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INNOVATIVE DAMAGE CONTROL SYSTEMS USING REPLACEABLE ENERGY DISSIPATING STEEL FUSES FOR COLD-FORMED STEEL STRUCTURES

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Abstract

This paper describes the development of innovative seismic technologies for cold-formed steel structures; a rocking steel shear wall system with replaceable energy dissipating steel fuses for low rise housing units. In this system, the fuses are placed at the base of a folded-steel sheet wall connecting an anchor bolt and the steel sheet wall. It is designed so that most of the earthquake energy can be dissipated by plastic deformation of the fuse elements, while the shear wall remains intact and resists vertical and horizontal forces caused by large earthquakes.

As expected in seismic events, the fuses at the base move cyclically into plastic regions when the wall behaves in a rocking manner. As a result, the wall system is expected to show a stable energy absorption behavior. To maximize its energy absorption capability in this research, the shape of the fuse is optimized, such that a butterfly shape is employed to have a greater yielding region.

To verify the seismic performance of the proposed system, static shear wall tests and earthquake response analyses were respectively conducted. It was confirmed, with both results, that the developed fuses have high energy absorbing capacity and the rocking shear wall systems using them also have high seismic performance in comparison with conventional shear wall systems. The proposed system contributes to increased sustainability of the building systems through which damaged fuses are replaced after strong earthquakes.

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1. Introduction

To minimize damages of both structural and nonstructural members in a building structure during strong earthquakes, a damage control system using replaceable energy dissipating elements is widely applied as one of the effectively advanced seismic technologies. The energy dissipating elements, namely fuses, have been developed by using various materials, for instance, steels, leads, superplastic alloys and viscoelastic polymers. Steel is renowned for its advantages over other materials, for instance, low costs by mass productions, compatibility of strength with ductility and insensitivity for both velocity and temperature under repeated stress. It is also advantageous for the fuse. In fact, buckling restrained braces and shear panels using the steel fuses have been respectively put to practical use.

While both damage control systems and fuses are applied to various types of structures, they are not necessarily optimized for individual structural characteristics. This is explained by an example in the case of shear wall structures. The shear wall structure generally possesses a high stiffness in a horizontal direction by the high in-plan shear stiffness of the shear wall. Drift angles of this structure remain small when it behaves elastically. On the other hand, the fuses are generally required to be placed at positions where work loads of external forces, that is, both external forces and deformations become large. Placed in parallel to the shear wall, they cannot effectively absorb the energy while the shear walls behave elastically. They are finally effective after the shear walls have been widely damaged with increasing plastic deformations. It is strongly suggested that the conventional damage control system is unsuitable for the shear wall structure and a specialized system must be developed.

This paper proposes an innovative damage control system for cold formed steel structures including the shear walls. This paper focuses on a controlled rocking system for low-rise housing units. Recently, it is recognized that the controlled rocking system using the fuses is one of the effective seismic technologies to realize a damage control system. Several systems have been proposed in previous studies (Midorikawa et al., 2006, 2010; Luth et al., 2008; Hajjar et al., 2010; Deierlein et al., 2010; Kishiki et al., 2010). They mainly focus on rigid or braced steel frames, concrete shear walls and detached wooden houses. In contrast, we have individually developed a controlled rocking system for low-rise housing units, in particular, cold formed steel structures. In this paper, both rocking systems and high performance steel fuses are respectively proposed. Seismic performances of the proposed systems are minutely investigated by experimental and numerical approaches.

2. Concepts of Rocking Shear Wall Systems including the Steel Fuses

Figure 1 shows a schematic diagram of the rocking shear wall system equipped with the steel fuses. This is a multi-storied shear wall system for a low-rise cold formed steel structure. In the system, high strength fasteners are respectively placed at both the upper and bottom of the shear wall at each floor. Two shear walls placed adjacent to the up and down floors are rigidly connected by the fasteners and anchor bolts cutting through steel channels of the floor joists. By rigid connections between the stories, an entire wall from the bottom to upper stories behaves as one body.

