# Predicting damage of wooden houses using fatigue response spectral intensity index considering number of seismic response cycles

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**ABSTRACT :**

In general, seismic intensity, peak ground acceleration (*PGA*), peak ground velocity (*PGV*) and spectral intensity (*SI*) have been used as the indices of destructive power on earthquake motion. These indices are not taken account of the repetition of an earthquake motion. However, the repetition of an earthquake motion influences damage of wooden houses. So it is quite important to consider the number of earthquake response cycles in the vicinity of the maximum response and natural period of structures for predicting damage to structures. Especially, destruction of the wooden houses was expanded by aftershock after the main shock in 2004 Niigata-ken Chuetsu earthquake, 2007 Noto Peninsula Earthquake, and so on. In this study, the influence by accumulation of the earthquake motion on wooden houses destruction is considered. The fatigue response spectral intensity (*FSI*) of having taken the repetition of earthquake motion into consideration is proposed, and a relation with wooden houses damage is considered. In addition, existing probability of natural period and the construction age of wooden house is taking into account in this index. It is predicted to the wooden houses damage using the *FSI* index in recent earthquake. As a result, it was clarified that the earthquake motion destructive power index proposed by this research that accumulation of the earthquake motion can be taken into consideration is effective. And It is better to take the construction age into account, when the damage to wooden house is estimated.

**KEYWORDS:** *Indices of destructive power, Fatigue response spectral intensity, Damage to wooden houses*

## 1. INTRODUCTION

Many of the dead at the Hyogoken-Nambu earthquake are presumed to be squeezed by collapse of wooden houses. The destructive power index of the earthquake motion predicts structural damage quickly, correctly and immediately after that[1) ~ 6)], and this index is useful for mitigation of earthquake disaster. The purpose for using this is classified into early detection and urgent correspondence of earthquake damage, practical use for aseismic design and so on. In general, seismic intensity, *PGA*, *PGV*, and spectral intensity (*SI*) are used as the indices which show the destructive power of an earthquake motion. However, these indices do not take the concept of the structural response cycles into consideration. It is true that the spectral intensity uses the maximum seismic response for structures with natural periods within the range of 0.1s to 2.5s. However this index does not take into account the fatigue effect. Since the damage level to wooden houses becomes larger with the number of earthquake response cycles, it is necessary to take this effect into consideration.

In this study, the fatigue response spectrum intensity (*FSI*) which takes the number of seismic response cycles into consideration is proposed. It is discussed that the effect by the number of seismic response cycles to the wooden houses. And it is discussed that *FSI* is effective indices in representing as the destructive power of an earthquake strong motion.

## 2. DEVELOPMENT OF FRAGILITY FUNCTION FOR WOODEN HOUSES ON EARTHQUAKE MOTIONS

### *2.1 Outline of destructive power index*

The *FSI* value in which the number of seismic response cycles is considered has been proposed so far by researchers[7]. It is expectable that the *FSI* value serves as an accurate index since it takes into account the structure action. The conceptual diagram of $FSI_v$ (the fatigue response spectral intensity using pseudo-velocity response) is shown in Fig. 1. This index is defined as integrated value on tripartite coordinates; natural period of wooden houses ($T$) as $x$-axis, pseudo-response velocity spectra ($S_v$) as $y$-axis and number of seismic response cycles ($C_v$) as $z$-axis. The number of seismic response cycles is counted by using the bar graph of pseudo-response velocity as shown in Fig. 2. For the purpose of comparing with *SI* value, the natural period of wooden housess is considered in the range from 0.1s to 2.5s, and damping ratio $h$ is 0.05 in this study. The indices *SI* and $FSI_v$ are defined by the following formulas:

$$\begin{aligned} SI &= \int_T S_v dT \\ FSI_v &= \int_T \int_{S_v} C_{S_v} S_v^{\,2} dS_v dT \end{aligned} \tag{1}$$

