Seismic Resistant Mechanism of Two-by-four Wooden Frame with Vibration Control Device

Takumi Ito, Kurumi Kurokawa, Dong Hang Wu, Takashi Nagumo, Haruhiko Hirata

***Abstract*—**The structural system of wooden house by two-by-four method is widely adopted in any countries, and a various type of vibration control system for building structures has been developed on country with frequent earthquake. In this study, a vibration control device called "Scaling Frame" (SF) is suggested, and which is applied to wooden two-by-four method structures. This paper performs the experimental study to investigate the restoring force characteristics of two-by-four with SF device installed. The seismic resistant performance is estimated experimentally, and also the applicability and effectiveness are discussing.

***Keywords*—**Two-by-four method, seismic vibration control, horizontally loading test, restoring force characteristics.

I. Introduction

FOR wooden building structures, a various kind of structural system is adopted, and the two-by-four method wooden house is widely constructed in any countries. After two-by-four system has been appeared since late 19th century, its seismic resistant performance has been studied on past by enormous researches. And the number of application record for wooden house is increasing.

Recently, various types of vibration control device for building structures has been developed on country with frequent earthquake, and these applicability and effectiveness are clarified by past researches [1]-[5]. 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. Herein, from the viewpoints of mechanical characteristics and materials, these devices are categorized as shown Table I with damping system (viscous, hysteresis, friction), resistant mechanics (bending, shear, axial), materials (metal, oil, rubber). Additionally, the application on structural system and building scale are classified as shown Table II.

Herein, the vibration control device called "Scaling-Frame" (abbreviated as "SF") is suggested, and the characteristic of this device is hysteresis damper with the plastic bending behavior. The authors have already applied to wooden framework [6]. As shown in Fig. 1, SF structure consists of beam-column frame, diagonal bracing, and SF device. Moreover, SF device is made of steel or aluminum; that is, SF has some advantages such as workability, productivity and containment because of small size, light weight, durability and sustainability of metal materials.

In this paper, this SF structure is applied to two-by-four wooden frame, and the applicability and feasibility are investigated experimentally. So the loading test study is performed on test frame specimen. And also, the restoring force characteristics and seismic resistant performance are evaluated.

TABLE I
Summary of Vibration Control Devices

System	Mechanics		
	Axial	Shear	Bending
Hysteresis			**SF device**
Viscous			
Friction			

TABLE II
Application of Vibration Control Devices on Buildings

	Scale	Low	Middle	High	Tall
Style		10F	15F	25F	
Steel	SRS				
	VCS				
	SIS				
R/C	SRS				
	VCS				
	SIS				
Wooden	SRS				
	VCS				
	SIS				

SRS: Seismic Resistant Structure, VCS: Vibration Control Structure, SIS: Seismic Isolated Structure

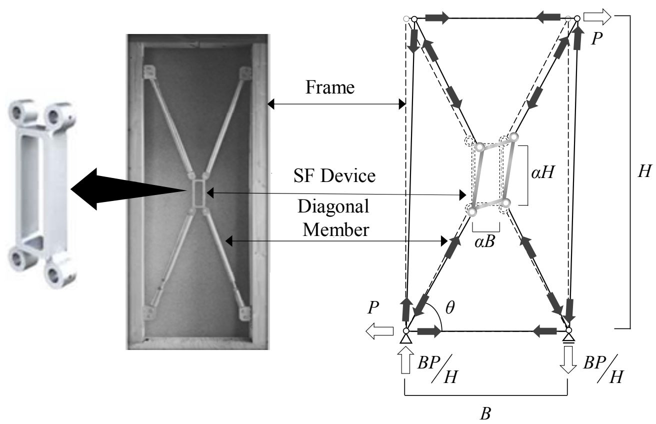

Fig. 1 Conceptual diagram of SF structure

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II. General Description of SF Structure and Layout of SF Device on Two-by-Four Frames

A. Test Frame Specimen and Test Parameters

Herein, the mechanical and geometrical property of SF structure are explained. According to a definition of SF structure, the relation between the size of out-frame and SF is defined as reduction rate α as shown in Fig. 1, and Fig. 2 shows the resistant mechanism of SF structure. From this model, the rigidity K_{SF} and yield strength P_y of SF are obtained theoretically by using α as follows:

$$K_{SF} = \frac{12\,E\,I_{SF}\;L^2 \cos^2\theta}{\alpha^3\;B^2\;H^2\;(B+H)} \tag{1}$$

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

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 SF.

