Study on Seismic Damage Conditions of Wood-frame Houses in Snowy Region Considering Dynamic Behavior of Roof Snow

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SUMMARY:
In this study, the authors examined analytically the damage conditions of wood-frame houses induced by strong ground motion during snow season. The analysis with dynamic behavior such as roof snow slide occurred by the strong motion was performed using the seismic diagnosis results of existing houses built in Sapporo of Hokkaido. As the results, the seismic damage induced by the strong motion decreased by the dynamic behavior of roof snow. In addition, seismic reinforcement of the houses was accentuated decrease of seismic damage.

Keywords: Earthquake during snow season, Seismic response analysis, Wood-frame houses, Fragility curve

1. INTRODUCTION

North Nagano Prefecture Earthquake occurred in 12 March 2011 after the Tohoku Region Pacific Coast Earthquake. Strong ground motion as intensity 6 upper was observed in Sakae village and Tsunan town, which are heavy snow fall area. Ground snow depth, when the earthquake occurred, was 227cm in Tsunan town. Roof snow depth on wood-frame houses was 50cm. On the other hand, dynamic behavior of roof snow, such as fall and sliding of snow induced by the strong motion, was confirmed in the disaster research (Kamiishi et al. 2012). According to the seismic design standard, it is necessary to consider snow load addition to weight of building. However, relationship between the dynamic behavior and seismic response on the houses can't be evaluated using the current design standard.

In previous study of the authors, relationship between roof snow sliding and response characteristics of structure model with flat roof was examined by the shaking table tests (Chiba et al. 2009). As the results, seismic response of the structure decreased by stable slide of roof snow. In addition, the authors tried to reproduce the shaking table tests using seismic response analysis. As the results, difference of friction coefficient on roofing material, and slide-down on sloped roof, could be reproduced by the analysis. In this study, to evaluate seismic performance of wood-frame houses in snowy region, the authors examined the damage conditions induced by strong motion during snow season based on seismic response analysis considering the dynamic behavior of roof snow.

2. METHODS OF THE SEISMIC RESPONSE ABALYSIS

2.1. Analysis Model with Dynamic Behavior of Roof Snow

The analysis model is multi-mass system in this study. In two-story house, roof snow on 2F was set as third mass. The time history of response acceleration, velocity, and displacement was calculated using three simultaneous equations configured by equation of motion on each mass. Figure 2.1 shows equilibrium of forces acted on roof snow while roof snow sliding. m is mass of roof snow, g is gravity acceleration, μ_k is kinetic friction coefficient of roofing material, and θ is roof slope. The inertia force affected by gravity and the kinetic friction resistance force are acting in roof snow. The friction resistance force of opposite direction is acting to the structure below roof snow. Equation 2.1 shows equilibrium of these forces. In this study, the analysis must deal the horizontal displacement of each mass in order to the mass system. Therefore, equation 2.2 decomposed to *x* direction was used as the roof snow's equation of motion in the analysis.

