SAFETY EARTHQUAKE-RESISTANT FOR SMART BUILDING

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Abstract

As all we know that Japan is the seismic active country and all buildings in Japan are required to have earthquake-resistant structures. Buildings are designated based on basic earthquake resistant *(taishin)*, vibration control *(seishin)* and base isolation *(menshin)*. The improvements in earthquake-resistant and smart cities are always the same in Japan. Besides making the energy-saving buildings, we are improving both smart cities and earthquake-resistant while building better earthquake-resistant buildings to avoid collapse. In this paper, we are going to report the improvement of earthquake-resistant buildings facing on smart cities. For improving earthquake-resistant, the structure to be strong and ductile enough to survive the shaking with an acceptable damage using structural vibration control (known as *Seishin*) technologies to minimize any forces and deformations. Based on this, we are doing the vibration control structure called "Scaling-Frame" (SF structure) and it already applied to the low-rise wooden housing. SF structure is based on the principle of geometry and makes easy to install by using general materials. The mechanism is simple and structures are visibility. SF structure has some advantage such as no maintenance required, the metal will not become hard or soft due to temperatures, and also workability, productivity, and containment because of small size, light weight, durability and sustainability of metal materials. In the SF structure, vibration energy is absorbed by the plastic behavior of the diagonal deformation of SF device during earthquake occurs. By using this, the safety property of the building is improved. Furthermore, using this as a member of the smart building, from now on we will report the safety of the buildings and damages after the earthquake will be seen on smart using gauges and IoT(as monitoring). IoT can be used to monitor and control the mechanical and electronic systems used in various types of buildings. So we can judge the damage of the vibration control device and on the necessity of replacement.

Keywords: earthquake-resistant, vibration control, safety, smart building

1. Introduction

Japan is widely known around the world for its earthquakes, all buildings in Japan are required to have an earthquake-resistant structure. Buildings are designated based on basic earthquake resistance, vibration control and base isolation. The improvements in earthquake-resistant and smart cities are always the same in Japan. Japanese vision of future cities includes resilience to disaster. Smart cities should also be safe cities with building codes and earthquake. For the first step in creating smart cities start with smart construction. Furthermore, Japanese experience of smart cities is the type of re-development of existing cities and areas. Therefore, various types of vibration control systems have been developed for building structures, and have been extensively recognized as an effective system against seismic excitations [1]. And these applicability and effectiveness are clarified by past researches. From the viewpoints of mechanical characteristics and materials, these devices are categorized as shown Table.1 with damping system (viscous, hysteresis, friction), resistant mechanics (bending, shear, axial), materials (metal, oil, rubber). However, they have some problems of durability and stability velocity. Furthermore, they sometimes consist of special device and material, so there are some difficulties of getting material and construction technics. Based on this, the vibration control device referred to as the "scaling-frame (SF) structures" has been introduced as shown in Fig.1 [2], and it has been already adopted on low-rise wooden houses as shown in Fig.2 and middle-rise steel frame structures in Japan. By installing SF structures, the safety of the building is improved and prevents the collapse of buildings.

Experimental studies have been performed by authors to investigate the resistant mechanism and seismic mitigation effects of SF structures. In this paper, SF structure is applied to wooden frame and steel frame, and the applicability, effectiveness and feasibility are investigated experimentally. So the static loading test is performed on the wooden frame and steel frame. And also, to investigate the mitigation effects and restoring force characteristics of SF structure during dynamic response, shaking table test is conducted on wooden frames with structural plywood and SF structure installed.