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

Herein, 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. 3. 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 the diagonal axial force will be reduced in large deformation range as shown in Fig. 4. 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. 4. So, bending reflection of the SF is restricted in large deformation range, and rigidity in the axial direction of the SF becomes dominant.

B. Layout of SF Device on Two-by-Four Frame

The conceptual diagram and layout of SF structure are illustrated as shown Fig. 1; the standard layout of two-by-four frame is illustrated on Fig. 5. From the relation of each layout, it is assumed that the SF device intersects the vertical member of two-by-four frame. Of course, the size and aspect ratio of SF structure is arranged to fit in the space; however, manufacturing process of SF device becomes difficult in case of small size or large aspect ratio of SF device.

In this study, to avoid the intersecting of SF device and vertical member of two-by-four frame, the center of vertical member is cut out as shown Fig. 5. So then, the effects of the cut off of member are investigated experimentally.

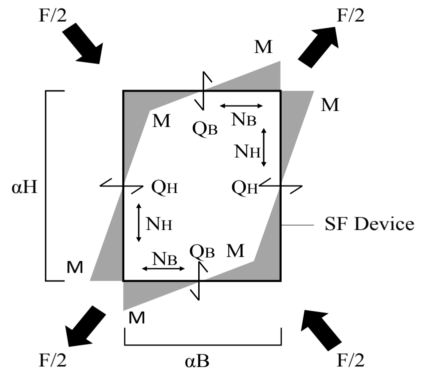


Fig. 2 Diagram of bending stress of SF subjected to lateral load

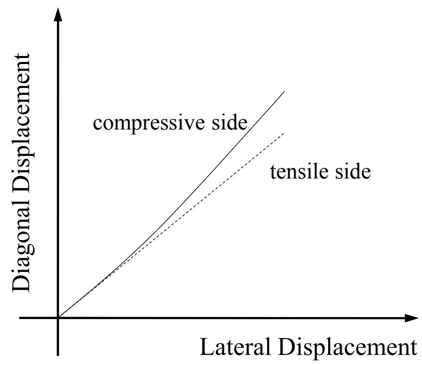


Fig. 3 Relation of compressive and tensile deformation

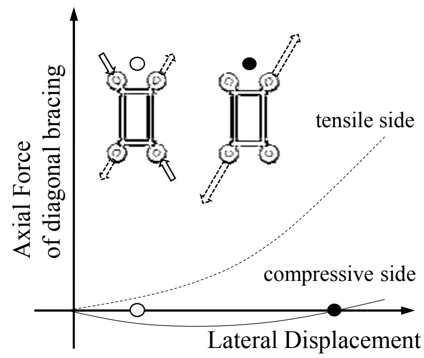
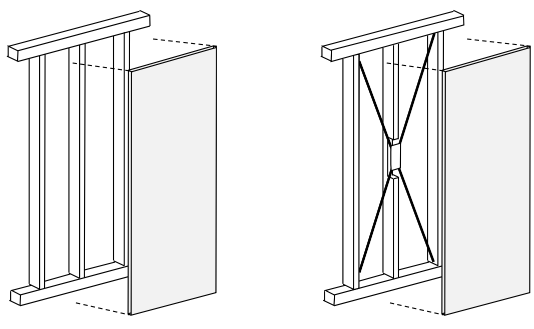


Fig. 4 Relation of axial force and lateral displacement



(a) layout of 2X4 frame (b) combination of 2X4 and SF

Fig. 5 Relation of two-by-four frame and SF structures

III. Summary of Horizontal Static Loading Test

A. Test Frame Specimen and Test Parameters

The configurations of test frame specimen are illustrated on Fig. 6. The SF device and structural plywood are installed on wooden two-by-four frame test specimen, and two types of height of two-by-four frame which are called as low-stud type and high-stud type are prepared. The horizontal loading tests are performed with parameters as shown in Table III, and the names of test specimens are as follows;

(1) L-SF/ H-SF specimen: two-by-four frame with SF device,
(2) L-PLY specimen: two-by-four frame with plywood,
(3) L-SF&PLY specimen: SF device and plywood both.

