test Specimen and Setup*

The configuration of test specimen and setup are shown in Fig.7. The SFD is connected with column jig through gusset plate and diagonal bracing. Columns are supported on the beam using pin joints. Table.1 shows the mechanical properties of steel members.

The horizontal force is measured from the load cell built into the loading jack. The horizontal displacement at the top of the column is measured using a rod type displacement transducer. The strain gauges are placed on each SFD as shown in Fig.7.

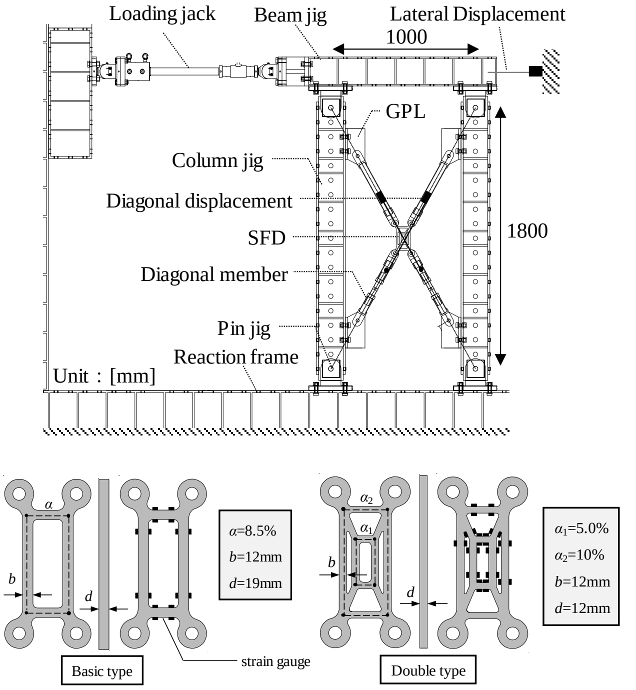

Fig. 7: Elevation of test setup (unit: mm) and location of sensors

Table 1 Mechanical properties of steel materials

| SFD Shape | α[%] | JIS Grade | Young's modulus [N/mm²] | Yield stress [N/mm2] | Yield strain [μ] | Strain of starting point of strain hardening [μ] |
|---|---|---|---|---|---|---|
| Basic type | 8.5 | SS400 | 200,000 | 252 | 1,220 | 20,300 |
| | 4.0 | | 213,000 | 257 | 1,210 | 22,200 |
| Double type | 10/5.0 | | 209,000 | 249 | 1,190 | 23,000 |
| | 8.5/4.0 | | 213,000 | 257 | 1,210 | 22,200 |

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### *C. History of Deformation Amplitude*

Herein, one of the experimental variables is the history of deformation amplitudes as shown in Fig.8. Test types include the 1) constant amplitude cyclic loading, 2) incremental amplitude loading, and 3) earthquake loading.

In regard to constant amplitude cyclic loading, the plastic ratios of SFD are assumed to be equal to 23 (large amplitude), 12 (middle amplitude), and 6 (small amplitude), which are almost equal to the story drift angle of the frame with 1/25, 1/50, and 1/100rad, respectively.

Furthermore, in regard to earthquake loading, the history of deformation is obtained by conducting inelastic seismic response analysis on four-story and ten-story steel frames with SF structures.

## V. EXPERIMENTAL RESULTS

### *A. Constant Amplitude Cyclic Loading Test and S-N Curve*

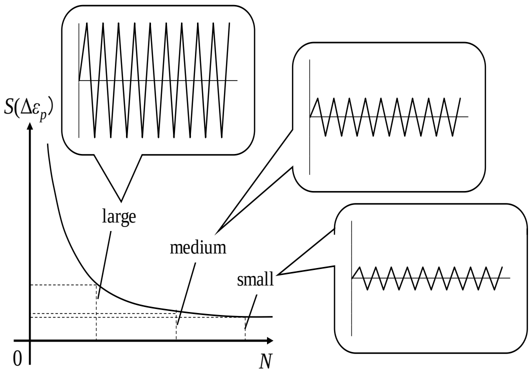
From test results in the case of constant amplitude cyclic loading, the cumulative deformation – load curves are shown in Fig.9, the examples of ultimate state of test specimen are shown in Fig.10, and the number of cycles at the fracture – plastic amplitude curves are shown in Fig.11, the strain of SFD – drift angle curves are shown in Fig.12, respectively. Furthermore, the average value of the plastic amplitude, the number of cycles at fracture are summarized in Table 1.