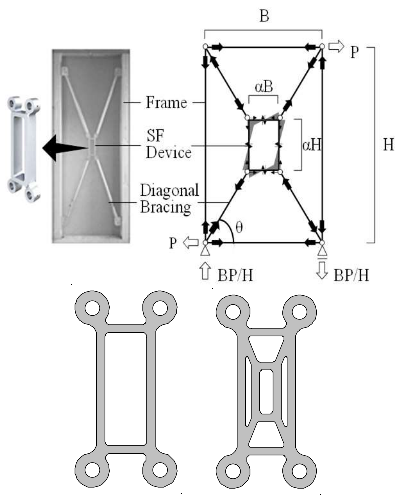


Figure 1: Conceptual diagram of SF structures and various type of SFD

Figure 2: Example of SF structures on wooden frame and steel frame

Table 1: Summary of vibration control devices

System	Mechanics			Materials
	Axial	Shear	Bending	
Hysteresis			SF device	Metal
Viscous				Oil
Friction				Rubber

1.1 General Description of SF Structure

SF structures consist of beam-column frames, diagonal bracings, and SF devices (SFD) as shown in Fig.1 [2], and the basic principle is to absorb vibration energy by 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. Herein, the mechanical and geometrical properties of SF structure are explained. As a definition of SF structure, the relations of size of out-frame and SF is defined as the "reduction rate α" as shown in Fig.1. Fig.3 shows the resistant mechanism of SF structure. From this model, the rigidity K_0 and yield strength P_y of SF are obtained theoretically by using α as follows:

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

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

Where, E: the Young's modulus of the SF, I_{SF}: moment of inertia of area of the SF, Z_{SF}: elastic modulus of SF, B: the length of the beam, H: the length of the column, L: the diagonal length of beam-column frame, f_b: allowable bending stress of the SFD. From the above equations, it can be said that rigidity K_{SF} 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. However, in case of very small reduction rate of SFD, the fracture would be occurred, so it is desirable that the limitation of reduction ratio is decided.

1.2 Characteristics of SF Deformation

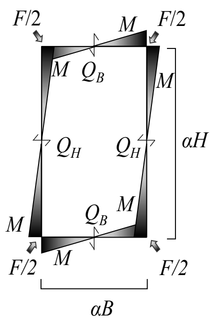


Figure 3: Diagram of bending stress of SF subjected to lateral load

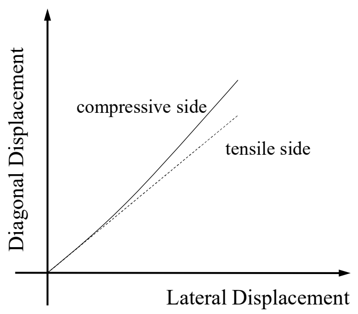


Figure 4: Relation of compressive and tensile deformation

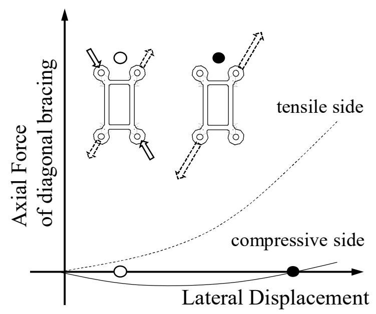


Figure 5: Relation of axial force and lateral displacement

The next, when shear deformation of rectangular frame progresses, it is clarified geometrically that the diagonal displacement of compressive grows larger than the one of extension. This property is applied to SF structure as shown in Fig.4. Especially, in the diagonal deformation of the SF, this property appears more conspicuously. Thus, the compressive deformation of the diagonal bracing on compressive side is small, and diagonal axial force will be reduced in large deformation range as shown in Fig.5. So the lateral buckling of diagonal member on compressive side is prevented. On the other hands, the diagonal axial force on tensile side will resist increasingly with progress of the deformation as shown in Fig.5. So bending reflection of the SF is restricted in large deformation range, and rigidity in the axial direction of the SF becomes dominant.

2. Experimental Studies of SF Structure

For the experimental study, the objective is to examine the effectiveness and applicability of vibration damping of wooden frame and steel frame with SF structure. To elucidate the load carrying mechanism and the restoring force characteristic at the ultimate seismic behavior, a shaking table test on wooden shaft assembly method (beam, column frame) has been conducted. To estimate the seismic resistant performance, the static loading test study is performed on the structural system of wooden house by platform framing method sometimes called light framed wall construction method with SF structures. For expanding the scope of application of SF structure, the horizontal static loading test was carried out on the steel framework with SF structure. The concluded results of some of the experimental results are as following.