A web panel of the shear wall is made by a folded steel sheet (corrugated steel shear walls) with both high yield strength and high elastic stiffness (Tipping et al., 2008; Tanaka et al., 2009). All sides of the web panel are connected to the steel channel members by drilling screws. Hold down fasteners are respectively placed at the left and right bottoms of the shear walls at the basement floor and connected to anchor bolts standing from footing concrete slabs. The conventional hold down fasteners are elastically resistant to overturning moments of the shear wall during a strong earthquake. In this case, most of the earthquake energy is generally dissipated by plastic deformations of the shear walls, that is, the damages to

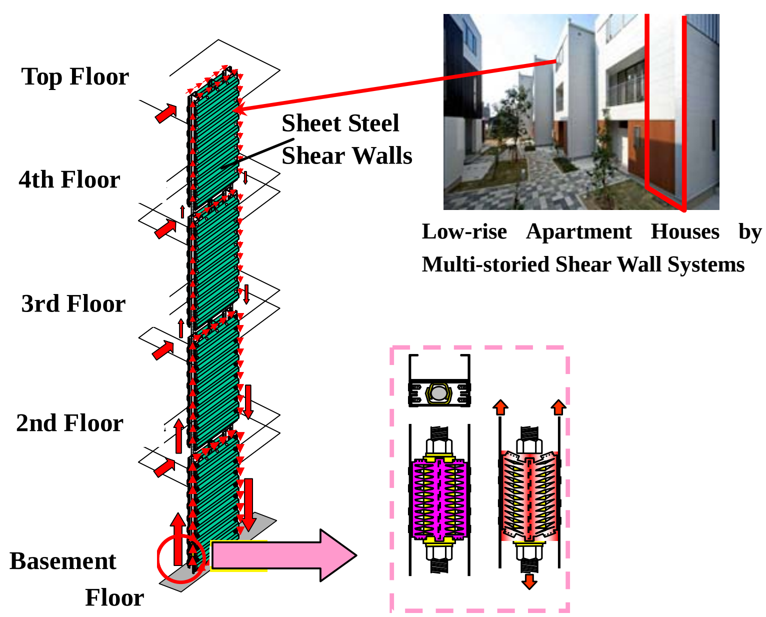


Fig-1 Rocking Shear Wall Systems using Fuses

themselves. On the other hand, a new concept proposed in this paper is that the hold down fasteners function as the fuse. While they dissipate the energy, the multi-storied shear wall wholly behaves in a rocking manner with up and down movements in a gravity direction.

Figure 2 shows the schematic diagrams of the hold down fastener equipped with the fuse function (hereafter, HDFF). A fuse panel of the HDFF is made by a steel plate pre-cutting using a laser beam machine. It bisymmetrically possesses plural rhomboid slits to create multiple energy dissipating elements. They are sandwiched between up and down rhomboid slits and have a butterfly shape; its cross section at the center is minimized and linearly increased toward both right and left ends. Both strength and stiffness of the HDFF can be controlled by numbers of butterfly elements. The steel fuse panels including the slits have been, for instance, proposed by past studies (Hitaka et al., 2003; Luth et al., 2008; Hajjar et al., 2010; Deierlein et al., 2010).

The fuse panel is connected to a fitting steel channel by a slot weld. A pair of fuse panels faces each other and is inserted into an inner hollow space of the steel channel attached to the shear wall. Finally, the HDFF is respectively connected to the steel channel and the anchor bolt by the drilling screws and nuts.

In a medium-grade earthquake, the HDFF behaves elastically and does not absorb the earthquake energy. In a strong earthquake, it moves cyclically into the plastic regions and most of the energy is dissipated by the plastic deformations of the butterfly elements. The severely damaged HDFFs after the earthquakes are detached from the shear walls and replaced by the intact HDFFs.

