UDC 691 . 714 : 699 . 841

Seismic Resistance and Design of Steel-Framed Houses

Yoshimichi KAWAI*(1) Ryoichi KANNO*(1)
Nobuyoshi UNO*(1) Yoshifumi SAKUMOTO*(2)

Abstract

This paper is on the seismic design of steel framed houses and outlines the research activities for evaluating the seismic safety against severe earthquakes. To investigate the safety level directly, seismic response analyses were applied in this study. For the analyses, a hysteresis model under cyclic loading was developed and dynamic vibration tests of real steel houses and shaking table tests of steel framed walls were conducted. Based on these, the response of a typical steel house during large earthquakes was analyzed. The results showed that the maximum story drift angle was about 1/300 rad. These results show that typical steel houses have quite high safety against severe earthquakes encountered in Japan.

1. Introduction

Light-gauge cold-formed steel-framed houses (hereinafter referred to as steel-framed houses) are based on wooden two-by-four houses (wooden houses)[1], whose high earthquake resistance was demonstrated in the Great Hanshin Earthquake of January 17, 1995. In combination with the high strength and quality of steel members, the steel-framed houses are expected to provide higher earthquake resistance than the wooden houses. The dearth of the construction results, however, makes it difficult to validate the safety of steel-framed houses. Currently, there are no design methods for properly evaluating and reflecting the seismic resistance of steel-framed houses. The underlying wooden houses has few examples in which its safety in severe earthquakes has been directly studied, and as a result, the direct application of wooden house design methods to steel-framed houses involves problems. Therefore, the establishment of rational seismic design methods is an important issue for steel-framed houses.

Since 1996, the Steel House Committee of the Kozai Club has been engaged in research and development efforts devoted to establishing design methods for steel-framed houses in cooperation with the largest six steel companies in Japan. Through these activities, comprehensive studies have been conducted by testing various structural ?compornents, conducting shaking table tests and performing seismic response analyses[2-5]. Nippon Steel has played a leading role in these research activities and has carried out shaking table test and seismic response analyses. As a result of these activities, rational seismic design methods have been proposed for steel-framed houses[6].

The proposed design methods are developed by introducing a definite criterion for the seismic safety of steel-framed houses and are as simple to use as the conventional design methods for wooden houses. It merits special mention here that the safety of steel-framed houses in severe earthquakes is quantitatively and directly evaluated by considering their structural characteristics through the seismic response analyses and is reflected in their design methods. This report gives an overview of the steel-framed house design methods. As background information, the research results on the seismic resistance of steel-framed houses are presented, and the seismic resistance is quantitatively discussed.

2. Steel-Framed House Design Methods

Steel-framed houses differ from wooden houses mainly in the studs and the fasteners used to connect the sheathing to the studs. Steel-framed houses use zinc-coated metal studs with a thickness of about 1 mm[7] and self-drilling screws[8], whereas for wooden houses timbers and nails are used respectively. Research to date shows that these differences have little effect on the seismic performance and as a result, suggests that the steel-framed houses can be designed by methods similar to those used for wooden houses[4,5].

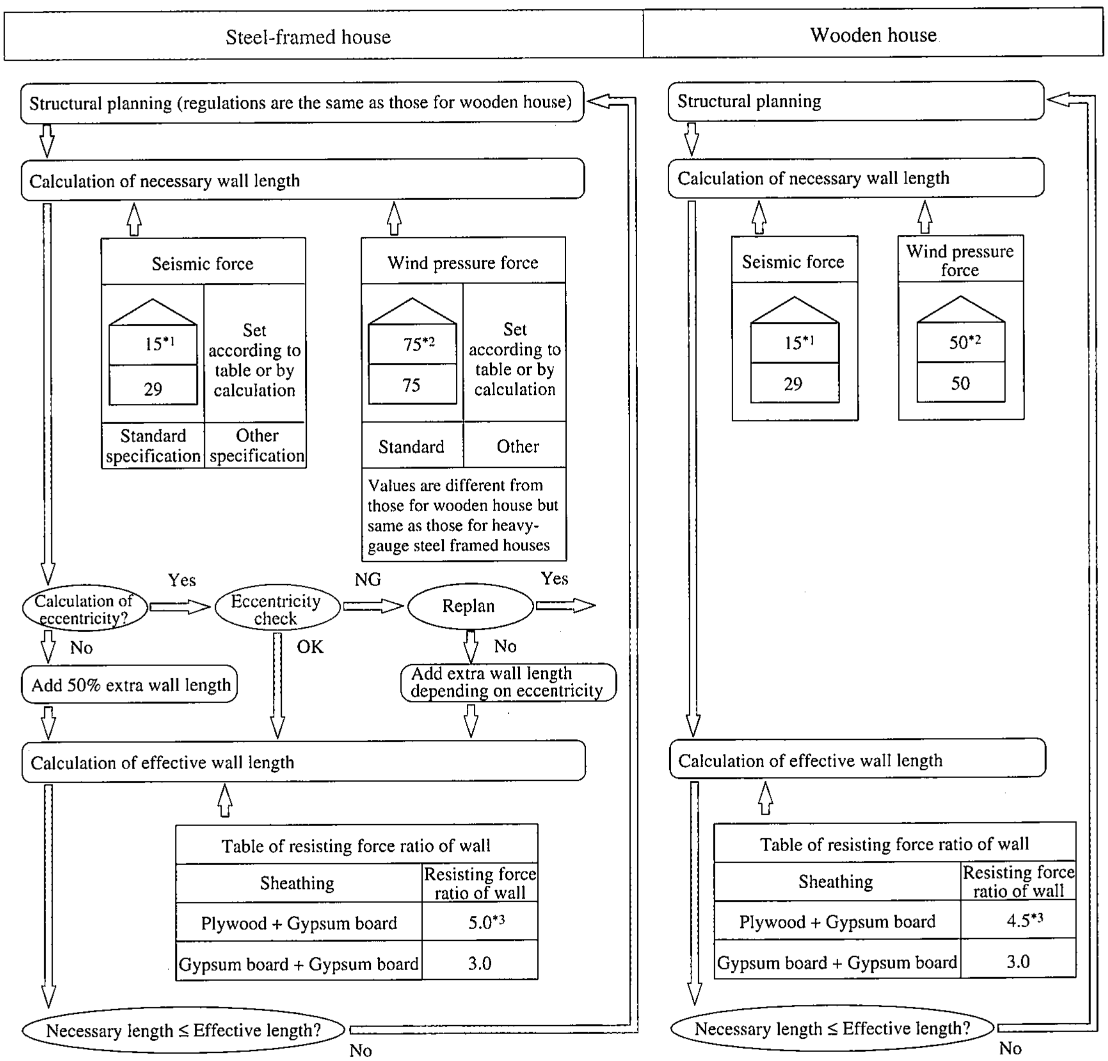
Of the two-story residential housing design methods granted gen-