2.1 Shaking Table Test of Wooden Frame with SF Structure

Summary of test specimens: Fig. 6 shows the example layout of test specimen and test set up image [3]. In this test, the specimens are one-layer wooden frames, the plane is 1,950×910mm and the height is 2,790mm. SF device is made of aluminum (A1050P) by cutting. Diagonal bracing is made of steel (SS400). SF device and diagonal bracing are connected by pin joint; also diagonal bracing and framework are connected by the end hardware structure. Reduction rate α of SF device is 8.5%. Table 2 summarizes the list of test specimens. Herein, four test specimens are prepared;
(1) PLY-4: a framework with four of plywood
(2) SF-4: a framework with four SF devices
(3) SF&PLY: a framework with two plywood and two SF devices
(4) FRAME: an only framework
Moreover, SF devices and plywood are located the location of Y1 and Y3 in Fig. 7. As superimposed load, the steel plate weigh 3.3ton is set on the roof. Table 3 shows the vibration program and the input seismic waves. The input earthquake motions are BCJ-L1 and BCJ-L2, which are artificial earthquake motions of the Building Center of Japan. Also, JMA Kobe NS (1995) is adopted too.

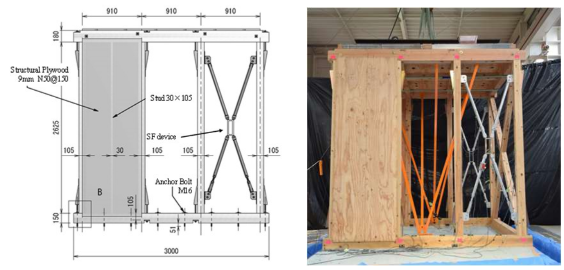


Figure 6: SF&PLY specimen and image of test set up

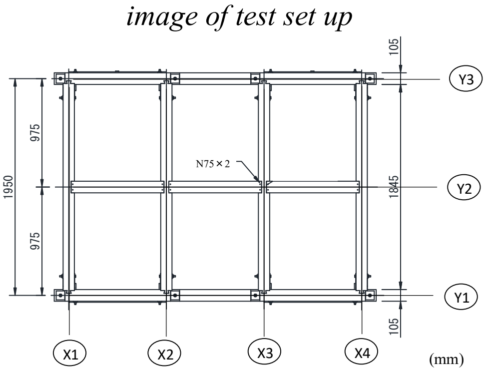


Figure 7: Floor plan of test specimens

Table 2: Summary of test specimens

Specimens	Mass	Plywood	SF	Period (design)
PLY-4	3.3 ton	4	-	0.280s
SF-4		-	4	0.218s
SF&PLY		2	2	0.243s
FRAME		-	-	-

Table 3: Vibration program & collapse mode

Step	Frame	PLY4	SF4	SF &PLY
1.BCJ-L1 1^{st}	4		1	1
2.BCJ-L1 2^{nd}	4		1	1
3.JMA Kobe 1^{st}	-	3	1	1,2,3
4.BCJ-L2	4	2,4	1	1,2,3
5.BCJ-L1 3^{rd}	-	2	1	1,2,3
6.JMA Kobe 2^{nd}	-	2,4	1	1,2,3
7.JMA Kobe 3^{rd}	-	-	1	1,2,3