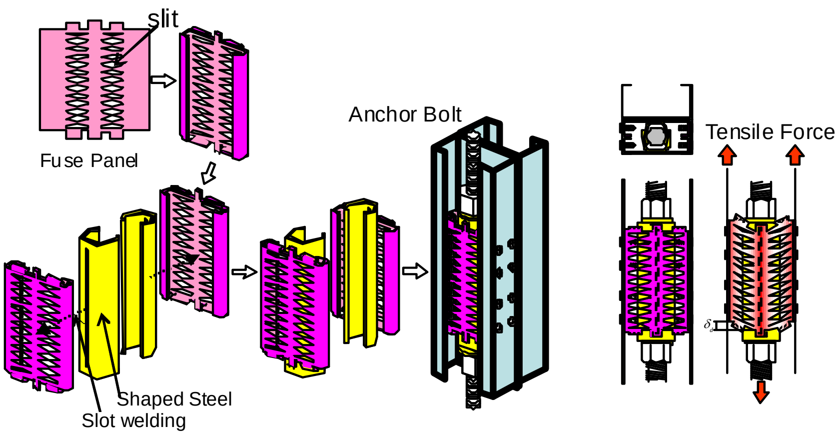


Fig-2 Hold Down Fastener Equipped with Fuse Functions

To maximize energy dissipating performance, both working forces and deformations must be concentrated in the HDFFs. The multi-storied shear wall can satisfy the above condition by large pull out forces induced by the overturning moments. On the other hand, it is necessary that the multi-storied shear wall remains intact while the HDFFs absorb the energy. Minimizing the damage of the shear wall is one of the most significant factors to guarantee the performance of the rocking shear wall system. As a matter of course, the HDFFs must have large plastic deformability maintaining a high resistant force. If these conditions cannot be satisfied, the energy absorbing capacities might decrease.

3. Static Experiments of the Rocking Shear Wall using the HDFF

3. 1 Summaries of the Experiments

To verify the seismic performance of the HDFFs, statically loaded experiments were conducted. Figure 3 shows the experimental system. The shear wall is set in the center of the system. Its section and steel material are respectively I-500x200x16x10 and JIS (Japan Industrial Standard)-SS400 (design yield strength 235N/mm^2 and design tensile strength 400N/mm^2). Both strength and stiffness of the shear wall are extremely larger than those of the HDFF. It is, consequently, considered that the shear wall behaves as a rigid body. Two steel channels are rigidly connected to both the right and left vertical sides of the shear wall by the drilling screws. Two HDFFs are symmetrically placed into both the right and left bottoms of the shear wall and respectively connected to both the steel channel and anchor bolt by the same process described in Fig. 2. Figure 4 shows the HDFF placed into the steel channel.

In the experiment, two types of energy dissipating elements are respectively used: the steel fuse panel with the butterfly shapes and rhomboid slits (Specimen A) and that with the rectangular shapes and rectangular slits (Specimen B). Figure 5 shows the fuse panels of the specimens. To verify the influence on plastic strain zones in the fuse elements, the butterfly and rectangular shapes are respectively conducted. To expand the plastic zones in the butterfly element (Specimen A), its sectional areas are optimized by the following equations.

$$\frac{M}{Z_e} = \sigma_y \qquad (1)$$

$$\frac{1.5N}{A_c} = \frac{\sigma_y}{\sqrt{3}} \qquad (2)$$

Where,
M : bending moment at the ends of the energy dissipating element,

N : shear force at the center of the energy dissipating element,
Z_e : section module at the ends of the energy dissipating element,
A_c : sectional area at the center of the energy dissipating element,
σ_y : yield stress of the fuse plate.
The equations (1) and (2) indicate that most parts in the butterfly elements start to simultaneously yield by both shear and bending stresses.

The steel material of the fuse panel is SS400. Its material property is shown in Table 1. The thickness of the fuse plates is given by 2.0 mm. Yield forces N_y of the HDFFs are given by the same value (33.3kN) for two specimens.

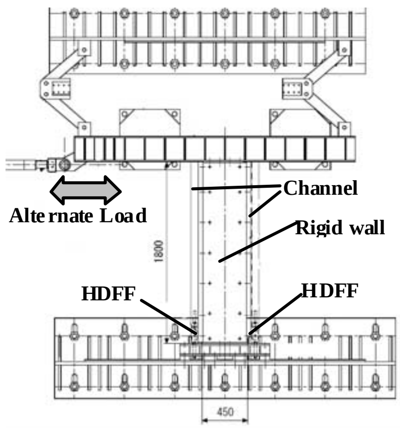
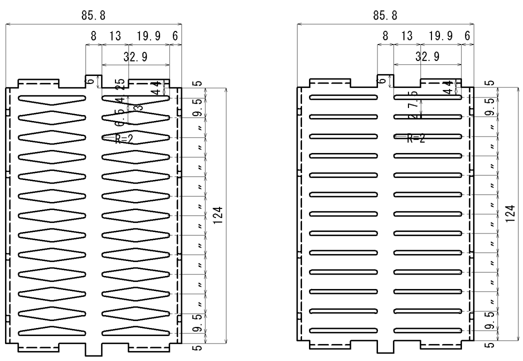


Fig-3 Overview of Experimental Systems

Fig-4 HDFF



Specimen A　　Specimen B

Fig-5 Fuse Panels of the Specimens

A peak to peak alternative horizontal load at the top left of the shear wall is systematically applied by controlling the drift angle of the shear wall. The uplift deformation of the shear wall rapidly increases after the fuse panel of the HDFF moves into the plastic regions. The experiments were conducted until the fuse panels were fractured.