Additionally, regression analysis on Fig.11 is conducted to determine the constants $k_1$ and $C$, the results are summarized on Table 3 and Fig.11 too. Herein, the past fatigue test results of steel materials (Nishimura, 1978) is compared on Fig.11.

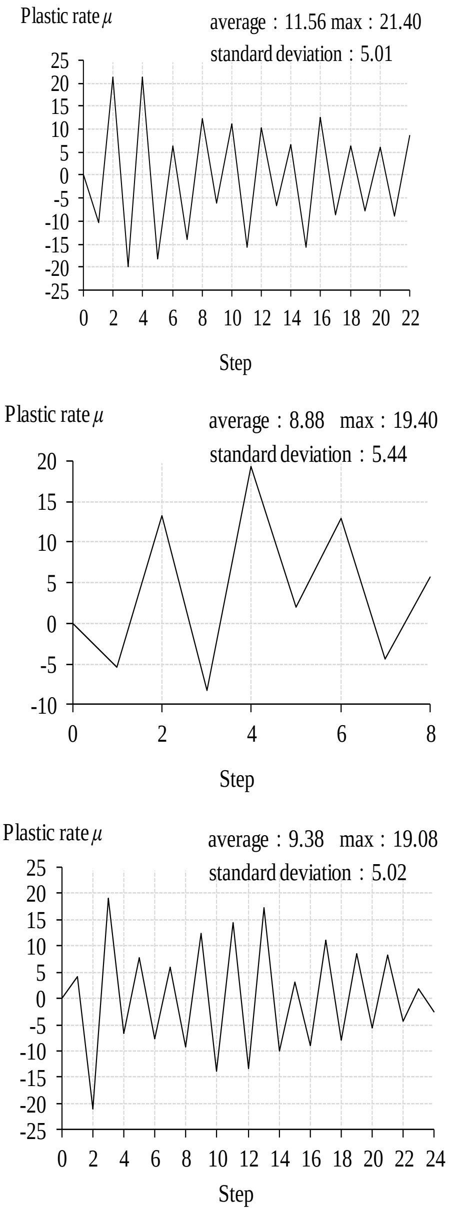
From the comparison of Fig.11 and Table 3, the S-N curves of each test specimen are generally corresponding each other. It means that the fatigue characteristics of SFD is corresponding with the characteristics of the steel material from the viewpoint of strain.

From the results of Table 3, the values of constant $k_1$ is in the range of 0.5~0.6. Manson proposed that $k$=0.6. Additionally, the constant $C$ of the basic type of SFD is two times of the values of other type of SFD. Herein, the constant $C$ is equivalent to the intercept of the equation. This means that the fatigue life at the fracture of basic type of SFD exhibits an excellent performance compared to other SFD type.

From the Fig.12, it is confirmed that the strain of SFD and the drift angle are correlated. Herein, the curves of Eqs.(3) and (4) described in Fig.12 present almost the same trends as those elicited by the test results. The S-N curve of the drift angle amplitude vs. the number of cycles is calculated from Fig.11 using with Eqs.(3), (4), it is shown in Fig.13.



**(a) Constant amplitude**



**(b) Earthquake**

**Fig. 8: History of deformation amplitude**

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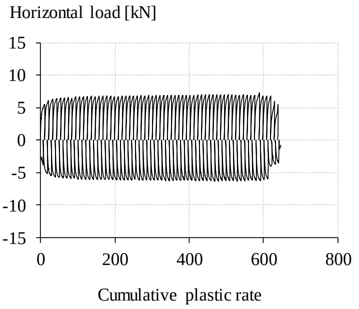
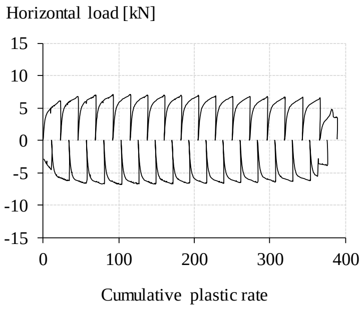
**Table 2 Summary of experimental parameters and test results**