The vertical and horizontal member of test frame are connected by use of hole down hardware. SF device is made of aluminum (A1050, JIS grade) by cutting, and diagonal bracing is made of steel (STK400, JIS grade). SF device and diagonal bracing are connected by pin joint. Reduction ratio α of SF device is 8.26%, and its thickness is 40 mm. The mechanical properties of members of test specimen are summarized on Table IV.

As above mentioned, the original layout of SF device intersects the vertical frame member of two-by-four. To avoid intersecting, the center of vertical frame member is cut out. Moreover, the steel hardware is attached to this cut out portion.

B. Test Setup and Measurement Layout

The elevation of test setup is shown in Fig. 7. The horizontal force is measured from the load cell built into the loading jack. The horizontal displacement at the top of the frame is measured by using a tape measure type displacement transducer. The uplift of column base, the diagonal displacement, and the displacement of out-of-plane of SF device are measured.

C. Test Setup and Measurement Layout

The cyclic loading pattern is applied under loading test. The loading program is arranged by the reference of the target displacement, and the maximum angles of the frame at each loop are 1/450, 1/300, 1/200, 1/150, 1/100, 1/50, 1/15 rad, which are referred by the Japanese standard of structural experimental studies.

TABLE III
List of Test Frame Specimen and Parameters

Name	2X4	SF	plywood
L-SF	Low-stud	Install	None
L-PLY	Low-stud	None	Install
L-SF&PLY	Low-stud	Install	Install
H-SF	High-stud	Install	None

TABLE IV
Mechanical Properties of Steel Member of Test Specimen

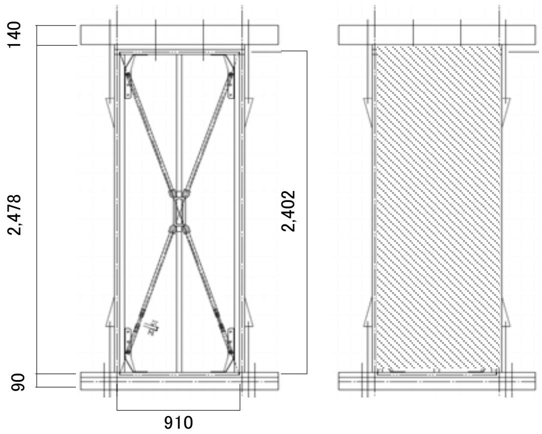
Parts	Steel grades*[1]	Yield strength (N/mm^2)	Tensile strength (N/mm^2)
SF	A1050P	-	115
Brace	STK400	419	478

*[1]Grade of JIS (Japanese Industrial Standards)

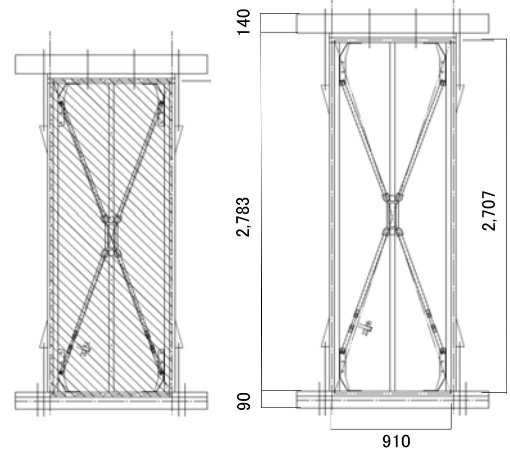
TABLE V
Mechanical Properties of Wooden Member of Test Specimen

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

*[2]Grade of JAS (Japanese Agricultural Standards)



(a) L-SF specimen (b) L-PLY specimen



(c) L-SF&PLY specimen (d) H-SF specimen

Fig. 6 Elevation of test frame specimens (unit: mm)

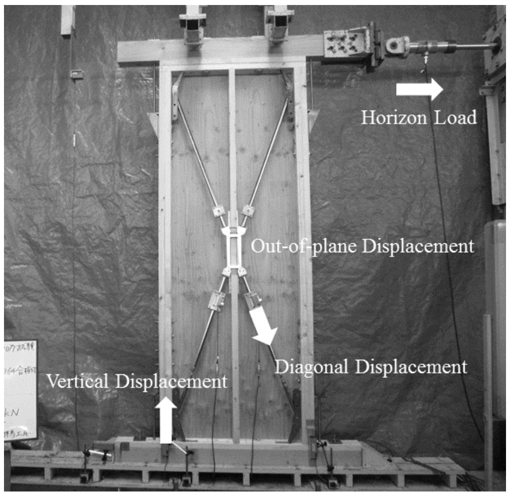


Fig. 7 Elevation of test setup and location of sensors

IV. Test Results and Observations

A. Failure Modes and Process during Loading Test

Fig. 8 shows the failure modes which are observed 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 V.