$$F_s = mg\sin\theta - \mu_k mg\cos\theta \qquad (2.1)$$

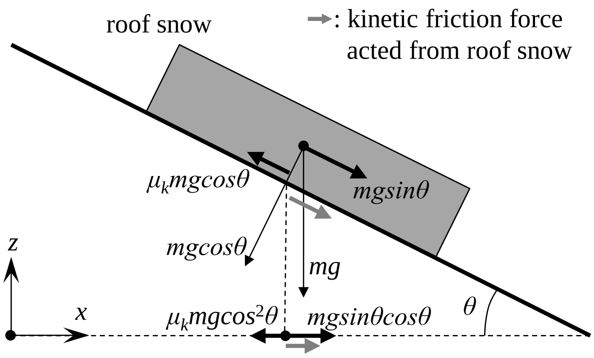

Figure 2.1. Equilibrium of forces on roof snow

$$F_{sx} = mg\sin\theta\cos\theta - \mu_k mg\cos^2\theta \qquad (2.2)$$

As an example three mass system considering mass of roof snow, slide condition of roof snow is shown in equation 2.3. The equation of motion on constant condition of roof snow is shown in equation 2.4. The equation of motion when roof snow sliding occurred is shown in equation 2.5 and 2.6. $\ddot{x}_0$ is ground acceleration, $\ddot{x}_1$, $\dot{x}_1$, x_1 is acceleration, velocity, and displacement of 1F. $\ddot{x}_2$, $\dot{x}_2$, x_2 is acceleration, velocity, and displacement of 2F. $\ddot{x}_s$, $\dot{x}_s$, x_s is acceleration, velocity, and displacement of roof snow. m_1, m_2, m_s is the mass. C_1, C_2, K_1, K_2 is dumping coefficient, rigidity of 1F and 2F. μ_s, μ_k is static and kinetic friction coefficient of roofing material.

$$|m_s\ddot{x}_s| > \mu_s m_s g\cos^2\theta \qquad (2.3)$$

$$\begin{bmatrix} m_1 & 0 \\ 0 & m_2+m_s \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \end{Bmatrix} + \begin{bmatrix} C_1+C_2 & -C_2 \\ -C_2 & C_2 \end{bmatrix}\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{Bmatrix} + \begin{bmatrix} K_1+K_2 & -K_2 \\ -K_2 & K_2 \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \end{Bmatrix} = -\begin{bmatrix} m_1 & 0 \\ 0 & m_2+m_s \end{bmatrix}\begin{Bmatrix} 1 \\ 1 \end{Bmatrix}\ddot{x}_0 \qquad (2.4)$$

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}\begin{Bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \ddot{x}_s \end{Bmatrix} + \begin{bmatrix} C_1+C_2 & -C_2 & 0 \\ -C_2 & C_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_s \end{Bmatrix} + \begin{bmatrix} K_1+K_2 & -K_2 & 0 \\ -K_2 & K_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} x_1 \\ x_2 \\ x_3 \end{Bmatrix}$$
$$+\begin{bmatrix} 0 & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_s \end{bmatrix}\begin{Bmatrix} -\mathrm{sgn} \\ -\mathrm{sgn} \\ \mathrm{sgn} \end{Bmatrix}\mu_k\cos^2\theta = -\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{Bmatrix} 1 \\ 1 \\ 1 \end{Bmatrix}\ddot{x}_0 + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_s \end{bmatrix}\begin{Bmatrix} 1 \\ 1 \\ 1 \end{Bmatrix} g\sin\theta\cos\theta \qquad (2.5)$$

$$\mathrm{sgn} = \frac{|\dot{x}_s - \dot{x}_2|}{\dot{x}_s - \dot{x}_2} \qquad (2.6)$$

When inertial force is more than static friction resistance force, it was set that roof snow slides by strong motion. When roof snow was constant condition, it was analyzed in two-mass system, which was added to the snow mass to 2F mass (Takahashi et al. 2010). On the other hand, when roof snow slide by strong motion, it was analyzed in three-mass system based on the equation 2.5. The force of opposite direction from kinetic friction force was acted to 2F. The direction was calculated based on equation 2.6, which is used relative velocity of 2F and roof snow. The seismic response analysis considering the dynamic behavior was performed based on the above equations. Newmark-β (β=1/4) was used as analysis method.

2.2. Settings in the Analysis

76 wood-frame houses built in Sapporo that was evaluated by seismic diagnosis were used as the data of the analysis (Chiba et al. 2008). The gross area and 2F area / 1F area are shown in figure 2.2. The gross area, which was distributed between 100m^2 and 140m^2, was 125,9m^2 as average. The variation of relationship between 1F area and 2F area was large due to 2F area was smaller than 1F area. Therefore, a lot of wood-frame houses had roof on 1F. The evaluation of the seismic diagnosis is shown in figure 2.3. In *sd* (snow depth)=0,0m, the average evaluation was 1,13. The wood-frame houses that had seismic performance based on the current seismic standard were more than half. On the other hand, in *sd*=2,0m, the average of evaluation was 0,61. The damage conditions induced by strong motion during snow season were examined using the above data.