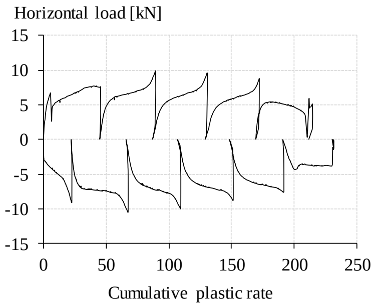
| ID | SFD Shape | $\alpha$[%] | Amp. type | Amp. Level | Test results | |
|---|---|---|---|---|---|---|
| | | | | | Ave. Amp. $\varepsilon_p$ | Cycle $N_f$ |
| 1 | Basic type | 8.5 | Constant | $\mu$=6 (small) | 0.0257 | 125 |
| 2 | | | | $\mu$=12 (middle) | 0.0590 | 34.0 |
| 3 | | | | $\mu$=23 (large) | 0.102 | 10.9 |
| 4 | | | Incremental | - | - | 70.9 |
| 5 | | | El Centro | - | - | 59.0 |
| 6 | | | JMA Kobe -4th | - | - | 28.9 |
| 7 | | | Kumamoto | - | - | 60.4 |
| 8 | | | JMA Kobe -10th | - | - | 31.0 |
| 9 | | 4.0 | Constant | $\mu$=6 (small) | 0.0539 | 35.0 |
| 10 | | | | $\mu$=12 (middle) | 0.113 | 9.60 |
| 11 | | | | $\mu$=23 (large) | 0.130 | 6.80 |
| 12 | | | El Centro | - | - | 10.6 |
| 13 | | | JMA Kobe-4th | - | - | 20.8 |
| 14 | | | Kumamoto | - | - | 12.2 |
| 15 | Double type | 10/ 5.0 | Constant | $\mu$=6 (small) | 0.0338 | 148 |
| 16 | | | | $\mu$=12 (middle) | 0.0599 | 42.0 |
| 17 | | | | $\mu$=23 (large) | 0.189 | 4.8 |
| 18 | | | Incremental | - | - | 73.3 |
| 19 | | | El Centro | - | - | 16.0 |
| 20 | | | JMA Kobe-4th | - | - | 44.7 |
| 21 | | | Kumamoto | - | - | 26.3 |
| 22 | | | JMA Kobe -10th | - | - | 41.1 |
| 23 | | 8.5/ 4.0 | Constant | $\mu$=6 (small) | 0.0585 | 24.6 |
| 24 | | | | $\mu$=12 (middle) | 0.0807 | 14.0 |
| 25 | | | | $\mu$=23 (large) | 0.136 | 5.00 |
| 26 | | | El Centro | - | - | 6.9 |
| 27 | | | JMA Kobe-4th | - | - | 18.7 |
| 28 | | | Kumamoto | - | - | 11.3 |



**(a) ID=1**



**(b) ID=2**



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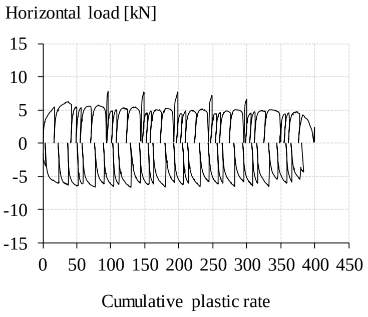
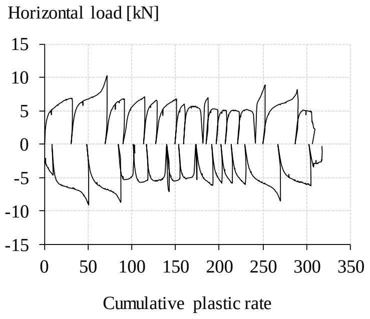
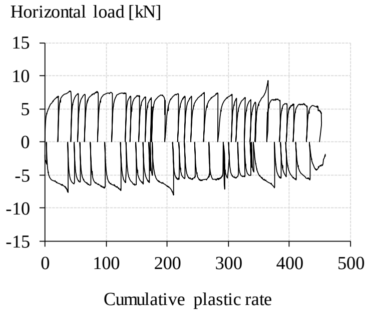


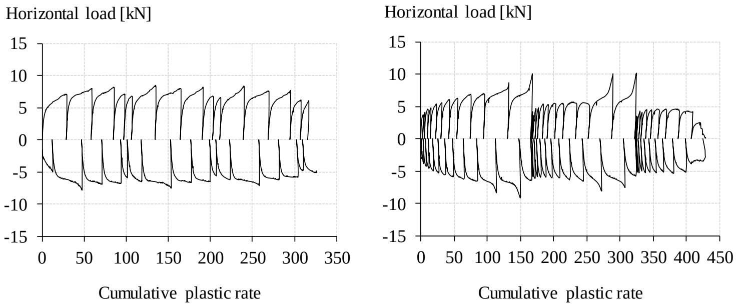
**(d) ID=4**



**(e) ID=5**



**(f) ID=6**



**(g) ID=7** **(h) ID=8**

Fig. 9 Examples of test results of cumulative deformation – load curves (in case of α=8.5%)