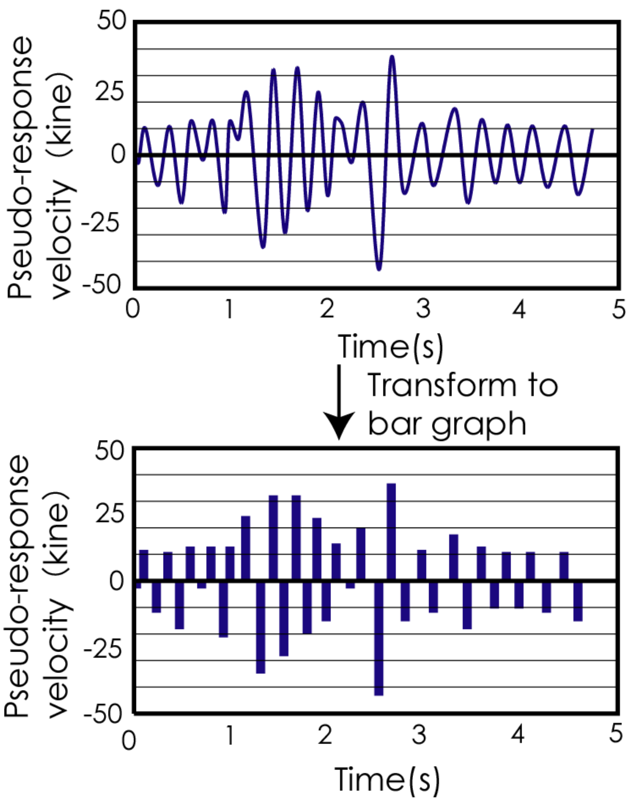


Fig.1 Conceptual diagram of *FSIv*
(Bar graph of response velocity)

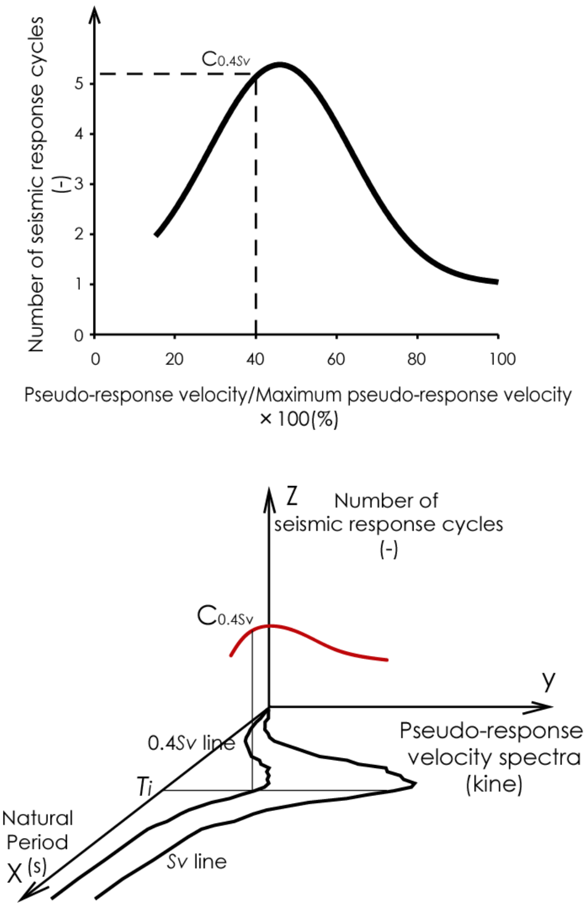


Fig.2 Conceptual diagrams of *FSIv*

***2.2 Development of seismic response analysis model for wooden houses***

A wooden house is modeled by 2-DOF shear type. The parameter used in this analysis is decided by the detailed investigation of the 1995 Hyogoken-Nambu earthquake. The height and weight of each story are 2.75(m), 155.73(kN) as 1st, 2.5(m), 112.97(kN) as 2nd, respectively. Story shear force $P_i$ is defined by the following equations:

$$P_i = \alpha\beta C_i W_i$$
$$C_1 = C_B \tag{2}$$
$$C_2 = 0.3\nu C_B$$

In which, $\alpha$ is a strength coefficient; $\beta$ is regional coefficient; $C_i$, $C_B$ are base shear coefficients as shown in Fig. 3; $W_i$ is a concentrated weight of each story and $\nu$ is a multiple factor for story shear coefficient ($\nu$=1.0, 1.4, 1.8). Normalized hysteretic restoring force $\Phi$ is defined by the following equation:

$$\Phi = \mu\Phi_{QL} + (1-\mu)\Phi_{SL} \tag{3}$$

In which, $\Phi_{QL}$ is poli-linear hysteresis; $\Phi_{SL}$ is slip hysteresis. Normalized hysteretic restoring force of the analytical model is interlaced by poly-linear type and slipped type at the rate of 2:3 as shown in Fig. 4, and the point for 1/6,000rad is added to the poly-linear type hysteretic restoring force for giving the initial rigidity corresponding to the predominant period during vibration with small amplitude. Moreover, framework rigidity of wooden house begins to fall at 1/30 (rad). Then, the point is added to poly-linear type hysteretic restoring force so that stability may decline from 1/30 (rad). It is said that the wooden house will disintegrate due to P-⊿ effect if deformation angle of a layer exceeds 1/10 (rad). So, the inclination is introduced after 1/30 (rad) so that scaling stability may become zero at 1/10 (rad). The resonant frequency of this model is 4.0 (Hz) with base shear coefficient $C_B$=0.2.