*(1) Technical Development Bureau

*(2) Construction & Architectural Materials Development & Engineering Service Div.

eral approval by the Minister of Construction in 1997, the portions concerned with the seismic design of steel-framed houses are simple and comparable with those for wooden houses as shown in **Fig. 1**[6]. Like wooden houses, steel-framed houses can be designed by comparing the necessary wall length with the effective wall length. As seen in Fig. 1, steel-framed houses can assume practically the same wall length ratios as wooden houses. Steel-framed houses, however, have had a sufficient consideration on the seismic resistance and feature the following:

1) Steel-framed houses are designed based on the wall established seismic design method[9] for heavy-gauge steel-framed houses, and on seismic response analyses[10], which are typically applied for the design of high-rise buildings in Japan. The seismic response analyses evaluate the seismic safety of steel-framed houses by a criterion that the story drift angle should be held to a maximum of 1/50 rad in a severe earthquake. The steel-framed house design methods of Fig. 1 are derived based on allowable stress design where the base shear coefficient is put at $C_0 = 0.2$. It should be noted, however, that in the proposed design methods, the ultimate state is inherently checked by both capacity design and the above mentioned seismic response analyses.
2) A check of the eccentricity, which is not usually performed for wooden houses, is specified so that serious earthquake damage should not occur due to torsional vibration. As a result, full consideration is given to a well-balanced load-bearing wall arrangement (see Fig. 1).
3) Given the recent trend toward performance design, the calculation of seismic resistance is made possible for various interior and exterior finish specifications. The values of wind pressure forces for heavy-gauge steel-framed houses are adopted to make up for the lack of technical background in the wooden house design, which have been traditionally using the smaller wind forces.



*1 : Necessary wall length ratio against seismic force. The necessary wall length is calculated by multiplying the necessary wall length ratio and each floor area (unit: m^2) together.
*2 : Necessary wall length ratio against wind pressure force. The necessary wall length is calculated by multiplying the necessary wall length ratio and the projection area for each floor (unit: m^2) together.
*3 : Resisting force ratio for a 100 cm wide wall. Effective wall length is calculated by multiplying the actual wall length (unit: cm) and the corresponding resisting force ratios together.

Fig. 1 Design flows for steel-framed house and wooden house

3. Seismic Performance Characteristics of Steel-Framed Houses

Steel-framed houses are of bearing-wall-framed construction, and the seismic behavior under severe earthquakes is governed by the behavior of load-bearing walls. From this standpoint, this chapter clarifies the seismic resistance characteristics of steel-framed houses based on those of load-bearing walls, and discusses considerations to be taken into account when directly evaluating the seismic performance of steel-framed houses.

The plane shear test results[4] of a steel-framed load-bearing wall (see **Fig. 2**) designated 2P (1P refers to a 910-mm wide wall) and sheathed with 9-mm thick plywood on one side and 12-mm thick gypsum board on the other side are shown in **Fig. 3**. The sheathing and studs are connected by self-drilling screws at intervals of 150 and 300 mm on the external and internal peripheries, respectively. The plane shear test results[4] of a wooden load-bearing wall are shown in **Fig. 4** for comparison. In this case, nails (2.51 and 2.87 mm in diameter) are driven into wooden studs at intervals of 100 and 200 mm on the external and internal peripheries, respectively.

The steel-framed walls exhibit such behavior that the self-drilling screw connections to the sheathing undergo bearing pullover failure[11] before they reach the ultimate state. The characteristics of the load-bearing walls are strongly influenced by the failure characteristics of the self-drilling screw connections. Similar behavior is observed in the wooden walls. When steel-framed and wooden walls are compared, the following can be said: 1) Both types exhibit relatively similar cyclic behavior; 2) The steel-framed house walls have greater initial stiffness and maximum strength than the same sized wooden walls; 3) Both types exhibit pronounced pinching behavior, but this tendency is slightly greater for the steel-framed walls. The change in the equivalent viscous damping ratio h_{eq} calculated from the loop of the second cycle at each displacement amplitude is shown in relation to the nondimensional displacement (ductility factor) in **Fig. 5**. The tendency that the damping effect of the steel-framed wall becomes smaller with increasing displacement can be clearly understood.

The differences between the steel-framed and the wooden walls arise from the differences in the behavior of the connections between the sheathing and the studs. With the wooden house, the nails are low in strength but are greatly restrained by the lumber. When a wall is subjected to shear force, the nails deform and yield due to the shear force, and the nails themselves absorb the applied energy. When