From Table V, in cases of L-SF and H-SF, the plastic deformation of SF device was observed at 1/75 rad; however, it was not observed until 1/50 rad in case of L-SF&PLY. It is because the SF device.

B. Restoring Force Characteristics and Hysteresis Behavior

From the test results, the relations of horizontal load – drift angle are presented on Fig. 9. Also, to investigate the feasibility of summation rule of each resistant element, the skeleton curves of sum of L-SF / L-PLY and L-SF&PLY specimens are compared on Fig. 10. Additionally, to study of the effects of height of frame, the comparison of L-SF and H-SF is shown on Fig. 11. From the test results, the strength and rigidity are summarized on Table VI. Furthermore, the hysteresis rules are presented in Table VI too.

From the results of Fig. 6, in case of L-PLY, the deterioration of strength is observed during ultimate state. The inelastic behavior such as pinching and slip are observed. These 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.

From the results of Table VI, the sums of strength or rigidity of L-PLY and L-SF are calculated, and it is confirmed that these summations are almost equal to the results of L-SF&PLY. From this result, the summation rule of SF device and structural plywood is satisfied. And also, this relation is confirmed from the comparison of skeleton curve as shown in Fig. 10.

From the results of Fig. 11 and Table VI, the strength and rigidity of tall frame specimen become small in comparison with low frame specimen, and the hysteresis loops of L-SF and H-SF show similar rule.

Finally, the uplifts and damages of joint fasteners are observed on ultimate states of all test specimen, and the members of frame are collapsed too.

C. Analytical Study of Skeleton Curve

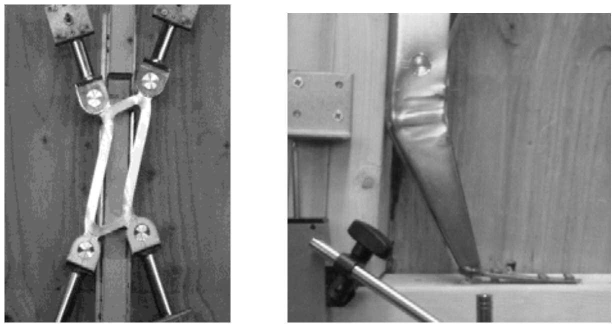
From the test results, the skeleton curves of each resistant element (SF, plywood and frame) are extracted, and these results are shown in Fig. 12. Also, the theoretical skeleton curve of SF device is calculated from (1) and (2), and the comparison with test result is presented on Fig. 12 too.

From the comparison of Fig. 12, the strength and rigidity of SF device and plywood within 0.02 rad are corresponding to each other, and the frame is regarded as non-seismic resistant element. Furthermore, it is confirmed that the theoretical curve can chase test results.

TABLE VI
Failure Mode Observed during Loading Test

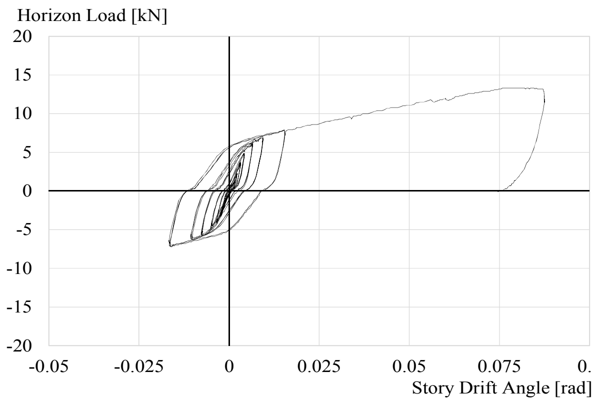
Drift angle	L-SF	L-PLY	L-SF&PLY	H-SF
1/75rad	a	-	-	a
1/50rad	b	b, d	a, b	b
1/15rad	c	-	c, d	c
final	E	-	-	e