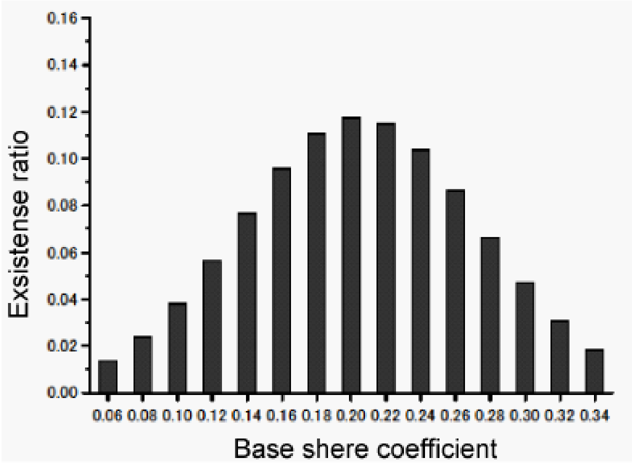


Fig.3 Distribution of Base shear coefficient

### *2.3 Evaluation of strength coefficient by considering construction age*

It is evaluated the strength coefficient $\alpha$ by considering construction age using the observed damage at Takarazuka city in the 1995 Hyogoken-Nambu earthquake. Input earthquake motion uses JR-Takarazuka NS component. The observed damage ratio of the wooden houses ($D$) is defined by the following equation:

$$D = \frac{D_1 + D_2/2}{h_a} \times 100 \tag{4}$$

In which, $D_1$ is the number of serious damaged structures; $D_2$ is the number of medium damaged structures and $h_a$ is the total number of wooden houses. In this study, story displacement angle 1/30(rad) defines as the serious damaged structure and story displacement angle 1/60(rad) defines as the medium damaged structure. It is calculated to the analytical models defined by section 2.2, and identified the calculated damage ratio with the observed damage ratio. The relationship between damage ratio of the calculated and the observed is shown in Fig. 5 and the result of identification analysis is shown in Fig. 6, respectively. In this result, the strength coefficient $\alpha$ becomes larger than 1.0 in all. And the strength coefficient of after 1981 indicates twice more than as large as that of before 1960.

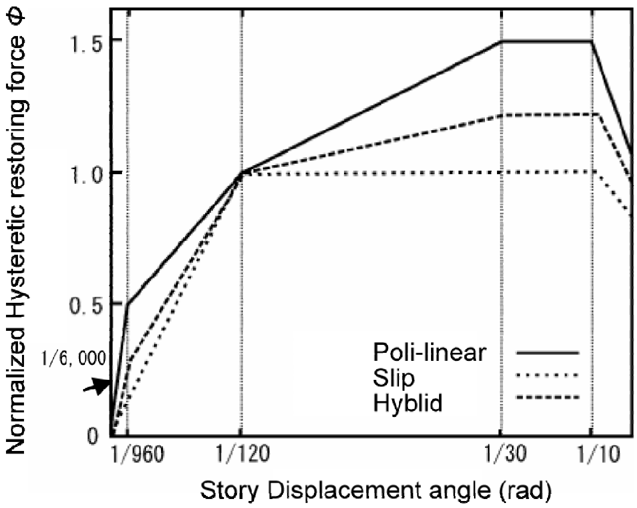


Fig.4 Hysteresis of analysis model

### *2.4 Evaluation of regional coefficient by considering construction age*

The strength according to each construction age was evaluated from the damage data of Takarazuka city in the 1995 Hyogoken-Nambu earthquake for the 2.3 section. However, it is thought that the strength has difference from every area in Japan. It is evaluated the regional coefficient $\beta$ at Kobe areas in 1995 Hyogoken-Nambu earthquake, Chuetsu areas in the 2004 Niigataken-Chuetsu earthquake and Wajima (Monzen) area in the 2007 Noto Peninsula earthquake. In this study, the damage ratio in considering construction age is assumed by the following equation to evaluate the influence of regional difference:

Damage ratio = damage ratio (~1960) × existence ratio of wooden houses (~1960)
damage ratio (1961~1970) × existence ratio of wooden houses (1961~1970) (5)
damage ratio (1971~1980) × existence ratio of wooden houses (1971~1980)
damage ratio (1981~) × existence ratio of wooden houses (1981~)

The regional coefficient $\beta$ at each area are shown in Fig.7 and Fig.8, respectively. In this result, regional coefficient of Chuetsu areas is larger than other areas.