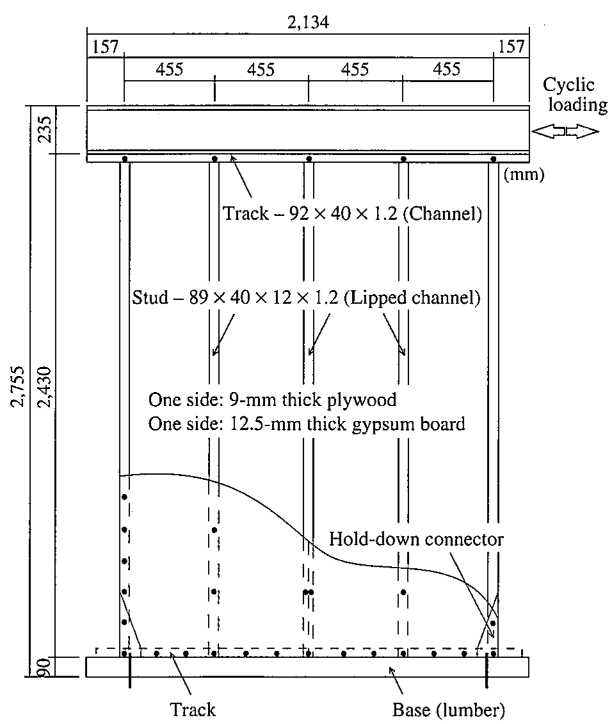


Fig. 2 Schematic of steel-framed load-bearing wall specimen

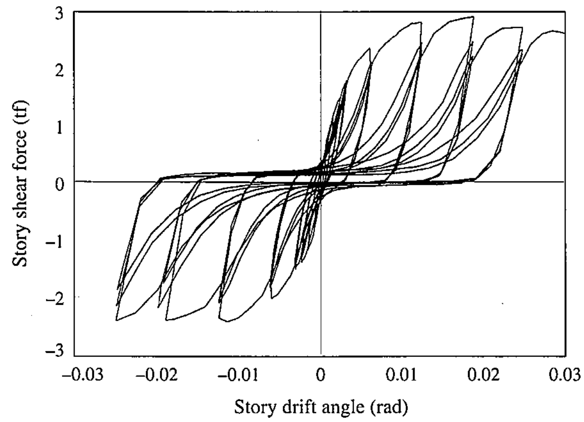


Fig. 3 Cyclic behavior of steel-framed load-bearing wall

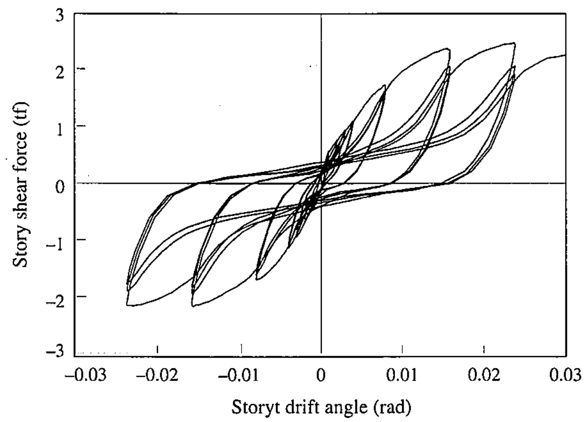


Fig. 4 Cyclic behavior of wooden load-bearing wall

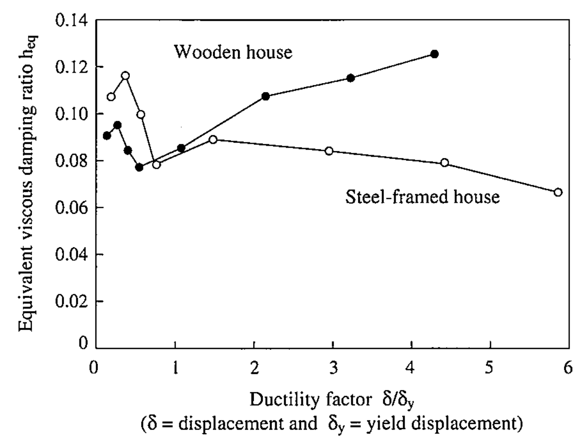


Fig. 5 Change in equivalent viscous damping ratio with ductility factor

a steel-framed wall is subjected to shear force, the self-drilling screws deform little, and the sheathing undergoes bearing pullover failure.

As discussed above, steel-framed houses may behave in a manner similar to that of wooden houses on a macro basis, but exhibit a somewhat large pinching behavior due to the failure of self-drilling screw connections between the sheathing and studs. It is thus important to study the seismic resistance of steel-framed houses by properly considering the effect of this hysteretic nature.

The behavior shown in Fig. 3 can be secured when the local deformation and buckling of the studs do not occur before the failure of the self-drilling screw connections between the sheathing and the studs in the walls. The design methods proposed in Fig. 1 satisfactorily prevent these local deformation and buckling by using fully strong studs and paying attention to the details of the connections.

4. Seismic Resistance Evaluation and Study Steps

In this study, the seismic performance of steel-framed houses is directly evaluated based on the seismic response analyses usually applied only to high-rise buildings. Existing studies on the inelastic response of small-scale buildings like single-family houses to earthquakes are limited in number[12,13]. As far as steel-framed houses are concerned, only research exists for non-load bearing steel-framed walls[14]. The seismic response analyses of steel-framed houses calls for the development of a hysteresis model capable of simulating their characteristic behavior. It is also important to accumulate basic data like the damping ratio.

The seismic safety of steel-framed houses was evaluated through the steps shown in **Fig. 6**. 1) A hysteresis model is proposed for steel-framed houses. 2) The damping ratio is set based on vibration tests of a steel-framed house in infinitesimally small amplitude regions. 3) Steel-framed walls are tested by shaking-table to investigate the behavior and validate the hysteresis model proposed here. 4) The response of a steel-framed house against severe earthquakes is analyzed by the model developed after the above steps, the seismic safety of the steel-framed house is evaluated, and then steel-framed house design methods are proposed. The outline of research in each step is described in the chapters that follow.

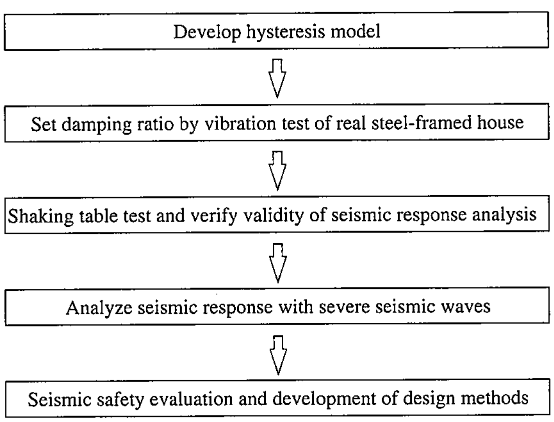


Fig. 6 Steps for evaluating seismic safety

5. Development of Hysteresis Model

For analyzing its seismic response, the steel-framed house was represented by a two-lumped mass system shear spring model (see **Fig. 7**). The program used for the analysis is called shearms.f[15] and was developed by Kumamoto University. The program shearms.f can represent the restoring force characteristics of each story by a parallel link of defferent shear springs and consider a variety of cyclic hysteresis characteristics.