The snow depth on roof, roof slope, friction coefficient of roofing material, and dynamic behavior of roof snow that were set in the analysis are shown in table 2.1. The snow load on roof was calculated by multiplying unit weight 3,0 kN/m^3 to *sd* (snow depth), which was 0,0m, 0,5m, 1,0m, 1,5m, 2,0m. The roof slope θ was 0° and 21.8° , the kinetic friction coefficient μ_k was 0,15. The static friction coefficient μ_s was μ_k / 0,7. The dynamic behavior was four kinds of "roof snow constant", "2F roof snow slide", "2F roof snow slide-down", "1F & 2F roof snow slide-down". These behavior are described schematically in figure 2.4.

The rigidity of the houses was set based on the skeleton curve that is shown in figure 2.5. The all houses of current state had the seismic walls using brace. In this study, it was assumed reinforcement of seismic walls using the structural plywood. The analysis was performed in each of current state,

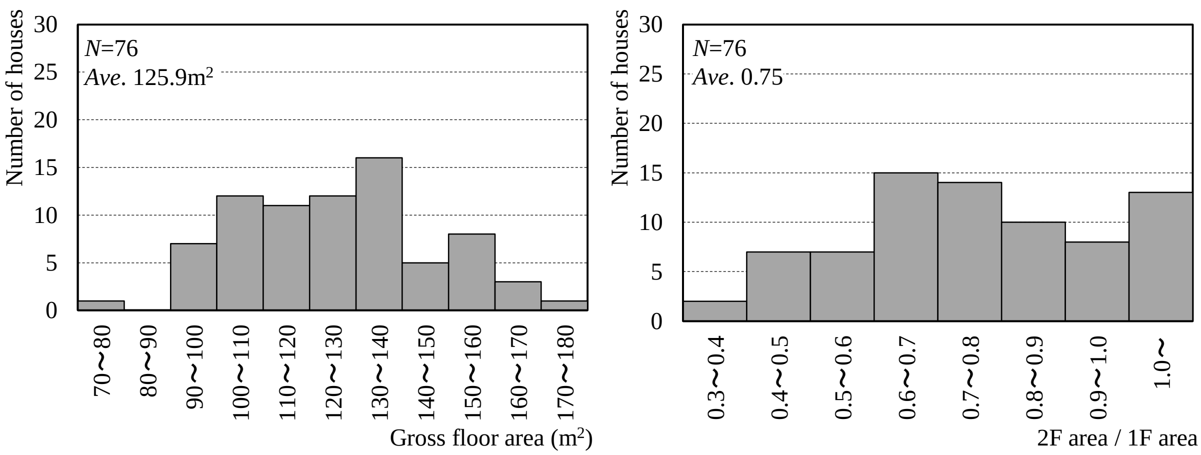

Figure 2.2. Gross floor area and 2F area / 1F area of the houses

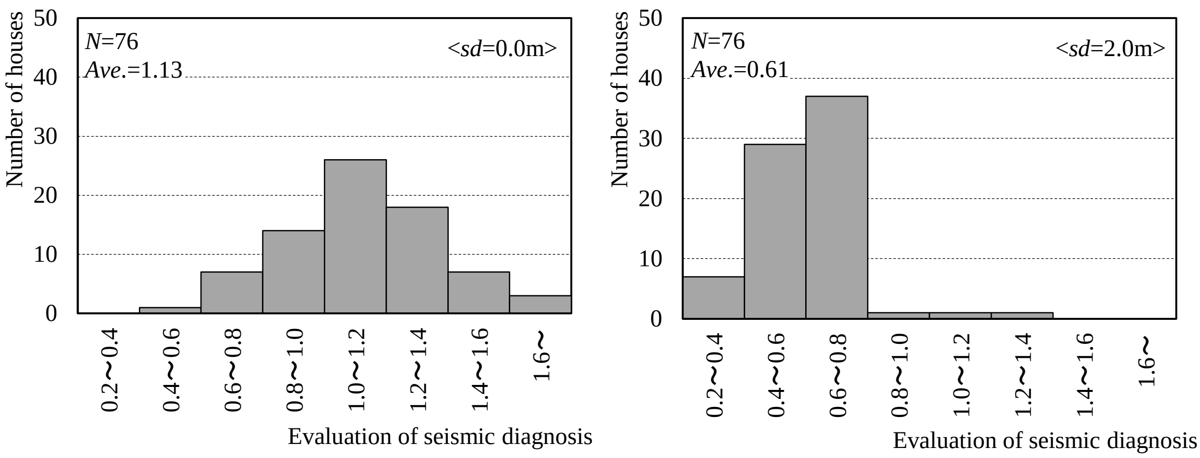

Figure 2.3. Evaluation of the previous seismic diagnosis

Table 2.1. Items and settings of the analysis

Items	Settings
Snow depth	*sd*=0.0m 0.5m 1.0m 1.5m 2.0m
Unit weight of snow	3.0 kN/m^3
Roof slope	θ=0° 21.8° (4/10)
Static and kinetic friction coefficient	μ_k=0.15 (μ_s=μ_k / 0.7)
Dynamic behavior of roof snow	roof snow constant 2F roof snow slide (θ=0°) 2F roof snow slide-down (θ=12.8° roof length: 9m) 1F&2F roof snow slide-down (θ=12.8° roof length: 9m)