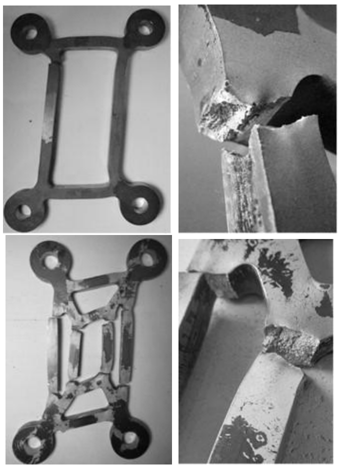


Fig. 10 Examples of ultimate states of test specimen of SFD

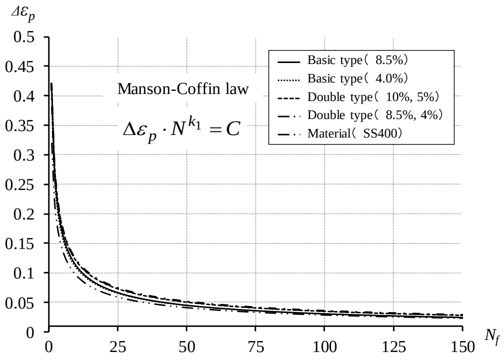


Fig. 11 Comarison of S-N curve

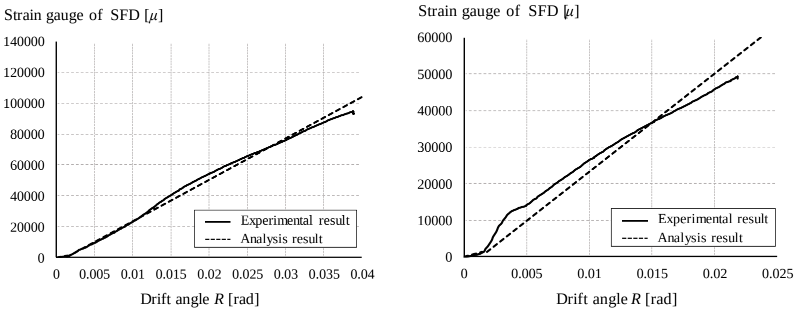


Fig. 12 Relation of strain of SFD vs story drift angle

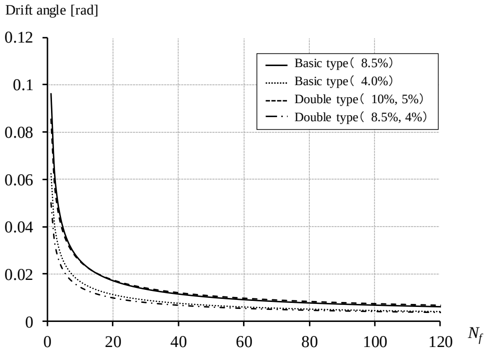


**Fig. 13 Relation of strain of SFD vs drift angle**

**Table 3 Results of constant of S-N curve**

| Test specimen | $k_1$ | $C$ |
|---|---|---|
| Material（SS400） | 0.540 | 0.420 |
| Basic type（8.5%） | 0.566 | 0.408 |
| Basic type（4.0%） | 0.549 | 0.381 |
| Double type（10/5.0%） | 0.506 | 0.414 |
| Double type（8.5/4.0%） | 0.527 | 0.320 |

### B. *Incremental Amplitude and Earthquake Loading Test*

From the test results of the incremental amplitude and earthquake loading, the cumulative damage is estimated based on Miner's rule (Eq.(7)) and on the Non-linear damage rule (Eq.(14)). And the results are summarized on Tables 4, 5. When these results are equal to unity, the estimation method is valid. Herein, the constants of Eq.(14) are summarized on Table 6.

From the Table 4, the cumulative damage *D* is distributed within the range of 0.79-1.53, and the average value indicates an approximate value that is equal to unity. In the case of the Kumamoto NS, the cumulative damage becomes large, and the gradually decreasing amplitude is thus influenced.

From the results of Table 5, the cumulative damage *D* values are distributed within the range of 0.73-1.31, and the average value is approximately equal to unity.

From the comparison of Tables 4, 5, it is confirmed that the distribution of cumulative damage based on the non-linear damage rule shows small variance. This indicates that the cumulative damage can be accurately predicted.