The steel-framed house studied here is two storied and modeled into Fig. 7. The data required for the analysis of the steel-framed house are the weights W1 and W2, shear stiffnesses k1 and k2, damping ratios h1 and h2, and input seismic waves (ground motion accelerations). The weights W1 and W2 can be set according to the dead and live loads for seismic design. For the shear stiffnesses k1 and k2, a hysteresis model is developed that can more faithfully reflect the shear test results of load-bearing walls. The damping ratios h1 and h2 are set according to the vibration test results of a real steel framed house, whose details are described in Chapter 6.

The hysteresis model developed is described below. The steel-framed houses have hysteretic characteristics with an envelope behavior that the stiffness gradually decreases without clear yield point and a somewhat strong slip nature while retaining some energy absorbing capacity. These characteristics are observed in reinforced concrete structures, and relatively many hysteretic models have been proposed to describe them[16,17]. This study has referred to these research results.

The hysteresis model consists of the envelope portion of the story shear force-story drift angle relationship and the hysteresis portion that defines the unloading and re-loading behavior. The envelope portion is approximated by lines that connect the origin, point a, point b and point c successively as shown in **Fig. 8**. The point a is the elastic limit. The point c is the yield point defined such that the envelope of the story shear force-story drift angle relationship is replaced by an equivalent bilinear envelope. The point b is established from

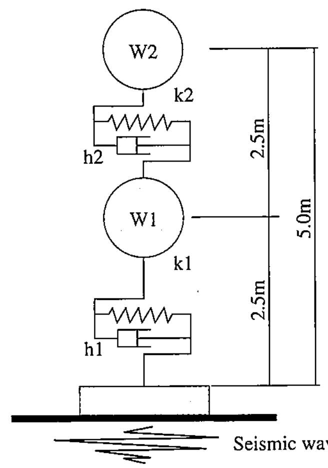


Fig. 7 Two-lumped mass system shear spring model

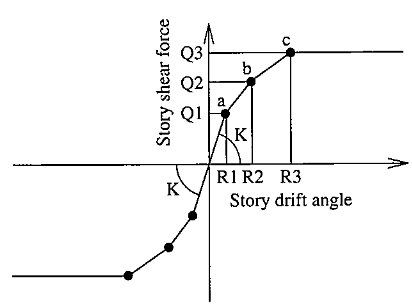


Fig. 8 Envelope of analytical hysteresis model

the experimental results as a point that can appropriately represent the curvature between the points a and c. The slope of the line that connects the origin with the point a is defined as the initial elastic stiffness K. The values of the story shear force and story drift angle at the points a, b and c are set based on the experimental results. They are given in **Tables 1 and 2** for a 1.82-m wide load-bearing wall sheathed with plywood on one side and a 1.82-m wide load-bearing wall sheathed with gypsum board on one side respectively.

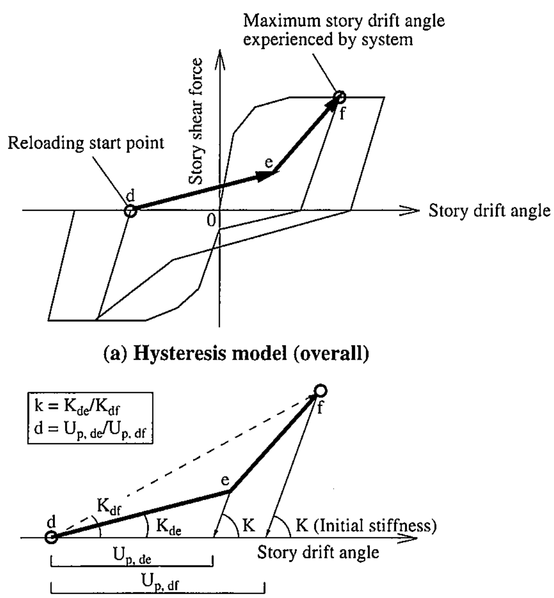
The behavior of the hysteresis portion is modeled by the polygonal line shown in **Fig. 9**. In the unloading process, the system is assumed to maintain the initial elastic stiffness K of the envelope portion until the load becomes zero. In the re-loading process, the maximum displacement point f on the envelope experienced previously by the system in the loading direction is taken as the target point. The system is assumed to move on the thick line d to e to f in Fig. 9. The point e is the point that characterizes the pinching behavior of the system and can be determined by the ratio k of K_{de} to K_{df} and the ratio d of $U_{p,de}$ to $U_{p,df}$ in Fig. 9. Thus, k and d become the parameters that govern the hysteresis characteristics accompanying the pinching behavior. The values of the parameters k and d set from the experimental results for the plywood and gypsum board are given in **Table 3**.

Table 1 Parameters governing envelope (1.82-m wide load-bearing wall sheathed with plywood)

Point	Story shear force Q (kgf)		Story drift angle R (rad)	
a	Q1	769	R1	1/606
b	Q2	828	R2	1/541
c	Q3	2,203	R3	1/106

Table 2 Parameters governing envelope (1.82-m wide load-bearing wall sheathed with gypsum board)

Point	Story shear force Q (kgf)		Story drift angle R (rad)	
a	Q1	231	R1	1/2,424
b	Q2	355	R2	1/1,333
c	Q3	748	R3	1/ 386



(a) Hysteresis model (overall)

(b) Detail of hysteresis portion

Fig. 9 Modeling of hysteresis portion

Table 3 Parameters governing hysteresis portion

	Sheathing	
	Plywood	Gypsum board
k	0.2	0.1
d	0.8	0.85

The analytical results with the hysteresis model and the experimental results of load-bearing walls are comparatively shown in **Figs. 10 and 11**. The hysteresis model developed is found to be capable of appropriately reproducing the cyclic behavior of the experimental results. The model proposed here does not take into account the strength degradation under cyclic loading. The model may also be applied to the design of wooden houses by changing the values of the parameters concerned.