## 3. EVALUATION OF THE FLAGILITY FUNCTION FOR WOODEN HOUSES ON EARTHQUAKE MOTIONS

### *3.1 Development of the fragility function for wooden houses*

When the existence ratio for the natural period of wooden houses takes the $FSI_v$ index into account, the equation (1) shown with section 2.1 is redefined as the following equation:

$$FSI_v' = \int_{\varsigma}^{\xi} p_t \int_{S_v} C_{S_v} S_v^{\,2} dS_v dt \qquad (6)$$

In which, $p_t$ is existence ratio for the natural period of wooden houses; $S_v$ is pseudo-response velocity spectra and $C_{sv}$ is number of seismic response cycles. In the period ζ, ξ, shown in the equation (6), a high precision index is expectable by changing the range of period for every construction age. In this study, it is evaluated the period ζ, ξ, by the regression using a logistic function. The logistic function is defined as the following equation:

$$y = \frac{A_1 - A_2}{1 + (x/x_0)^p} + A_2 \qquad (7)$$

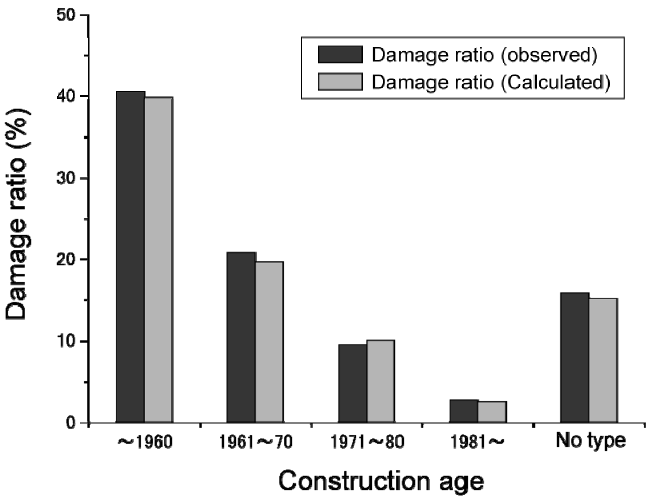


Fig.5 Identification of damage ratio


Fig.6 Calculation of strength coefficient α

In which, $A_1$=0, $A_2$=1 and $x_0$, $p$ are regression coefficients. The range of period for every construction age at Kobe areas in the 1995 Hyogoken-Nambu earthquake, Chuetsu areas in the 2004 Niigataken-Chuetsu earthquake and Wajima (Monzen) area in the 2007 Noto Peninsula earthquake are show in Fig.9 and Fig.10, respectively.

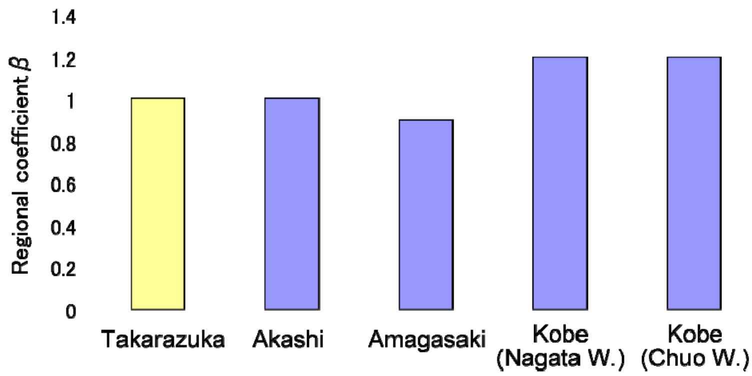


Fig.7 Calculation of regional coefficient $\beta$ (Hyogoken-Nambu Earthquake (1995))

### 3.2 Evaluation results

The relationships between coefficient of determination $R^2$ and construction age for each index ($FSI_v$', $SI$, $PGA$, $PGV$) are shown in Fig.10, and the relationships between damage ratio of every construction age and each index are shown in Fig.11~Fig.14, respectively. These figures show that the relationships between damage ratio of every construction age and $FSI_v$', $SI$ and $PGV$ have good correlation, and $FSI_v$' especially shows good correlation irrespective of the construction age. Moreover, it can be evaluated in the wooden house before 1960 and in 1981 and afterwards