Table-1 Material Properties of JIS-SS400

	YS(MPa)	TS(MPa)	EL(%)	YR(%)
SS400	362.3	506.5	34.1	71.5

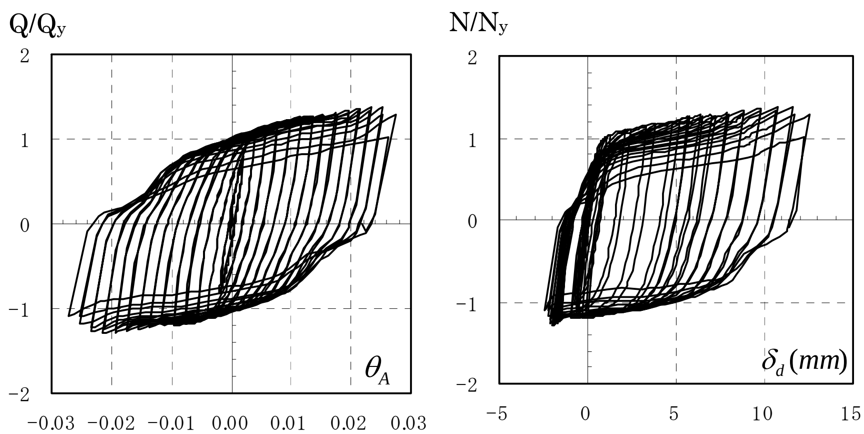
3.2 Experimental Results

Figure 6 shows the experimental results of both Specimen A and B. In the left figures, the horizontal and vertical axes respectively show the drift angle of the shear wall θ_A and the horizontal shear force Q. In the right figures, they respectively show the vertical deformation δ_d and the vertical force N for the HDFFs. Areas enclosed by the hysteresis of the force N - displacement δ_d relationships indicate the energy absorbing capacity of the HDFF. Its total energy value E is shown in Table 2. Both specimens exhibited ductile fractures of the energy dissipating elements.

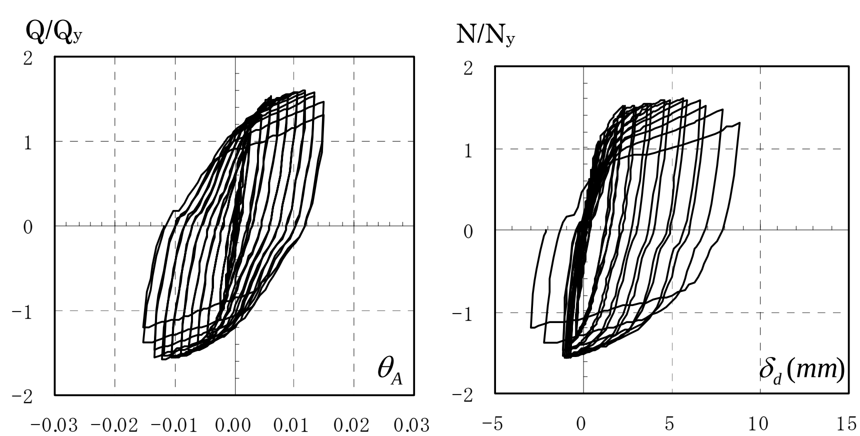
From observations of the experimental results, Specimen B has a smaller energy absorbing capacity than Specimen A. This is because the rectangular elements have narrow plastic zones and plastic strains are concentrated at both the left and right ends. Consequently, they fractured at the early stages of the deformations as shown in Fig. 6. In contrast, the maximum deformations of the HDFFs of Specimen A (the butterfly elements) exceed over 10 mm. Its total energy absorbing value is, also, twice as large as Specimen B. It is considered that the large plastic zone of the butterfly elements contributes to maximization of both energy absorbing capacity and plastic deformability.