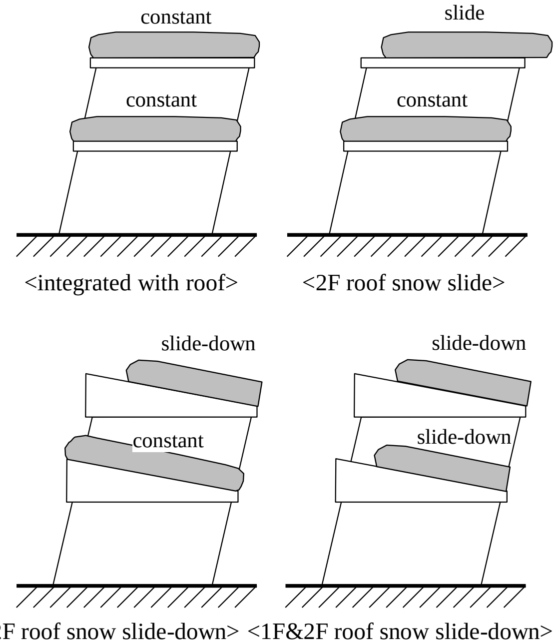

Figure 2.4. Dynamic behavior of roof snow

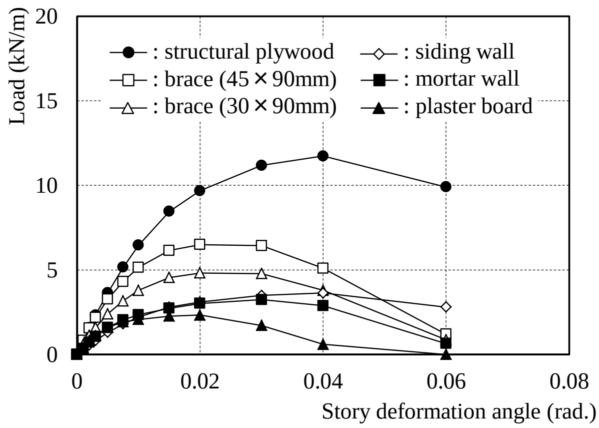

Figure 2.5. Skelton curves using the analysis

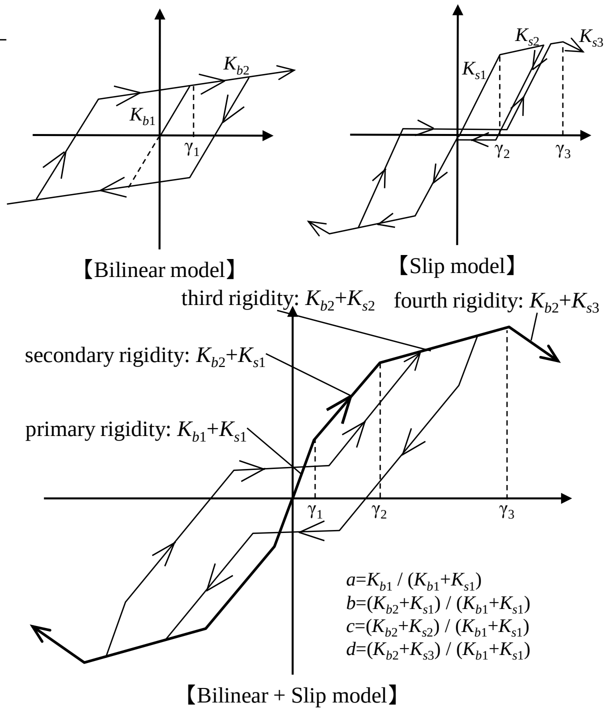

Figure 2.6. Analysis models of the structure

Table 2.2. Seismic motions using the analysis

Earthquakes	Year	Earthquakes	Year	Seismic intensity	Number of data
South Hyogo Prefecture Earthquake	1995	Miyagiken-Oki Earthquake	2005	3.2 ～ 6.7	Seismic Intensity 3・・・・ 1 4・・・・ 3 5 lower・・・6 5 upper・・・17 6 lower・・・6 6 upper, 7・・8 Total ・・・・41
North Iwate Prefecture Nairiku Earthquake	1998	Noto Hanto Earthquake	2007		
Miyagiken-Oki Earthquake	2003	Niigata Chuetsu-Oki Earthquake	2007		
Tokachi-Oki Earthquake	2003	Iwate- Miyagi Nairiku Earthquake	2008		
Mid Niigata Prefecture Earthquake	2004	North Iwate Engan Earthquake	2008		
Kushiro-Oki Earthquake	2004	The 2011 off the Pacific coast of Tohoku Earthquake	2011		

1F reinforcement, 1F & 2F reinforcement. The restoring force model in the houses is shown in figure 2.6. It was performed the elasto-plastic analysis using the model that was combined bilinear model and slip model. The primary rigidity, which was superimposed seismic element rigidity based on the houses situation, was set in each house. The second, third fourth rigidity were calculated multiplying the primary rigidity to the coefficients, which was a=0,35, b=0,7, c=0,15, d=-0,15. The data of ground motion using the analysis are shown in table 2.2. 41 waves of seismic intensity 3,2 to 6,7 that were observed so far were used in the analysis.

3. RESULTS OF THE ANALYSIS

3.1. Time History of Response Displacement

As an example *sd*=0.5m, the time history of response displacement in each behavior is shown in figure 3.1. The ground motion of seismic intensity was 6.5 (Mid Niigata Prefecture Earthquake 2004). In roof snow constant, the house collapsed in 1F due to dominate of the seismic response. For 2F roof snow slide, the collapse of the house escaped due to large roof snow slide. For 2F roof snow slide-down, the collapse of the house escaped by roof snow that disappears by the slide-down. As stated above, the seismic motion of the houses was small by the dynamic behavior of roof snow.

Relationship between the story deformation angle and story shear force in each reinforcement condition is shown in figure 3.2. In current state, the houses collapsed due to dominate 1F displacement. For 1F reinforcement, the house collapsed due to dominate response displacement of 2F, which was not reinforced. On the other hand, for 1F & 2F reinforcement, the house didn't collapse. As stated above, the story under roof snow was affected by the snow load. Therefore, it is necessary to perform the seismic reinforcement in 1F and 2F both.