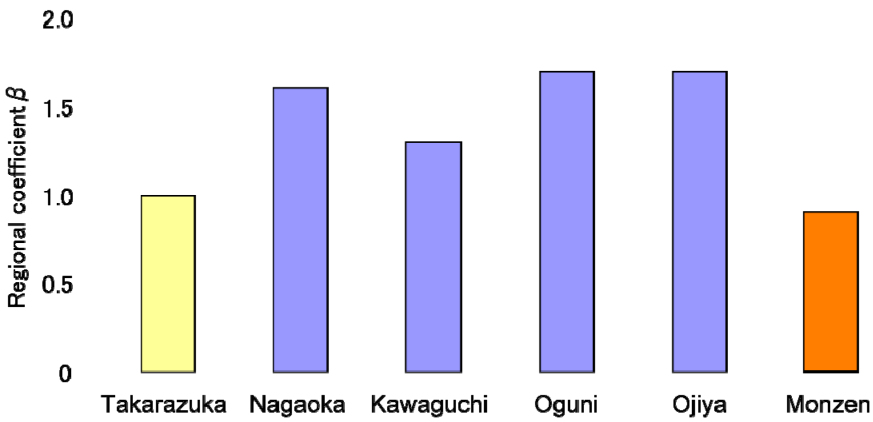


Fig.8 Calculation of regional coefficient $\beta$ (Nagaoka ~ Ojiya (Niigataken-Chuetsu Earthquake (2004)), Monzen (Noto Peninsula Earthquake (2007)))

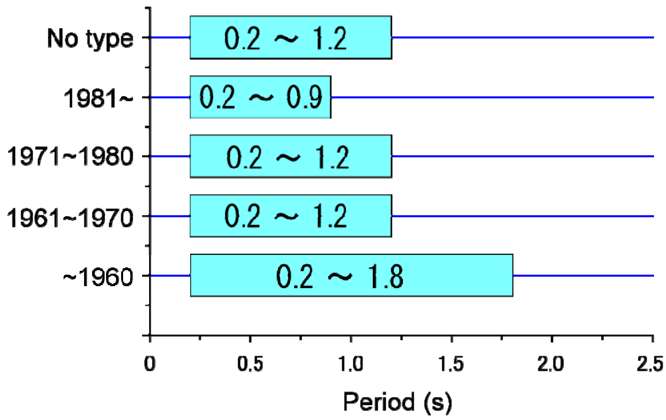


Fig.9 Range of period by the constructing age of wooden houses (Hyogoken-Nambu Earthquake, Niigataken-Chuetsu Earthquake)

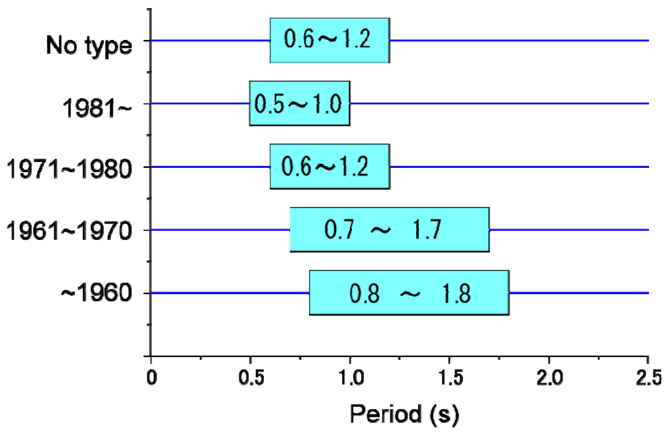


Fig.10 Range of period by the constructing age of wooden houses (Noto Peninsula Earthquake)

that about 3 times as many damage differences as this is produced. Therefore, it is suggested that the number of seismic response cycles influences strongly structure damage.

## 4. CONCLUSIONS

The conclusions of this study are summarized below.

(1) In the relationship between damage ratio of wooden houses and each destructive power index $FSI_v$' is effective parameters and should be considered as the destructive power indices of an earthquake motion.

(2) $FSI_v$' especially shows good correlation irrespective of the construction age. It is important to take the construction age into account, when the damage to wooden house is estimated.

(3) It can be evaluated in the construction age of wooden house before 1960 and in 1981 and afterwards that about 3 times as many damage differences as this is produced.