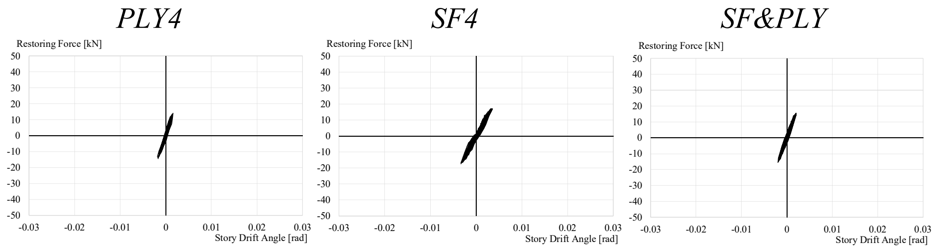
-: not complied with, 1: Plastic deformation of SF device, 2: Damage of screw of plywood, 3: Damage of hold down hardware, 4: damage of framework

Experimental results and discussion: During the test of SF-4 specimen, the connection loose of SF device and diagonal bracings has been observed, so then, the bolts were fastened after BCJ-L1 1st and JMA Kobe 1st. And also, during the test of PLY-4 subjected to JMA Kobe 1st and JMA Kobe 2nd, it was observed that the plywood had been experienced with severe damage, so the later test was canceled. Moreover, during the test of FRAME subjected to BCJ-L1 2nd, the terrible damages were confirmed, so the vibration input program was changed.

The collapse mode observed is shown in Fig. 8, and the damage occurrence record is shown in Table 3. Fig.9 shows the test results of hysteresis curve subjected to BCJ-L1 1st, JMA Kobe 1st and 2nd. From the results of BCJ-L1 1st, PLY-4 has the highest rigidity. Moreover, PLY-4 shows a non-slip on hysteresis loop subjected to BCJ-L1 1st, however, it presents the slip behavior subjected to JMA Kobe 1st. It is supposed that the damage of screw of plywood was occurred. In contrast, it is confirmed that SF-4 and SF&PLY draw near spindle-type on hysteresis loop. Furthermore, after JMA Kobe 2nd was input, the specimens with SF show equable behavior of spindle-type, against the slip of PLY-4 proceed even more.

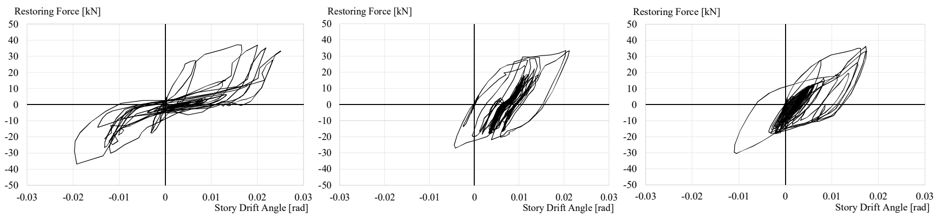
From the test results, the specimen by use of only plywood shows the slip on hysteresis loop because of damage of plywood, however, the specimen with SF device installed was prevented that from showing after plywood is damaged. Altogether, these results confirmed damper effect of SF structure.

(a)Plastic deformation of SF



(a) BCJ-L1 1st

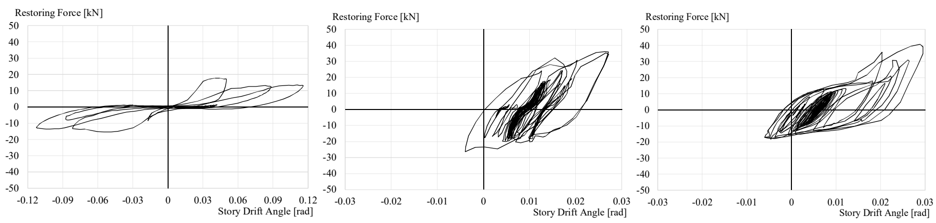
(b)Damage of screws



(b) JMA Kobe 1st

(c)Damage of framework

Figure 8: Collapse mode



(c) JMA Kobe 2nd

Figure 9: Hysteresis curve of each test specimen

The natural periods of the specimens at designing are shown as Table 2. Also, Fig.10 shows the transition of natural period, which is obtained from the results by white noise. As shown in these results, the natural period is almost similar each specimen before the damage is occurred. Moreover, from the result of Fig.13, it is confirmed that the natural periods of the specimens with plywood are smaller than that of SF-4 up to BCJ-L1 2nd; before the remarkable plastic deformation occurs. Therefore, the rigidity of plywood is probably larger than that of SF device.