Here, 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

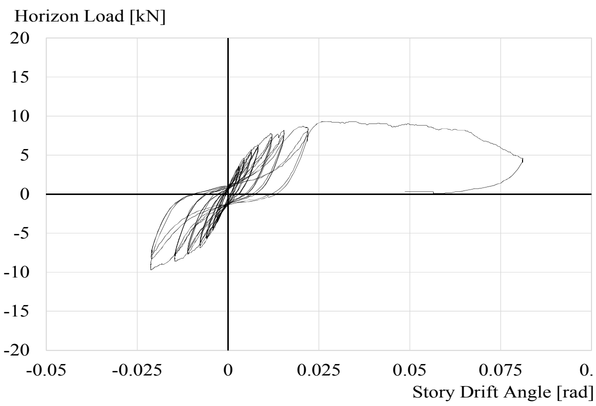


(a) plastic deformation of SF (b) damage of joint fasteners

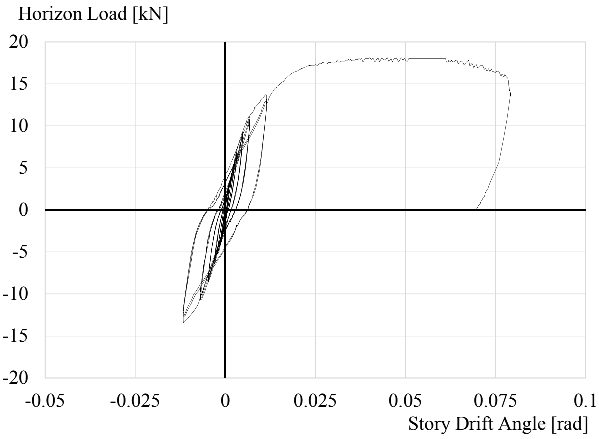
Fig. 8 Ultimate state of test specimen



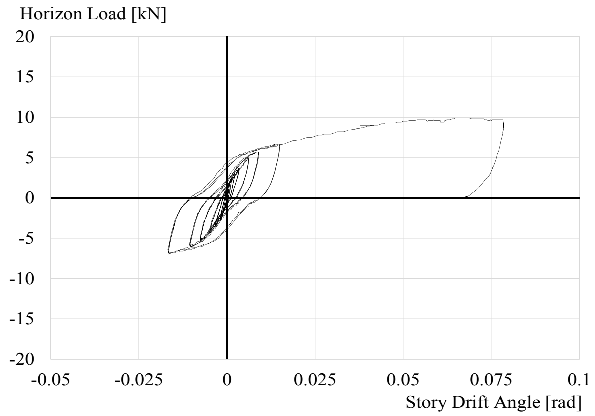
(a) L-SF specimen



(b) L-PLY specimen



(c) L-SF&PLY specimen



(d) H-SF specimen

Fig. 9 Relations of horizontal load – story drift of test result

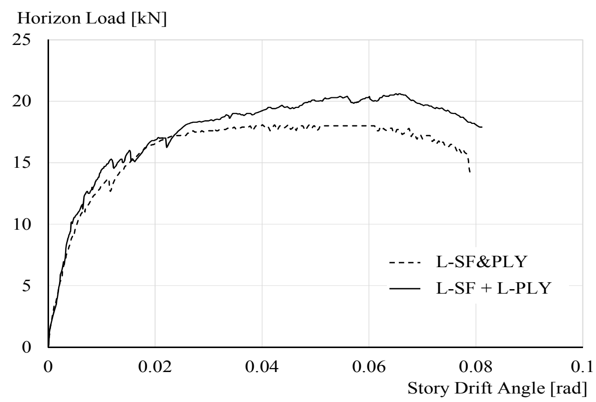


Fig. 10 Comparison of skeleton curve of L-SF&PLY and summation of L-SF and L-PLY

TABLE VII
SUMMARIES OF TEST RESULTS

specimen	Yield (kN)	maximum (kN)	rigidity (kN/mm)	Hysteresis rule
L-SF	6.62	13.3	0.228	stable
L-PLY	5.83	9.30	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