Table-2 Experimental Results of the HDFFs

	Specimen A	Specimen B
	Butterfly	Rectangular
Elastic Stiffness (kN/mm)	34.5	44.4
Yield strength (kN)	33.4	33.4
Tensile strength (kN)	45.8	53.5
Maximum deformation (mm)	12.5	7.5
Total Energy absorbing value (kNmm)	5 700	2 500



(a) Specimen A (Left : Shear Wall, Right : HDFF)



(b) Specimen B (Left : Shear Wall, Right : HDFF)

Fig-6 Experimental Results of Static Shear Walls with HDFFs

4. Earthquake Response Analyses of the Rocking Shear Wall System with the HDFF

4.1 Analytical model

In this chapter, behaviors of the rocking shear wall system with the HDFFs are minutely investigated using an earthquake response analysis which takes into account both material and geometrical nonlinear effects (Tada et al., 2006).

Figure 7 shows a plane analytical model of four-storied and one span multi-storied shear wall structures. Uniformly concentrated masses are respectively placed on the nodes. The total weight of the masses is given by 50 kN. Two elasto-plastic springs which play the role of the HDFFs are respectively inserted at the bases of the frame. The hysteresis rule of the spring element in the plastic region is based on a kinematic hardening law. The values of the elastic stiffness, yield strength and secondary hardening are respectively illustrated in Fig. 7. Rectangular and line elements are respectively used for the shear walls and channel members. Both elements always behave in the elastic region. The primary natural frequency of the model is 0.72 seconds. It is assumed that the damping factor of the model is given by 0.01.

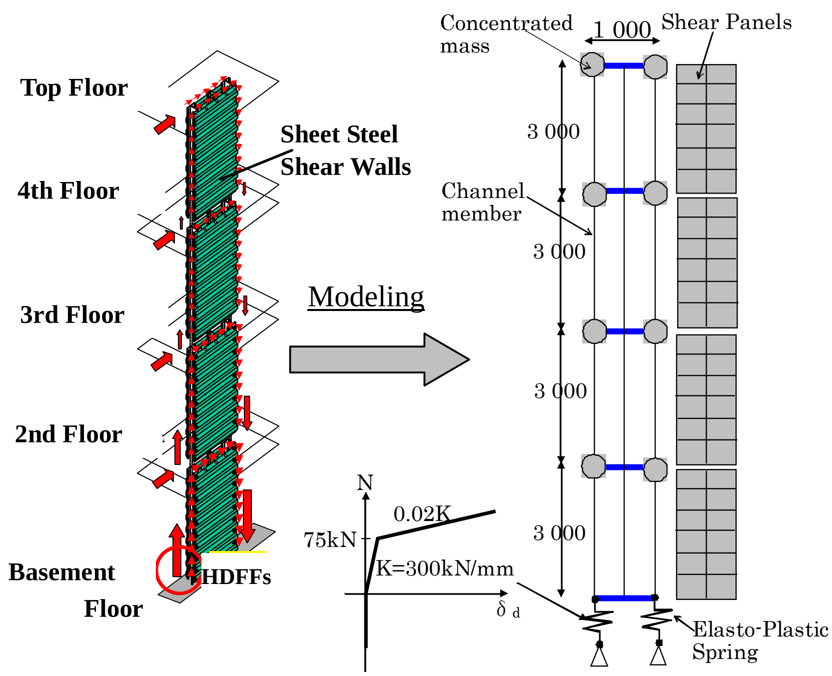
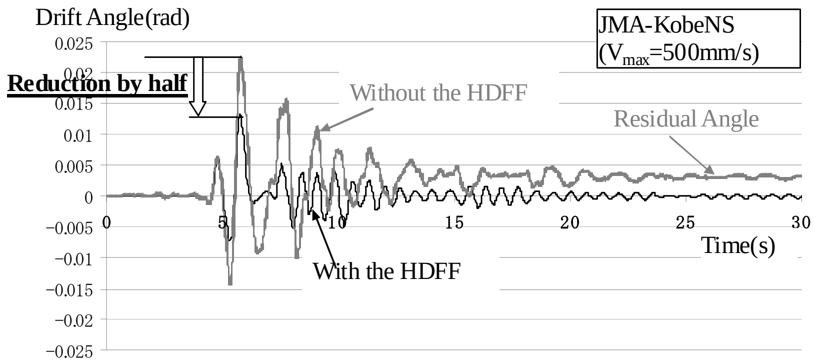
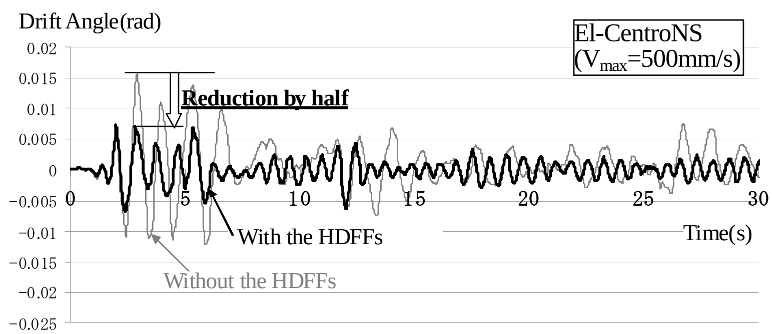