From the results of PLY-4, the natural period is almost similar to that of FRAME after plywood damage by JMA Kobe 1st. From the result, plywood probably does not function as resistant element during ultimate state. Moreover, at the same time, the natural period of the specimens with SF device is larger than that of the specimen with plywood. This shows SF structure has function as resistant element.

The transition of drift angle based on maximum response displacement is shown in Fig.11. From these results, it is confirmed that the response of PLY-4 is smaller than other specimen up to BCJ-L1 1st and 2nd. This is probably caused that the rigidity of plywood is higher than that of SF. However, the response of the specimens with SF device is smaller than that with plywood after JMA Kobe 1st occur damage of plywood. Therefore, this result indicates that SF structure maintains the enough seismic resistant elements during ultimate state. In addition, the response of SF&PLY is as large as SF-4. This result confirmed, against plywood that is the element of earthquake resistance, SF structure that is the element of vibration control has the effect that decrease the response.

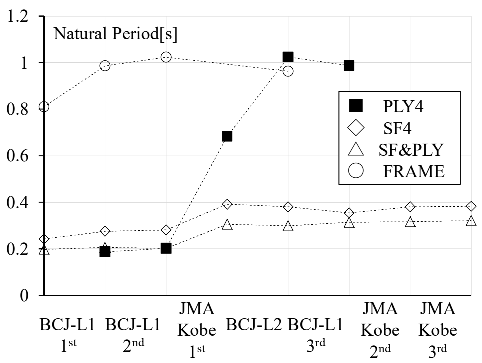


Figure 10: Transition of Natural Period

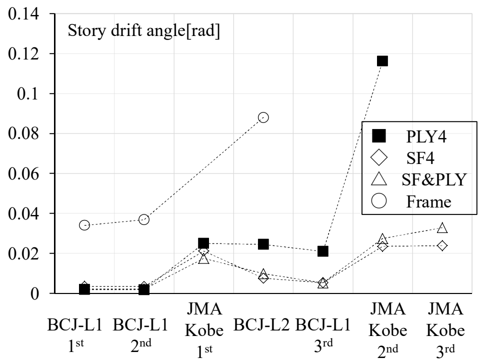


Figure 11: Transition of Maximum Story Drift

2.2 Static Loading Test of Wooden Platform Framing with SF Structure

Summary of horizontal static loading test specimen: Figs. 12, 13 show the configurations of test frame specimen [4]. SF device and structural plywood are installed on wooden light framed wall construction test specimen, and two type of height of frame is also prepared which are called as low-stud type and high-stud type. The names of test specimens are as follows;

(i) L-SF/ H-SF specimen: frame with SF device,
(ii) L-PLY specimen: frame with plywood,
(iii) L-SF&PLY specimen: SF device and plywood both

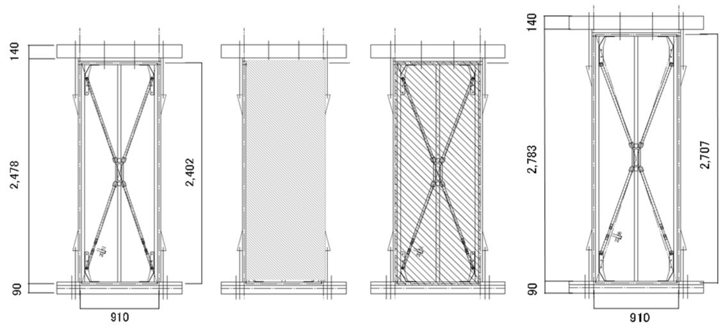
The vertical and horizontal members of test frame are connected by use of hold down hardware. SF device is made of aluminum by cutting, and diagonal bracing is made of steel. SF device and diagonal bracing are connected by pin joint. Reduction ratio α of SF device is 8.26%, and its thickness is 40mm. The mechanical properties of members of test specimen are summarized on Table 4. To avoid intersecting, the center of vertical frame member is cut out. And, the steel hardware is attached to this cut out portion. The cyclic loading program is arranged by the reference of the target displacement, the maximum drift angles of the frame at each loop are 1/450,1/300,1/200,1/150,1/100,1/50,1/15rad, referred by Japanese standard of structural experimental studies and loaded up to the stroke limit.