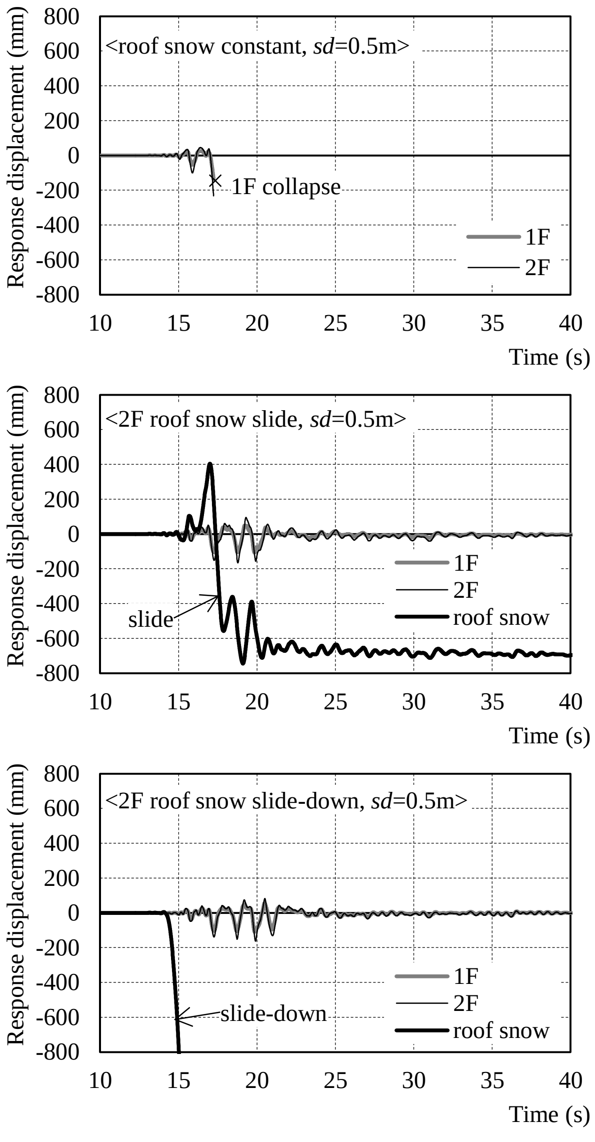

Figure 3.1. Time history of response displacement

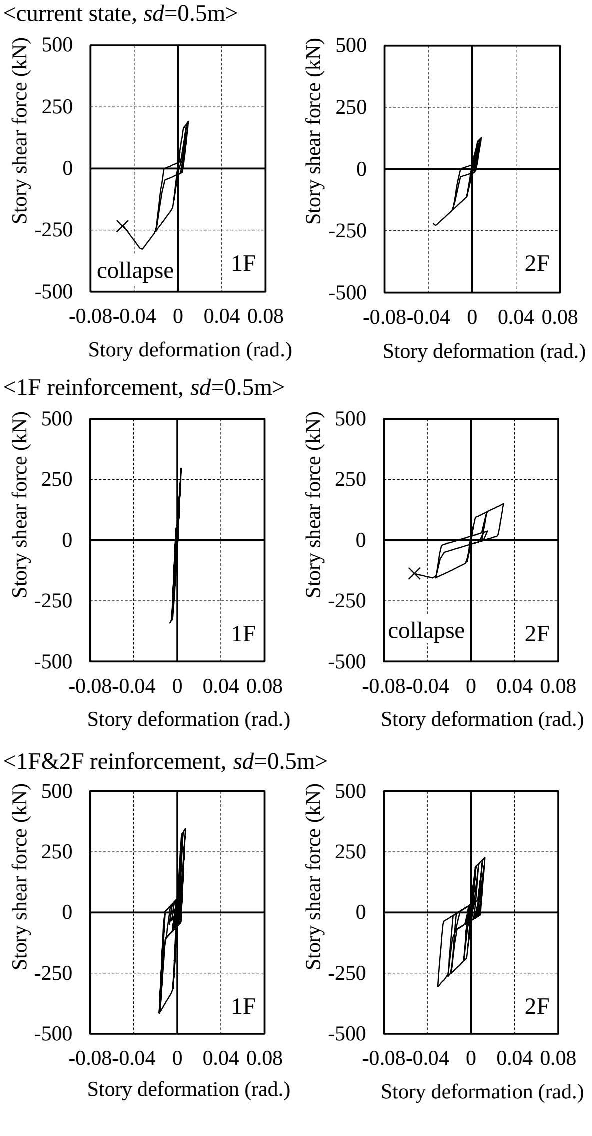

Figure 3.2. Story deformation angle and shear force

3.2. Seismic Fragility Curve Considering Dynamic Behavior of Roof Snow

In this study, the collapse ratio in each ground motion, when the story deformation angle was more than 1/20rad., was calculated. In addition, the seismic fragility curve was obtained from cumulative distribution function of log-normal distribution, which was applied relationship between the peak ground velocity (PGV) and the collapse ratio.

The fragility curves in each reinforcement condition and dynamic behavior are shown in figure 3.3. In current state and roof snow constant, the damage increased with the snow depth increase. In this case, the difference between *sd*=0,0m and *sd*=0,5m was remarkable. When the dynamic behavior occurred, the spread of damage was small. For 1F reinforcement and *sd*=0,0m, the damage was smaller than current state. However, for more than *sd*=0,5m, the damage was as well as current state. In this case, the story under roof snow, which didn't performed seismic reinforcement, was affected by snow load. On the other hand, for 2F roof snow slide and 2F roof snow slide-down, the damage was