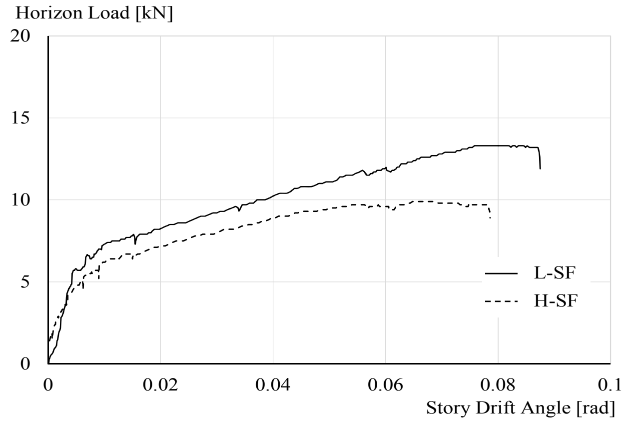
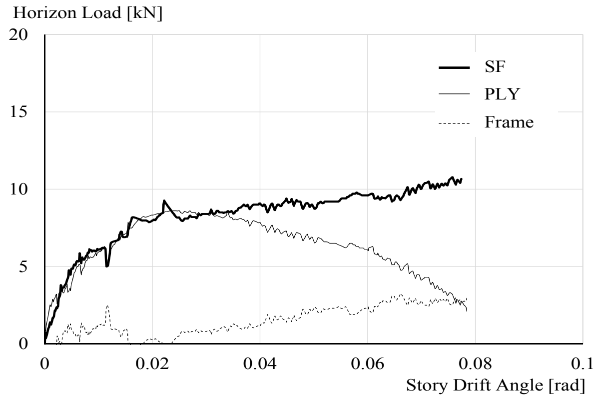
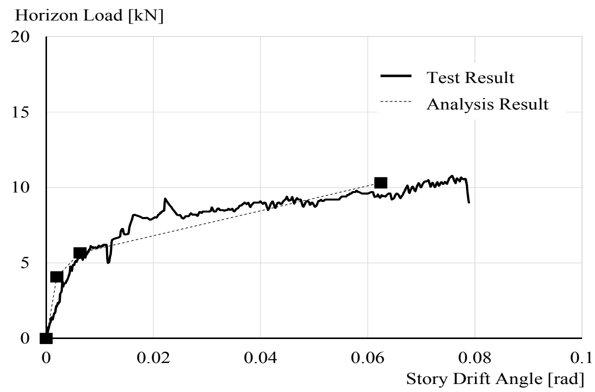


Fig. 11 Relations of horizontal load – story drift of test result



(a) test results of skeleton curve of each resistant element



(b) comparison of skeleton curve of SF device

Fig. 12 Comparison of skeleton curve of test results and analysis

V. CONCLUSIONS

In this paper, the seismic vibration controlled two-by-four wooden frame is suggested, and the SF structure made of metal is proposed for innovated vibration control device. Herein, the restoring force characteristics and inelastic behavior of this frame are investigated experimentally. The conclusions are as follows:

1. The fundamental theory of SF structures is explained. The theoretical equations show that the small reduction rate of

SF provides the large rigidity, strength, and high energy absorption. Furthermore, from the geometrical relation of SF structure, the compressive deformation of the diagonal bracing on compressive side is small, and the diagonal axial force will be reduced in large deformation range. So, the lateral buckling of diagonal member on compressive side is prevented.

2. When the vibration controlled two-by-four wooden frame is developed, the SF structure overlap the vertical member of two-by-four wooden frame. So then, to avoid the intersecting, the center of vertical member is cut out, and the effects of the cut off of member is investigated experimentally in this paper.
3. In this paper, the following test frame specimens are prepared; SF device and structural plywood, two type of height of two-by-four frame, and the horizontal loading tests are performed with parameters as these combinations.
4. From the test results, in case of L-PLY, the deterioration of strength is observed during ultimate state. The inelastic behavior such as pinching and slip are observed. These 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.
5. From the test results, it is confirmed that the summations of strength or rigidity of L-PLY and L-SF are almost equal to the results of L-SF&PLY. From this result, the summation rule of SF device and structural plywood is satisfied.
6. 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.
7. And also, the skeleton curves of each resistant element (SF, plywood and frame) are extracted, the theoretical skeleton curve of SF device compares with test result. From the comparison, the strength and rigidity of SF device and plywood within 0.02rad are corresponding each other. And the frame is regarded as non-seismic resistant element. Furthermore, it is confirmed that the theoretical curve can chase test results.
8. Finally, it concludes that the SF device is effective system for two-by-four wooden frame to enhance the seismic resistant performance.

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