Table 4: Mechanical properties of member of test specimen

Parts	Steel grades*1	Yield strength(N/mm^2)	Tensile strength(N/mm^2)
SF	A1050P	-	115
Brace	STK400	419	478

Parts	Material	Grading*2
Frame	SPF*2	A Grade 2
Plywood	Conifer	Special Grade 2

*1Grade of JIS(Japanese Industrial Standards)
*2Grade of JAS (Japanese Agricultural Standard)



L-SF L-PLY L-SF&PLY H-SF

Figure 12. Elevation of test frame specimens (unit: mm)

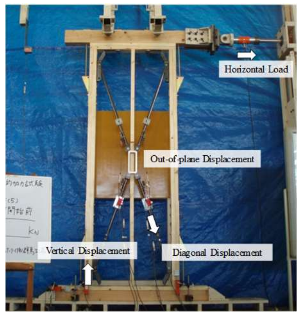


Figure 13. Elevation of test setup and location of sensors

Experimental results and observations: The following failure modes are confirmed from experiments during loading test; a) plastic deformation of SF device, b) uplift of column base, c) damage of test frame, d) damage of screw on plywood, e) bending deformation of vertical member. These results are summarized on Table 5. Fig. 14 shows the ultimate state of test specimen.

From the test results, the relations of horizontal load – drift angle are presented on Fig.15. And to investigate the feasibility of summation rule of each resistant element, the skeleton curve of sum of L-SF / L-PLY and L-SF&PLY specimens are compared on Fig.16. And also, to study of the effects of height of frame, the comparison of L-SF and H-SF are compared on Fig.17. From the test results, the strength and rigidity are summarized on Table 6. From Fig.15 and Table 6, in case of L-PLY, the deterioration of strength is observed during ultimate state. The inelastic behaviors are generated by damage of structural plywood. And in case of L-SF&PLY which has structural plywood, the degradation of strength is slightly observed, however, the stable hysteresis loop is appeared too. From this comparison, the SF device plays the role as resistant element to prevent the deterioration behavior after the structural plywood is damaged. That is, the SF becomes fail-safe system. And also, this relation is confirmed from the comparison of skeleton curve as shown in Fig.16. From the results of Fig.17, the strength and rigidity of tall frame specimen become small compared with low frame specimen. And the hysteresis loops of L-SF and H-SF show similar rule each other. Finally, the uplifts and damages of joint fasteners are observed on ultimate states of all test specimens, and the members of frame are collapsed too.

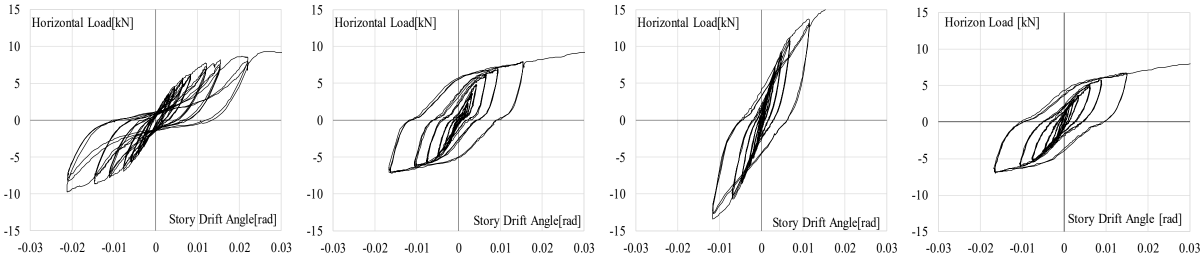
Table 5: Failure mode observed during loading test