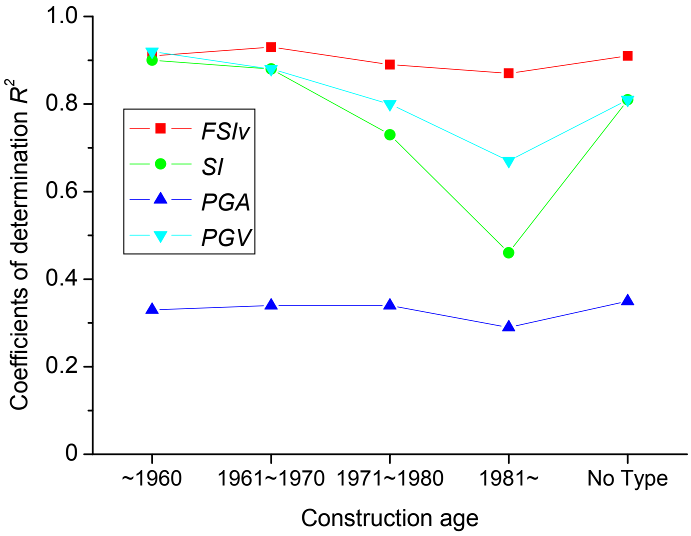


Fig.11 Relationship between coefficients of determination to every construction age and $FSI_v$, $SI$, $PGA$, $PGV$

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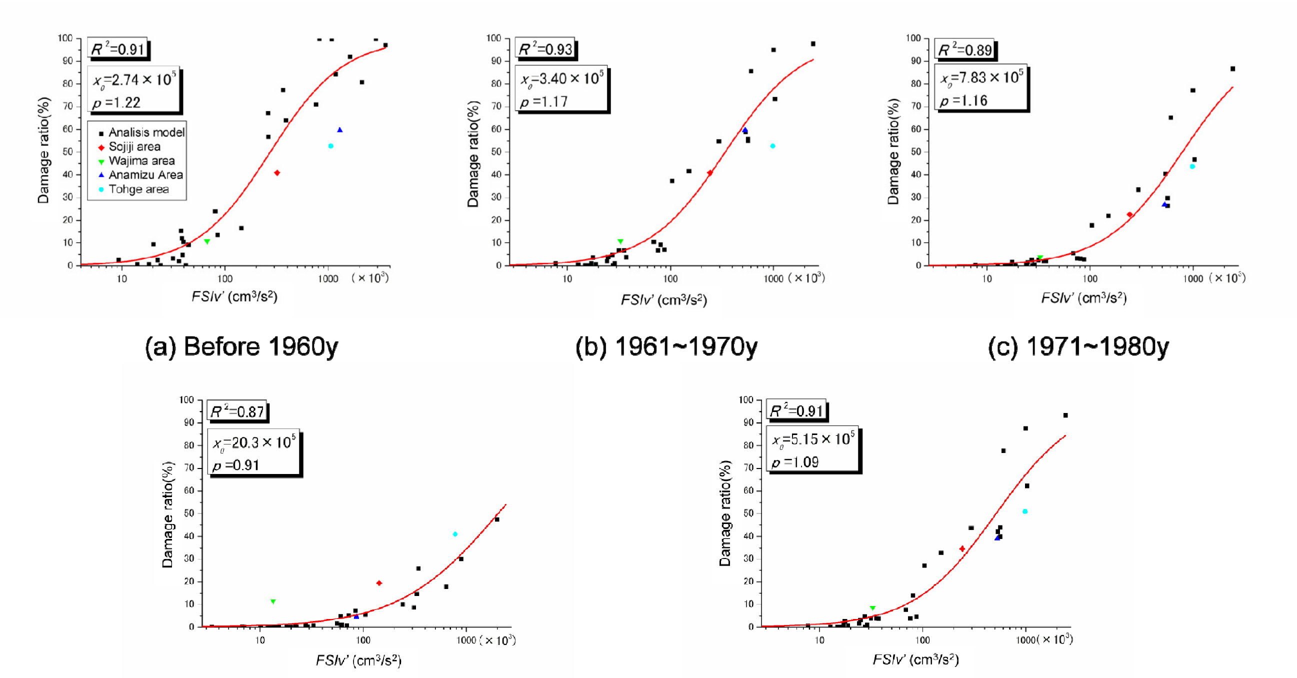
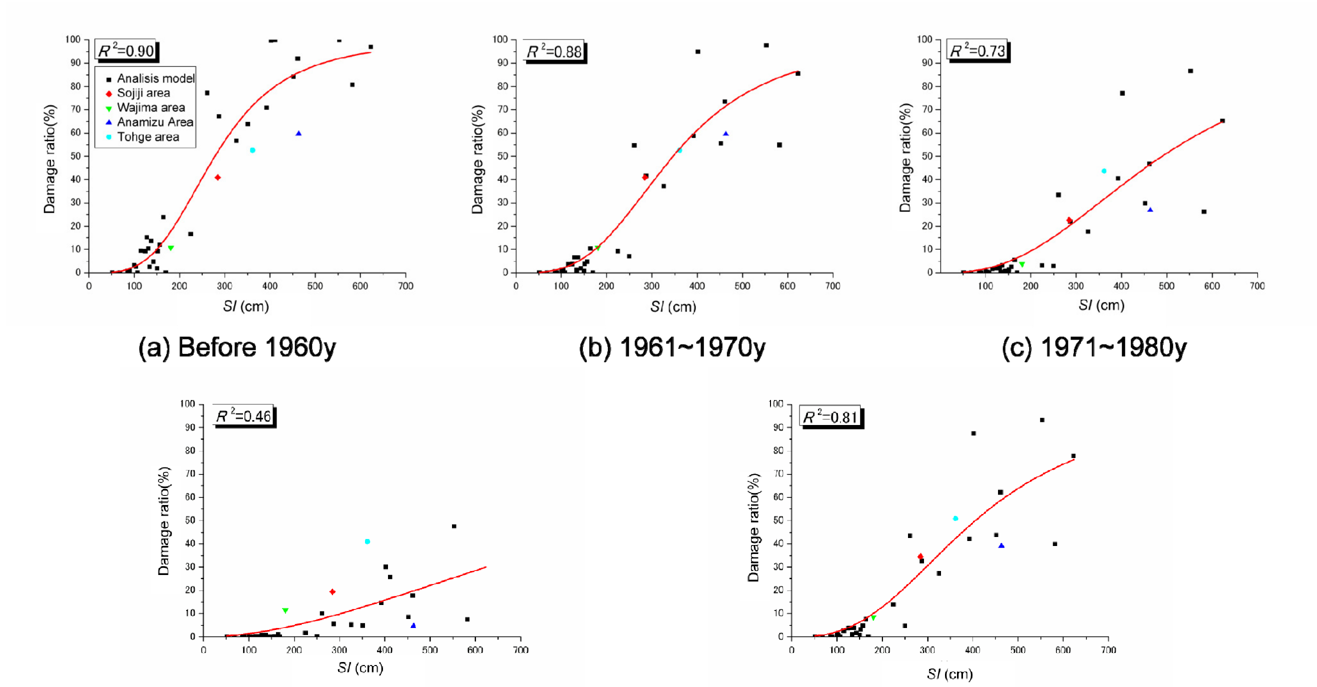