Fig-7 Analytical Models of Multi-Storied Shear Wall Structure using HDDFs

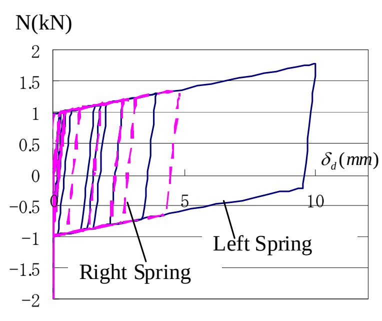


(a)Analytical results of JMA KobeNS

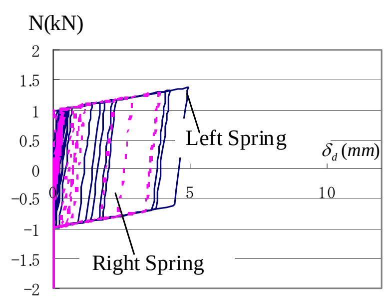


(b) Analytical results of El Centro-NS

Fig-8 Analytical Results of Drift Angles of Shear Wall



(a)Analytical results of JMA KobeNS



(b) Analytical results of El Centro-NS

Fig-9 Analytical Results of HDFFs

4.2 Analytical Results

Figures 8 and 9 show the analytical results in the cases when normalized earthquake motions of JMA Kobe-NS (1995) and El Centro-NS (1940) are respectively used. Both maximum velocities are normalized to 500 mm/s. The above value corresponds to a generally required design value (Level 2 earthquake) recommended by the national Building Standard Law of Japan. Maximum accelerations of the two earthquake motions are respectively given by 4 540 mm/s^2 (JMA Kobe-NS) and 5 110 mm/s^2 (El Centro-NS). In Fig. 8, two types of analytical cases under the same conditions (the same base shear coefficient at push-over analyses) are illustrated. They are the analytical results with/without the HDFFs. In the analytical case without the HDFFs, the spring elements are changed from the elasto-plastic element to the elastic type. Conversely, the shear panel elements are changed from the elastic rectangular element to the elasto-plastic type to absorb the energy instead of the HDFFs (Tada et al., 2006). The energy absorbing capacity of the shear panel is smaller than that of the HDFF so that its behavior is ruled by a slip hysteresis law in the plastic region.

As in Figs. 8 and 9, it is recognized that the drift angle of the first floor is reduced by the energy absorbing capacities of the HDFFs. The maximum drift angle is approximately reduced by 50%. From the observations of response behaviors around 30 seconds, the residual drift angle of the shear wall with the HDFFs is almost non-observable (black lines). Or, the overall frame is returned to the original positions without self-centering or post-tensioning force. Conversely, the analytical results without the HDFFs exhibit large residual deformations (gray lines), particularly, in the case of JMA Kobe-NS motion. This indicates that the shear walls remain significantly damaged and major repair works are needed for continuous use.

5. Summaries of Seismic Designs based on Energy Balance

We discuss general schemes of seismic designs based on an energy balance for the proposed systems. A total energy balance equation during the earthquake is given by the following equation (Akiyama, 1985).

$$W_k + W_g + (W_e + W_p) + W_h = W \qquad (3)$$

Where,

W_k : kinetic energy at earthquake end,

W_g : potential energy by the uplift movements at earthquake end,

W_e : elastic strain energy at earthquake end,

W_p : total plastic strain energy during the earthquake,

W_h : total damping energy during the earthquake,

W : total input energy during the earthquake.

Figure 10 shows an example of the analytical result of each energy value. The analytical model is the same as that in Fig. 8. As shown in Fig. 10, most of the total input energy W is absorbed by both damping of the structure and plastic strains of the HDFFs.