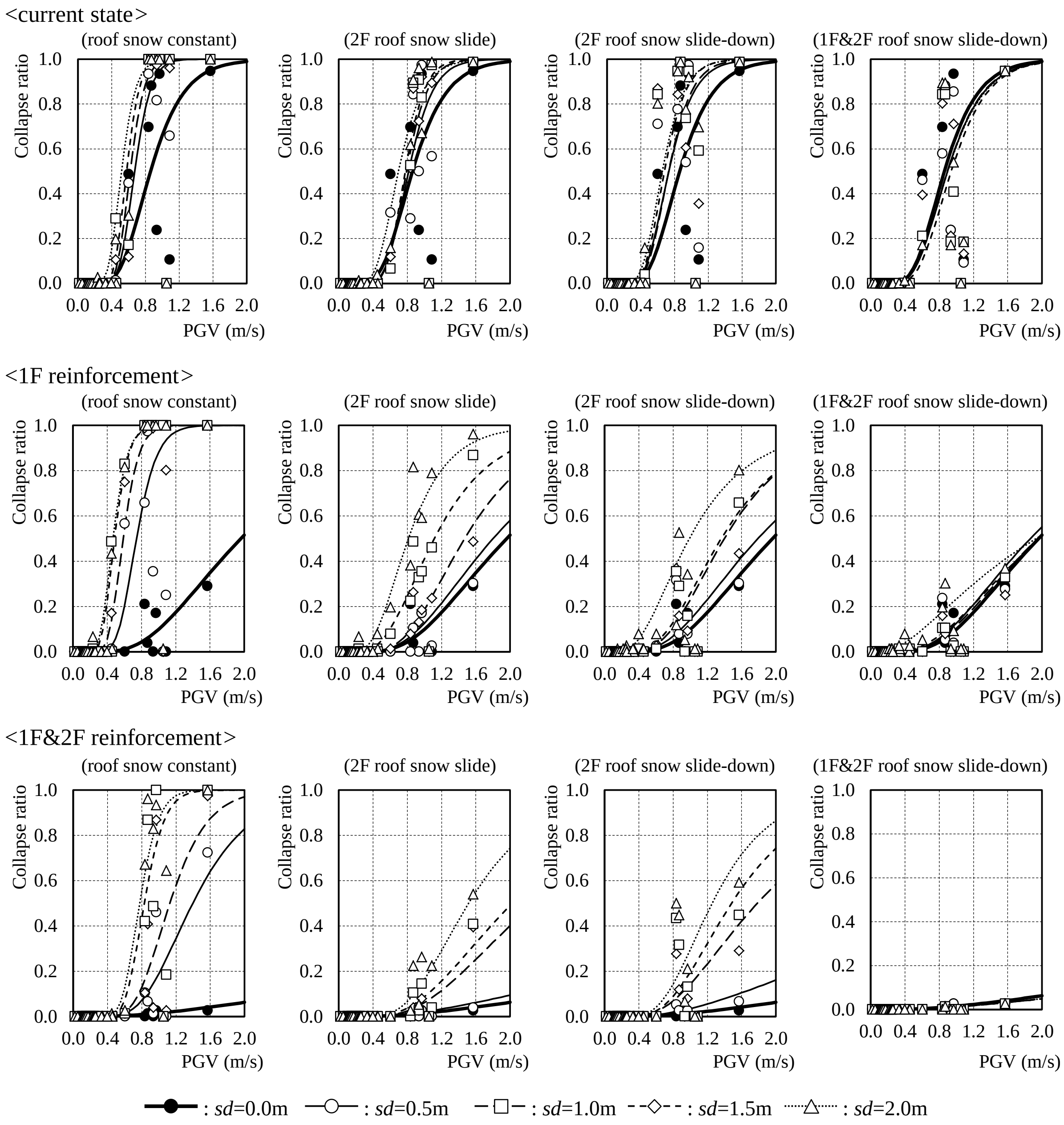

Figure 3.3. Seismic fragility curves in each the reinforcement and dynamic behavior

smaller than current state. For 1F & 2F reinforcement, the influence of roof snow was nothing. As stated above, when the dynamic behavior of roof snow occurred by strong motion, the response of houses became so small that the houses reinforced.

4. CONCLUSIONS

In this study, to evaluate seismic performance of wood-frame houses built in snowy region, the authors examined the seismic damage conditions during snow season based on the response analysis considering dynamic behavior of roof snow, which occurred in flat and sloped roof. The results obtained through the analysis were shown as following.

1) When the dynamic behavior of roof snow occurred by strong motion, the seismic response and damage became small.

2) When the dynamic behavior of roof snow occurred by strong motion, the decrease of the seismic damage was remarkable by seismic reinforcement of the houses.

REFERENCES