(a) Before 1960y (b) 1961~1970y (c) 1971~1980y

(d) After 1981y (e) No type

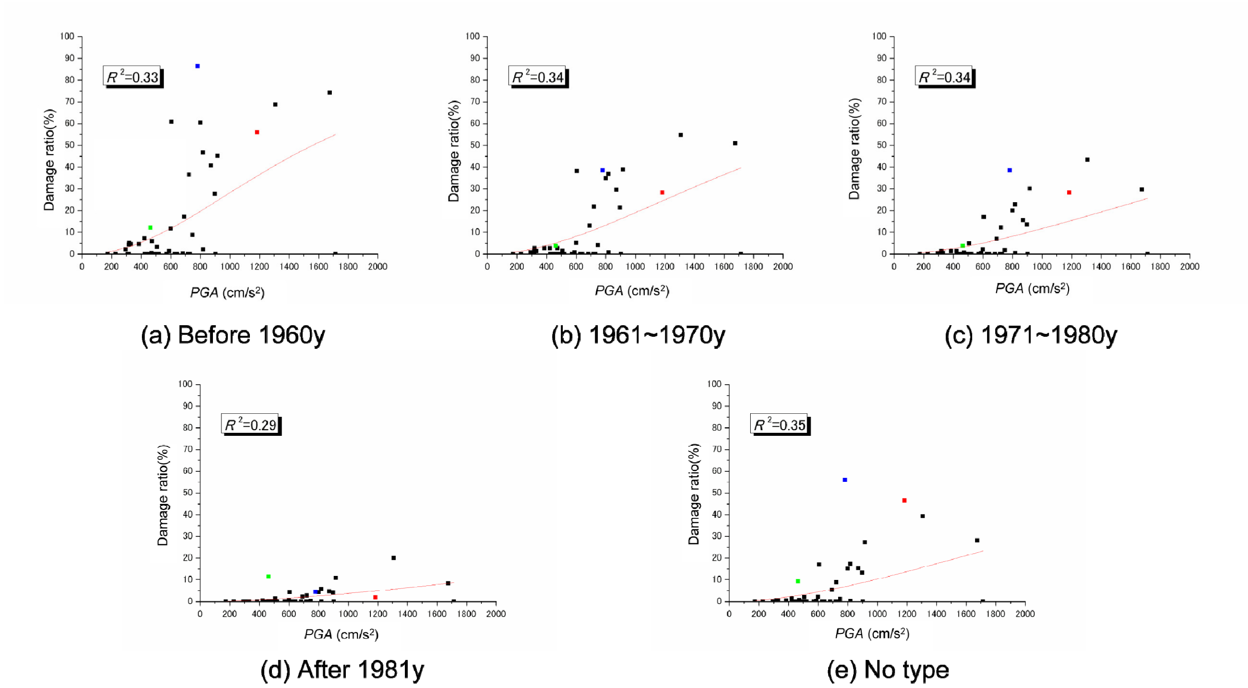
Fig.12 Relationship between damage ratio of wooden houses and *FSIv'*