In accordance with a notification of the national Building Standard Law of Japan, the energy on the damages of the structures, that is, restoring force energy in a strong earthquake can be estimated by the following equation (Hasegawa et al., 2004; MLIT (Ministry of Land, Infrastructure, Transport and Tourism of Japan), 2005).

$$\begin{aligned} W_e + W_p &= W - W_h - W_k - W_g \\ &= 0.5mV^2 \end{aligned} \quad (4)$$

Where,

m : total masses on the structures,

V : necessarily reduced velocities in a strong earthquake.

The necessarily reduced velocities V are dependant upon the primary natural frequency T_d and ground classes (soil types) as in Fig. 11. The above equation (4) has been verified by several parametrical analyses of various structural types (Hasegawa et al., 2004; MLIT, 2005). Assuming that HDFFs only move into the plastic region in a strong earthquake and W_e is much smaller than W_p (Fig. 10), the energy absorbing capacities of all HDFFs in the structure must satisfy the following equation.

$$W_p = 0.5mV^2 < \sum_{i=1}^{n} E_i \quad (5)$$

Where,

E : energy absorbing capacity that each HDFF possesses,

n : total numbers of the HDFFs in the structure.

The value of E is dependent upon the yield strength of the HDFFs, that is, the numbers of butterfly elements. To give an example, Table 3 shows relationships between the yield strength and the energy absorbing capacity, which are estimated using the experimental result of Specimen A.

When the above equation (5) is valid, the overall structures can absorb the earthquake energy by the work of the HDFFs during the earthquake.

Conversely, if it is not valid, specifications of the HDFFs must be changed to increase the energy absorbing capacity. In this case, numbers of the HDFFs or yield strength per unit HDFF must be increased. Additionally, both shear walls and footing members must be strengthened according to need.

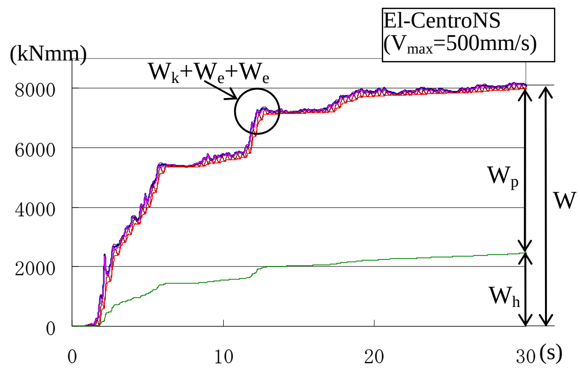


Fig-10 Analytical Results on Energy balance

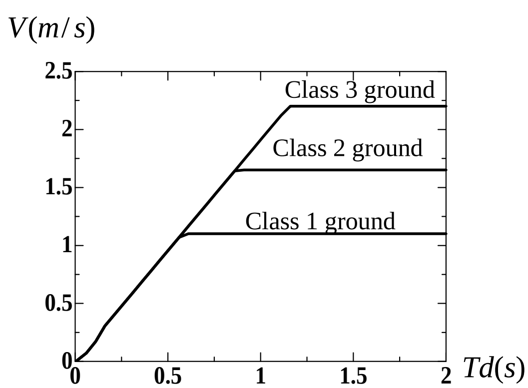


Fig-11 Relationships between Necessarily Reduced Velocities and Primary Natural Frequency

Table-3 Relationships between Ny and E of the HDFF

Yield Strength Ny (kN)	Energy Absorbing Capacity E (kNmm)
30	5 000
60	10 000
90	15 000
120	20 000

5. Conclusions

This paper draws the following conclusions:

1) We proposed an innovative seismic technology for a cold formed steel structure, which is a rocking multi-storied shear wall system using hold down fasteners with the fuse function (HDFF). The HDFFs are placed at the bases of the multi-storied shear walls and absorb the earthquake energy while the multi-storied shear walls exhibit the rocking behaviors with the uplift movements.

2) To verify the seismic performance of the HDFFs, statically loaded experiments of the shear wall with the HDFFs were conducted. From the observations of the results, it was clarified that the HDFFs possessed both high plastic deformability and large energy absorbing capacity.

3) Both seismic behaviors and performance of the rocking multi-storied shear wall system with the HDFFs were minutely investigated using the earthquake response analyses. Earthquake shaking was remarkably reduced by the large energy absorbing capacities of the HDFFs. It is considered that the proposed rocking shear wall system can offer among high seismic performance, low cost construction and increased sustainability for advanced seismic performance designs.

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