Kamiishi, I., Motoyoshi, H. and Ishizaka, M. (2012). The snow and earthquake mutiple disaster induced by North Nagano Prefecture Earthquake on 12 March 2011. *Research of mainly disaster on National Research Institute for Science and Disaster Prevention* **Vol.48**: 135-140.

Chiba, T., Tomabechi, T., Takahashi, T. and Uematsu, T. (2009). Study on seismic performance of wooden houses during strong motion in snow season. *Jounal of structural and construction engineering* **Vol.74 No.635**: 25-32.

Chiba, T., Tomabechi, T., Takahashi, T. and Uematsu, T. (2009). Study on relationship between roof snow sliding and seismic response of wood-frame houses by seismic response analysis. *Jounal of structural and construction engineering* **Vol.74 No.644**: 1777-1784.

Takahashi, T., Kobayashi, T., Chiba T. and Tomabechi, T. (2010). Seismic response analysis featuring friction between roof and snow. *Summaries of JSSI & JSSE conference on snow and ice research* **2010/Sendai**: 224.

Chiba, T., Tomabechi, T., Uematsu, T., Takahashi, T. and Ohashi, Y. (2008). Study on seismic diagnosis and seismic reinforcement for wooden houses in snowy region. *Jounal of structural and construction engineering* **Vol.73 No.630**: 1311-1316.