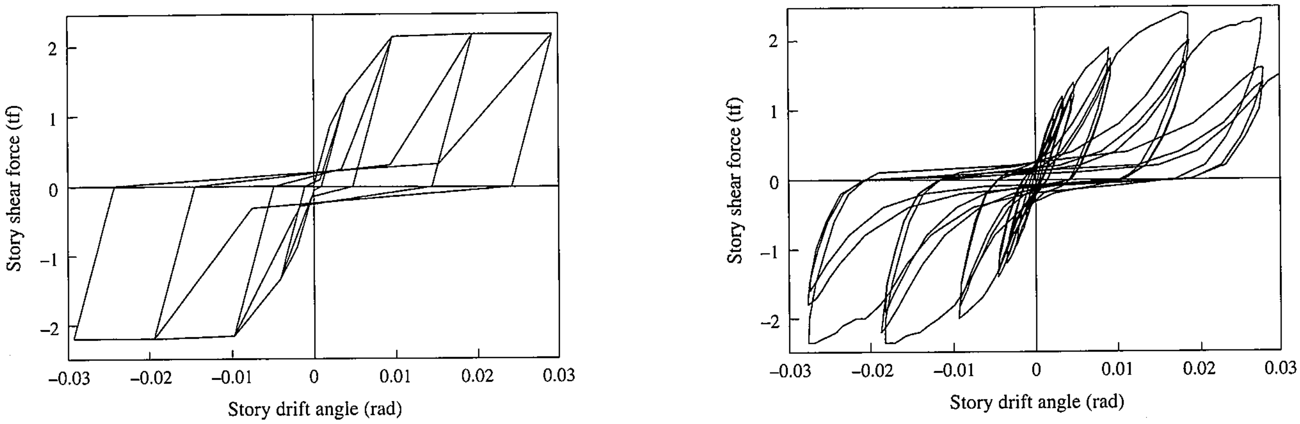
6. Vibration Test of Real Steel-Framed House[18]

The seismic response of a building is strongly influenced by the damping effect of the building. **Fig. 12** shows the effect of the damping ratio based on the results of seismic response analysis (as performed under the conditions described in Chapter 8). It suggests that proper evaluation of the damping ratio of a building is important. Damping ratios are generally set at about 2 to 3% for the analysis of steel-framed structures and reinforced-concrete structures. Few data of damping ratios are available for single-family houses[19,20].

The damping ratios of steel-framed houses were investigated by model houses built in Nippon Steel and other steel companies[4]. High damping ratios of about 4 to 10% were obtained. It was suggested that the damping was affected by the interior and exterior finishes used. If this effect is properly evaluated, steel-framed houses can be designed more economically.

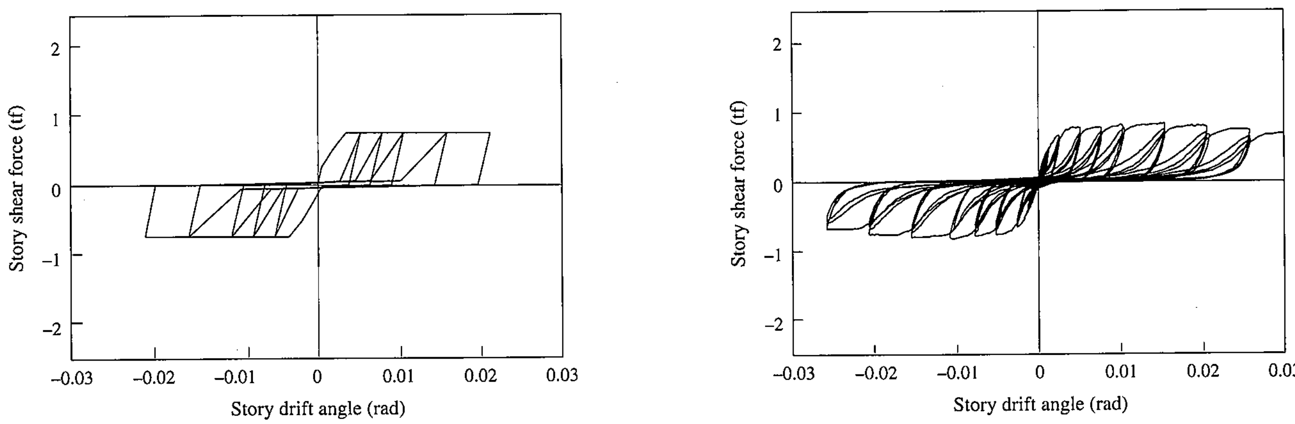
The present study investigated the vibration characteristics of a typical steel-framed house in each construction stage and quantified the effects of interior and exterior finishes and other materials[18]. The steel-framed house investigated is owned by Japan Development Co. and is a two-story house with a total floor area of about 132 m^2 and an equal floor area in each story as shown in **Photo 1**. The steel-framed house was examined in three stages as shown in **Fig. 13**. At the first stage, the house had plywood installed in the load-bearing walls, floors, and roofing. Gypsum board (excluding ceilings and some walls), roofing and some eastern and western external walls were installed at the second stage, and at the third stage, gypsum board (including ceilings) and exterior walls were installed, and interior finish was completed. The steel-framed house was tested by three methods: microtremor test, sweep test, and free vibration test[18]. To investigate the effect of the magnitude of the exciting force given by vibration devices, small, medium and large levels of exciting force were set at maximum velocity of about 10, 50 and 120 mkine, respectively.

The relationship between the damping ratio and the natural frequency is shown for each construction stage, test method, and exciting force magnitude in **Fig. 14**. The damping ratio ranges from about 2.5 to 7%, and the natural frequency ranges from about 6.4 to 7.8 Hz. The damping ratio and the natural frequency are found to increase with the progress of construction. This is because the installa-



(a) Hysteresis model (b) Experimental results

Fig. 10 Comparison of model and experimental results (plywood)



(a) Hysteresis model (b) Experimental results

Fig. 11 Comparison of model and experimental results (gypsum board)