(a) Before 1960y (b) 1961~1970y (c) 1971~1980y

(d) After 1981y (e) No type

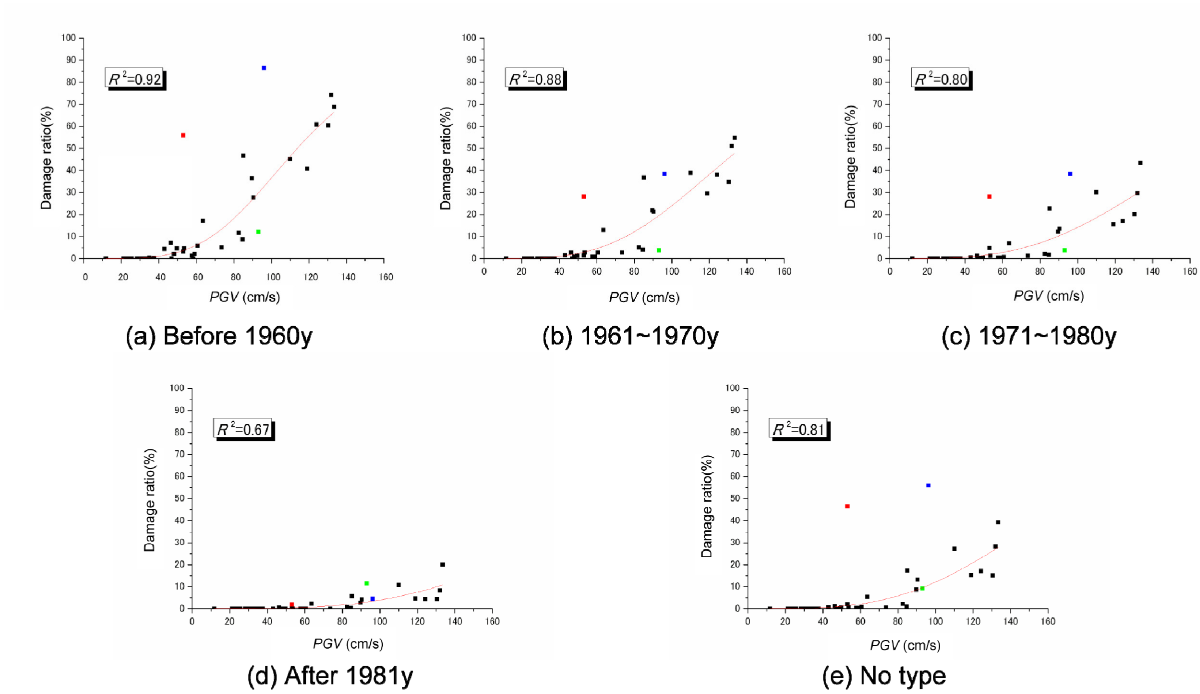
Fig.13 Relationship between damage ratio of wooden houses and *SI*




(a) Before 1960y (b) 1961~1970y (c) 1971~1980y

(d) After 1981y (e) No type

Fig.14 Relationship between damage ratio of wooden houses and *PGA*




(a) Before 1960y (b) 1961~1970y (c) 1971~1980y

(d) After 1981y (e) No type

Fig.15 Relationship between damage ratio of wooden houses and *PGV*