**Table 4 Results of prediction method of Miner's rule**

| SFD Shape | $\alpha$ [%] | El Centro NS | JMA Kobe NS (4-story) | Kumamoto NS | JMA Kobe NS (10-story) | Increasing Cycle Loading |
|---|---|---|---|---|---|---|
| Basic type | 8.5 | 1.12 | 1.19 | 1.53 | 0.945 | 1.22 |
|  | 4.0 | 1.03 | 0.976 | 0.867 | – | – |
| Double type | 10/5.0 | 0.891 | 1.00 | 0.794 | 1.10 | 1.37 |
|  | 8.5/4.0 | 0.940 | 1.51 | 0.836 | – | – |

**Table 5 Results of prediction method of non-linear damage rule**

| SFD Shape | $\alpha$ [%] | El Centro NS | JMA Kobe NS (4-story) | Kumamoto NS | JMA Kobe NS (10-story) | Increasing Cycle Loading |
|---|---|---|---|---|---|---|
| Basic type | 8.5 | 1.07 | 0.984 | 1.27 | 0.920 | 0.909 |
|  | 4.0 | 1.20 | 0.865 | 0.990 | – | – |
| Double type | 10/5.0 | 0.938 | 0.875 | 0.731 | 1.08 | 1.05 |
|  | 8.5/4.0 | 0.970 | 1.31 | 0.939 | – | – |

**Table 6 Constant of non-linear damage rule**

| SFD Shape | Part of fracture | $k_2$ | $A$ |
|---|---|---|---|
| Basic type (8.5%) | Edge of SFD | 1.75 | 171 |
| Basic type (4.0%) | Edge of SFD | 1.91 | 80.8 |
| Double type (10%,5%) | Edge of SFD | 1.90 | 74.0 |
| Double type (8.5%,4.0%) | Edge of SFD | 1.95 | 57.2 |

## VI. CONCLUSION

In this study, the low cycle fatigue characteristics at the instant of fracture of the scaling-frame structure are investigated experimentally. Furthermore, the evaluation method of cumulative ductility until fracture is discussed. The cumulative ductility of steel member is summarized in the "Similitude Law of Prefracture Hysteresis".

First, to obtain the relation of the number of cycles at fracture – the amplitude, the constant amplitude cyclic loading tests are conducted as the parameters of the shape and size of SFD. Based on the results obtained, the effect of ductility amplitude is expressed in accordance to a specific formula. Furthermore, the fatigue life at fracture of the basic type of SFD exhibits an excellent performance compared to other type of SFD. Additionally, it is confirmed that the S-N curve of the drift angle amplitude as a function of the number of cycles can be calculated theoretically.

Furthermore, the "Linear Damage Rule" is applied for the prediction, and the cumulative ductility under random plastic deformations is shown to be accurately predicted. Particularly, it is confirmed that the distribution of cumulative damage based on the non-linear damage rule shows small variance. Therefore, it is possible to make accurate predictions in regard to the passively controlled framed structure with SF.

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**Keita Saito** is a graduate student at Tokyo University of Science. He took the degree of department of architecture in Tokyo University of Science in 2017.3. He is now a master course student of Tokyo University of Science. His research interest includes vibration control structure called as Scaling-Frame structure proposed by the author, DongHang Wu.

**Akinobu Kano** is a structural designer at Azusa Sekkei in Japan, who analyze, design, plan, and research structural components and structural systems to ensure the safety and comfort of users of occupants. He received a master’s degree in building structural engineering from Tokyo University of Science in 2018. His master’s thesis is “Fatigue Capacities and Damage Evaluation Method of Scaling-Frame Structure on Steel Frames Under Plastic Strain Amplitude”.

**DongHang Wu** is a president of Wu Building Office in Japan since 1997, and he is a visiting professor at Shibaura Institute of Technology since 2017. He is a professor at South China University of Technology since 2016. He received a Ph.D. in building structural engineering from University of Tokyo in 1994. His doctoral thesis is “Industrialized Production Theory of RC Condominium Housing”. From 1994-1995, he was a foreign resident visiting researcher at the University of Tokyo. He has published 4 books deals with architecture, industrialization, planning, construction and other papers or reports. He received a good design award at Exhibition of earthquake-resistant and damping wall "WUTEC-SF" for wooden houses in 2013 and he received third prize award at Guangdong Provincial Technology Advancement in 1988.

**Takashi Nagumo** is an engineer of SRG TAKAMIYA, who mainly devoted to developing scaffolding materials and architectural equipment. Especially in architectural equipment development. He focuses on managing production techniques. As an achievement, he involved in the invention of numerous scaffolding materials productions, and he brought those products to market successfully over the years. Furthermore, he has also found the Scaling-Frame structure seminar and conduct research and development.

**Haruhiko Hirata** is an engineer of SRG TAKAMIYA, who works design and product development structural equipment. He is designing, research and developing structural equipment for wooden houses, and he promoted to spreading vibration control system. He has been doing research and development of Scaling-Frame structure for wooden framework construction, wood frame construction, steel frame as his achievement. In addition, he is also a member of the Scaling-Frame Structure study meeting.