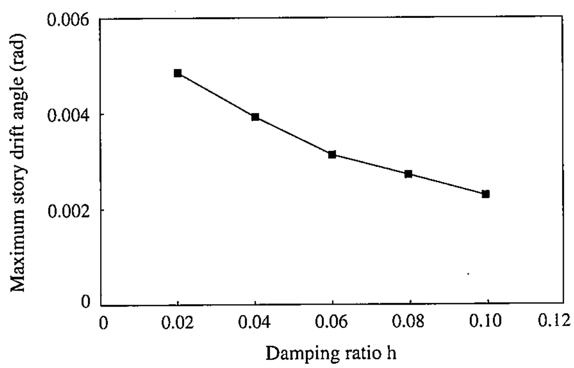
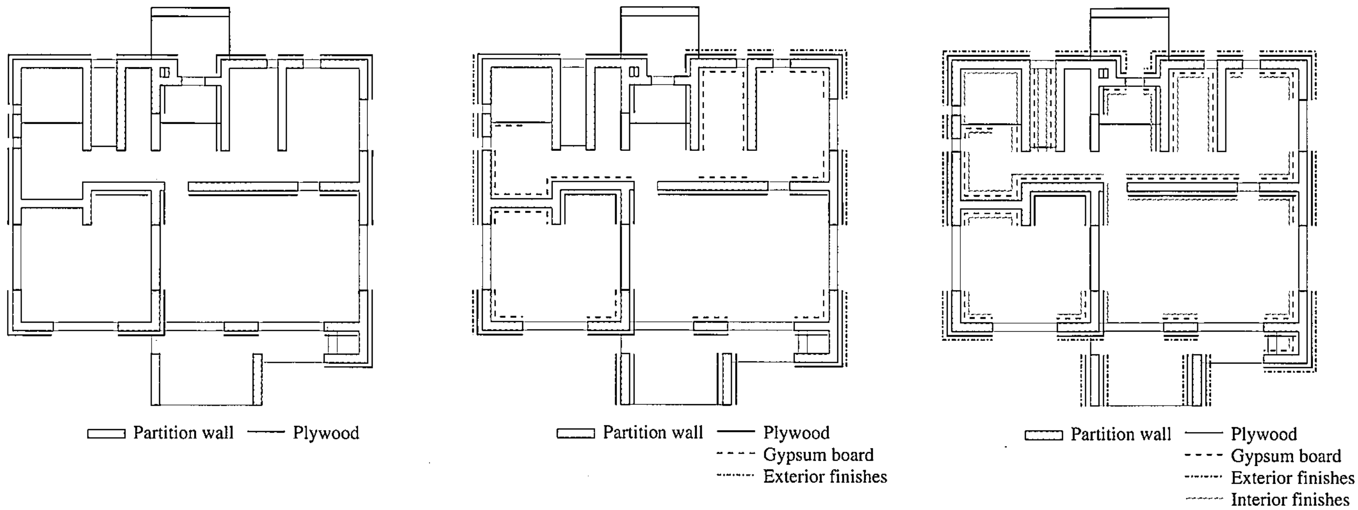


Fig. 12 Effect of damping ratio on seismic response

tion of interior and exterior finishes increases the stiffness and damping effects of the house. Increasing the exciting force increases the damping ratio and decreases the natural frequency. This is probably because the increase in the exciting force damages the sheathings, finishes, and their connections at a microlevel. The damping ratio obtained at the large exciting force level in the completed stage is about 5.5 to 7% and is considerably large.

As discussed above, the damping ratio of the steel-framed house is strongly influenced by the presence of interior and exterior finishes and the level of the exciting force, and is considered to assume a relatively large value. Based on the above findings, it was decided to set the damping ratio at 6% in the seismic response analyses.

Photo 1 Steel-framed house subjected to vibration test (owned by Japan Development Co.)



(a) Plywood installed (stage 1)
(b) Gypsum board installed (stage 2)
(c) Interior and exterior finishes completed (stage 3)

Fig. 13 Construction stages of steel-framed house subjected to vibration test

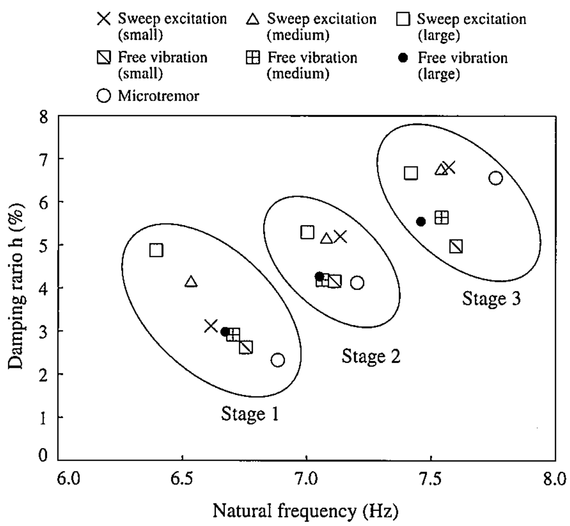


Fig. 14 Relationship between damping ratio and natural frequency in each construction stage

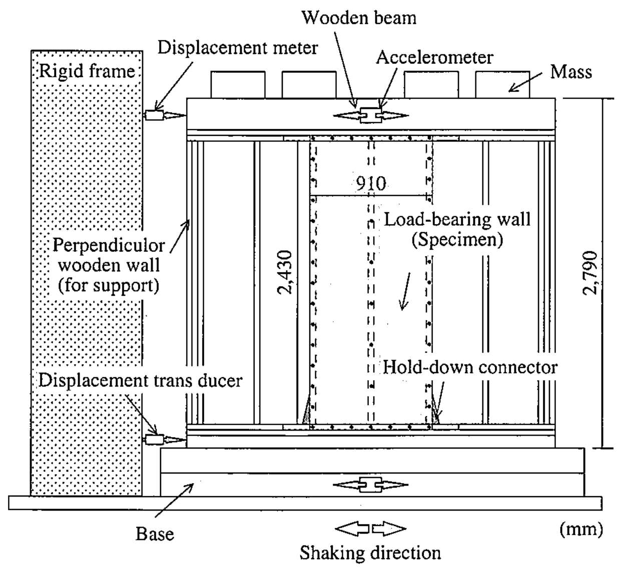


Fig. 15 Schematic of specimen

7. Shaking Table Test and Validity of Seismic Response Analysis[21)]

Steel-framed load-bearing walls were tested on a shaking-table to directly examine the seismic behavior and to verify the validity of the model described in Chapter 5.

The specimen shown in **Fig. 15** consists of two 910-mm wide (= 1P) steel-framed house load-bearing walls set facing each other and loaded with mass placed on their top as the dead and live loads. The input seismic waves were those of Taft EW 1952 and were introduced to produce a maximum velocity of 50 kine (maximum acceleration of 497 gal). Displacement transducers and accelerometers were placed at the positions shown in Fig. 15 to measure its displacement and acceleration.