Story Drift Angle	L-SF	L-PLY	L-SF &PLY	H-SF
1/75 rad	a	b	-	a
1/50 rad	b	d	a, b	b
1/15 rad	c	-	c, d	c
Final	e	-	-	e

Table 6: Summaries of test results

specimens	Yield (kN)	Max; (kN)	Rigidity (kN/mm)	Hysteresis rule
L-SF	6.62	13.3	0.228	Stable
L-PLY	5.83	9.3	0.446	Pinching Slip Deterioration
L-SF &PLY	9.87	18.1	0.374	Pinching slip
H-SF	5.62	9.90	0.169	Stable

Figure 14: Ultimate state of test specimen



L-PLY *L-SF* *L-SF&PLY* *H-SF*

Figure 15: Relations of horizontal load – story drift of test result

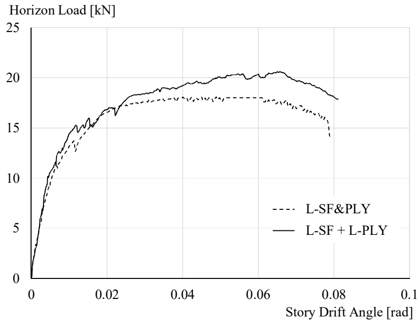


Figure 16: Comparison of skeleton curve of L-SF&PLY and summation of L-SF and L-PLY

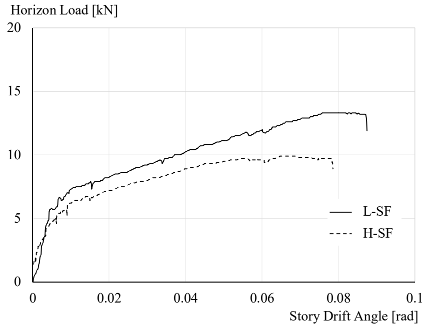


Figure 17: Comparison of skeleton curve of L-SF and H-SF

2.3 Horizontal Static Loading Test of Steel Framework with SF Structure

Summary of horizontal static loading test: To investigate the fundamental restoring force characteristics of SFD experimentally, the horizontal static loading tests are conducted on elementally test [5]. In Figs.18, 19 show the loading test setup and the test specimen of SFD. Herein, the reduction ratio of SFD is considered with parameters as 7%, 8.5%, and 10%. SFD (thickness 19mm) are made of steel. Table.7 shows member of test specimen and test parameters on elementally test and the mechanical properties of steel used for the test specimen. Herein, α is reduction rate. σ_y is yield strength and σ_u is tensile strength. And, E is Young's modulus. SS400 present the grade of JIS (Japanese Industrial Standards). The loading program is arranged by the reference of the target displacement, and the maximum angles of the column at each loop are 1/200, 1/100, 1/75, 1/50, and 1/30 rad. It is gradually increased and the same two angles of the column for each cycle are repeated.

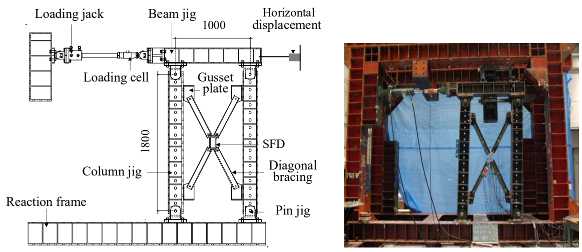
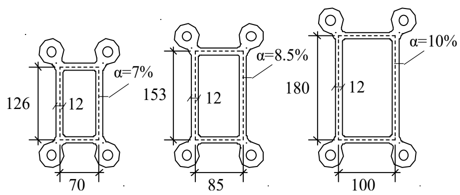