The relationship between the shear force calculated from ceiling-level accelerograms and the relative displacement is shown in **Fig. 16.** When shaken, the specimen entered the inelastic region and reached a maximum story drift angle of as much as 1/32. It did not collapse, however, and was confirmed to retain strength at the end of the test. The predominant failure mode was the bearing and pullover failure of self-drilling screw connections. The failure modes were similar to those observed in static loading tests. Unlike expectation in actual houses, the response tends to be large, probably because the specimen had no non-structural members and other vibration-reducing elements. The overall shape of the hysteresis loops is governed by the input of two or three large waves.

The experimental results were compared with the results of analysis. For the analysis, the envelope portion was approximated by polygonal lines from the experimental results of Fig. 16 and the parameters $k = 0.2$ and $d = 0.85$ were set for the hysteresis portion, in order to simulate as close as possible. The damping ratio h was assumed to be 0% because the specimen had no exterior walls and interior finishes. The results are shown in **Fig. 17**. The overall behavior of the specimen is simulated relatively well. Especially note that the story shear force-the story drift angle skeletons are determined by a few

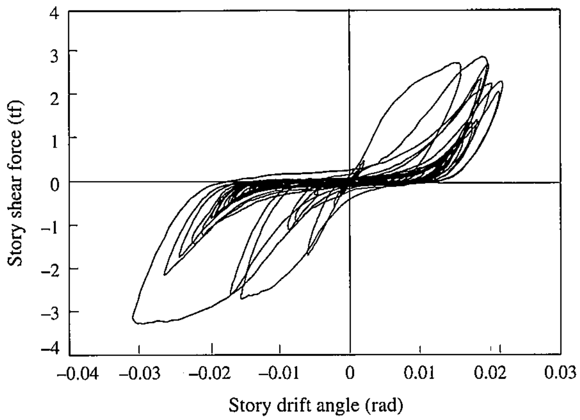


Fig. 16 Relationship between story shear force and story drift angle

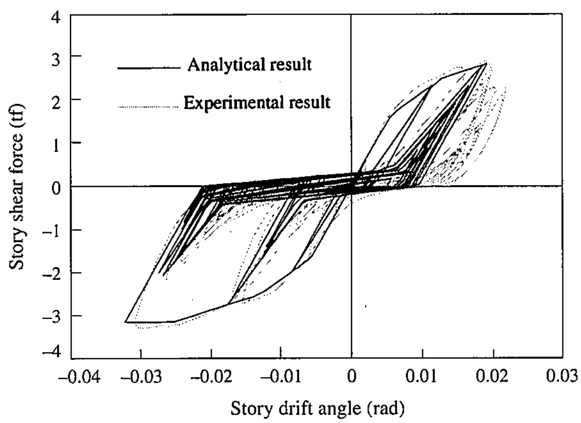


Fig. 17 Comparison of analytical results and experimental results

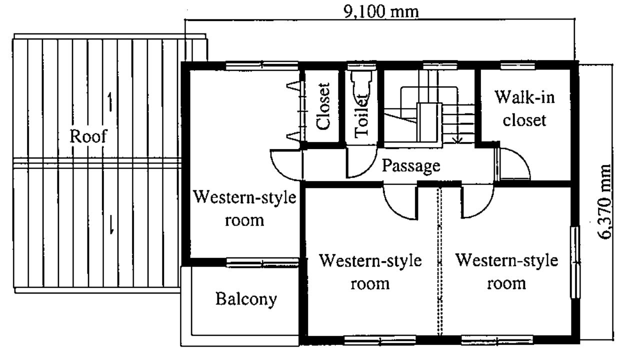
input waves as seen in the test. These results indicate that the analytical model shown in Chapter 5 can accurately evaluate the seismic behavior of steel-framed walls if appropriate parameters are selected.

8. Seismic Response Analyses of Steel-Framed House

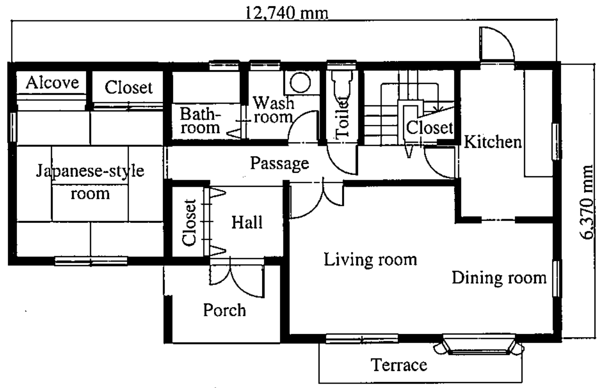
Based on the results discussed in the preceding chapters, here are presented the analytical results of the response of a standard steel-framed house to severe earthquakes.

The analyzed steel-framed house was typical of the Kozai Club Type A steel-framed houses structurally approved by the Building Center of Japan. The Type A includes a two-story house having a total floor area of 500 m^2 or less and intended for construction in areas without heavy snowfalls. For the house analyzed (see **Fig. 18**), the total floor area is 128 m^2 (75 m^2 for the first floor and 53 m^2 for the second floor), the weight is 18.8 tons for the first floor and 5.83 tons for the second floor, and the story height is 2.5 m. Structural plywood and gypsum boards were used as sheathing materials.

In general, the wall length arranged in actual residential houses is considerably greater than the required wall length by seismic design, because of the floor planning. In the standard plan studied here, the actual wall lengths on the first and second floors in the span direction are 3.17 and 7.55 times greater than the minimum required wall lengths, respectively. The actual wall lengths on the first and second floors in the ridge direction are 3.28 and 5.15 times greater than the required lengths, respectively. The second floor has more