Figure 18: Elevation of test setup



α-7 *α-8.5* *α-10*

Figure 19: Test specimen of SFD

Table 7: Name of test specimen and test parameters and Mechanical properties of steel

Member	Reduction ratio	JIS grade	σ_y [N/mm²]	σ_u [N/mm²]	E [kN/mm²]
α-7	7	SS400	285	433	210
α-8.5	8.5	SS400			
α-10	10	SS400			
Bracing	-	SS400	342	472	202

Result of test study: Fig.20 shows the relation of horizontal load - horizontal displacement of monotonic loading test result. From these results, it is confirmed that the rigidity and strength of the SFD become large in case of small reduction rate *α*. And also, the strain hardening is appeared during ultimate state. Moreover, strength and rigidity of SFD is raised strongly during ultimate states. From the analysis of axial and curvature of SFD obtained from strain gauges, the curvature is dominated during early stage, however the axial deformation is advanced during ultimate states. According to the above results, it can be said that resistance state of the SFD translates from the bending mechanism to axial force mechanism with progress of the deformation.

Fig.21 shows the relation of horizontal load - horizontal displacement of monotonic loading test result. From the results of Fig.21, it is confirmed that the stable inelastic behaviors are presented. From this, it is confirmed that SF structure function as a load bearing element to reduce the damage on frame.

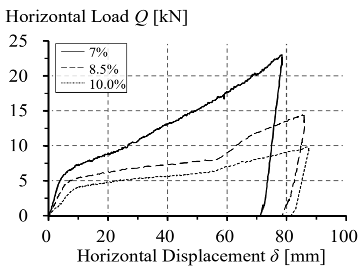
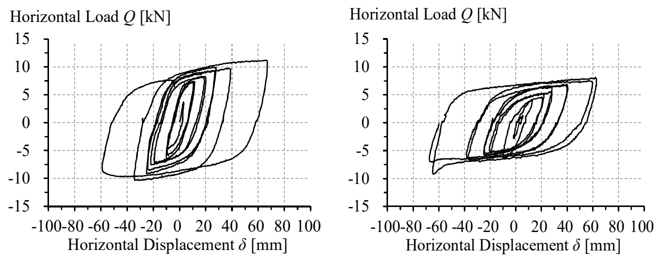


Figure 20: Monotonic loading test result of SFD



(a)α-8.5 *(b)α-10*

Figure 21: Cyclic loading test results of SFD

3. Conclusions

This paper suggested the innovated vibration control device called as scaling frame (SF) with wooden structure and steel structure. And, to investigate the inelastic behavior and restoring force characteristics of SF, shaking table test and horizontally loading tests are conducted. The conclusions are as follows:

1) In the wooden shaft assembly method, shaking table test was conducted with the aim of grasping the behavior during the earthquake. Based on the test results, in specimens having only structural plywood, slip behavior is shown due to plywood damage, but in test specimens with SFD, spindle type hysteresis behavior is shown even at the final level. In specimens using SFD and structural plywood in combination, although pinching and strength reduction were confirmed due to structural plywood damage, spindle shape is shown as the historical behavior. From this, by using SFD together, damage to the plywood was suppressed, and a stable vibration damping effect was obtained even after the damage.

2) In light framed wall method, static loading experiments were conducted to verify ultimate seismic performance due to difference in construction method. From this, it was shown that the restoring force characteristics of light framed wall method with SF structure can be evaluated by adding plywood and SFD. From the comparison of L-PLY and L-SF&PLY, the SF device plays the role as resistant element to prevent the deterioration behavior after the structural plywood is damaged. From the test results, the strength and rigidity of tall frame specimen become small compared with low frame specimen. And the hysteresis loops of L-SF and H-SF show similar rule each other.

3) To investigate the inelastic behavior and restoring force characteristics of SF, horizontally loading test are conducted on steel framework. From the results, the SF with small reduction ratio *α* shows large strength and rigidity. The resistance state of SF translates from the bending mechanism to axial force mechanism with progress of the deformation.

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