(a) Second floor plan



(b) First floor plan

Fig. 18 Steel-framed house analyzed

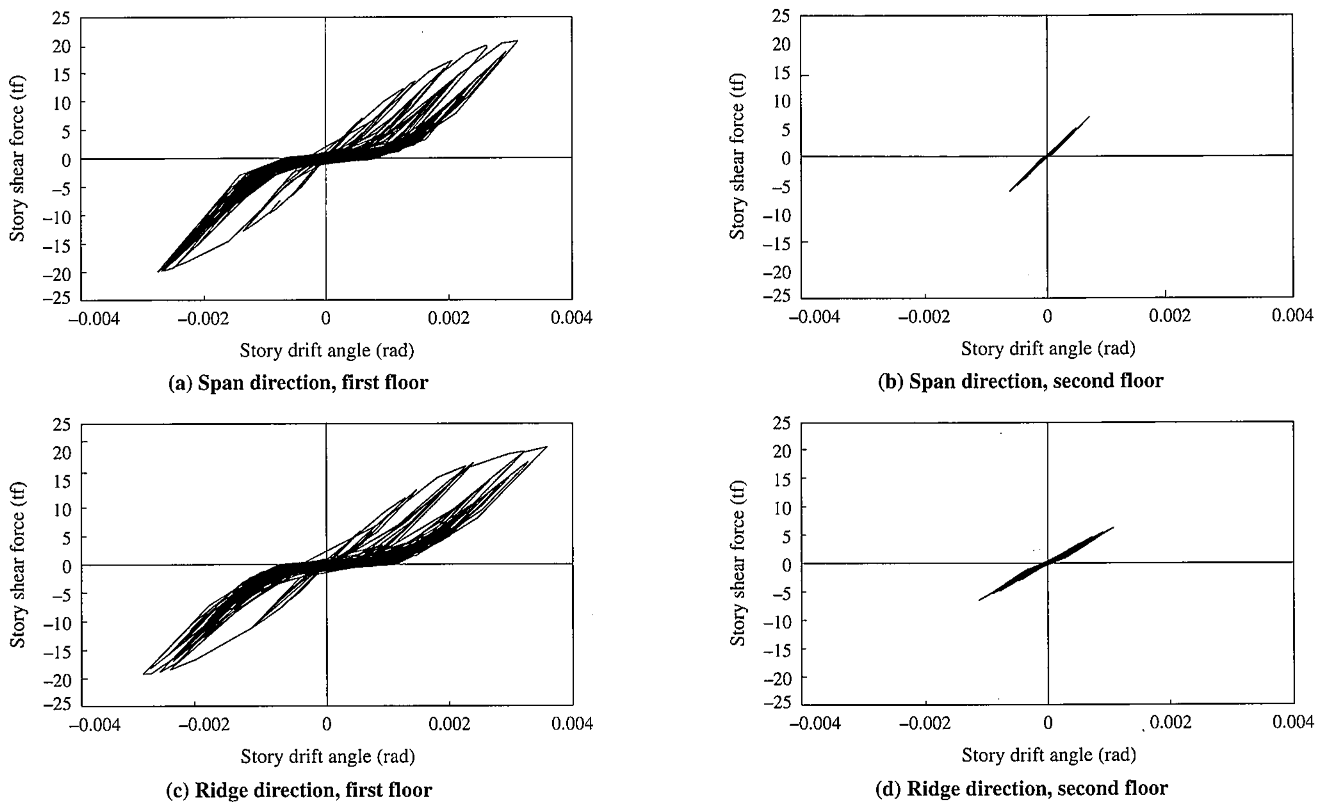
load-bearing wall ratios than the first floor.

The damping ratio was set h = 6% and given as stiffness proportional damping. The input seismic waves were the standard seismic waves Taft EW 1952 and were adjusted to level 2 magnitude with a maximum velocity of 50 kine[10].

Since plywood and gypsum board differ in hysteretic characteristics, the quantities of plywood and gypsum boards required for the first and second floors of the house were separately calculated, and the plywood and the gypsum board were considered as independent elasto-plastic springs. The parameters k and d that govern the hysteretic characteristics were the same as those of Table 3. The quantities of plywood and gypsum boards calculated directly from the plan in Fig. 18 were increased by 1.5 for analyses, in order to consider the resistance of small walls around openings and restraint effects between the walls.

The analytical results of the standard plan in the span and ridge directions are shown in **Fig. 19**. Since the second floor had more walls than the first floor with respect to the minimum required wall length, most of the damage was caused on the first floor. Focusing on the maximum response values, the maximum story drift angles were 1/320 and 1/279 rad in the span and ridge directions, respectively. These values were much smaller than 1/100 rad commonly adopted as a target story drift angle for high-rise buildings. It can be thus understood that the standard steel-framed house is sufficiently safe in a severe earthquake.

Since the seismic response of buildings is known to be significantly influenced by the type of seismic wave applied, the results of the effect of input seismic waves were examined (**Fig. 20**). In addition to Taft EW 1952, Hachinohe-NS 1968 known as waves with long-term period components, Yokohama[22] as artificial waves with



(a) Span direction, first floor

(b) Span direction, second floor

(c) Ridge direction, first floor

(d) Ridge direction, second floor

Fig. 19 Seismic response analysis results of steel-framed house with standard plan

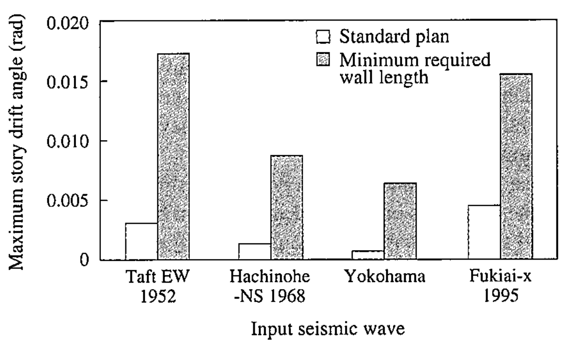


Fig. 20 Effect of input seismic waves on seismic response

a long duration of principal shock, and Fukiai-x 1995 recorded in the Great Hanshin Earthquake were considered. These input seismic waves were each adjusted to produce a maximum velocity of 50 kine. The house of the standard plan exhibited the largest response to Fukiai-x 1995 in the ridge direction; however, the house designed with the minimum required wall length as described later exhibited the largest response to Taft EW 1952.

9. Seismic Design Criterion and Seismic Safety

Evaluation of seismic performance by seismic response analyses and development of seismic design methods require establishment of an appropriate seismic safety criterion. The maximum story drift angle in an earthquake becomes a general index of seismic safety. For single-family houses, there are no information concerning the limiting value of the maximum story drift angle. It is uneconomical to design single-family houses in the same way as high-rise buildings with large axial forces; therefore, residential housing requires an appropriate criterion. The ultimate displacement of earthquake-resistant elements in low-rise buildings is typically specified as a maximum story angle of 1/30 to 1/15 rad[9]. In addition, a story angle of 1/60 rad is applied as a repairable displacement limit for houses[12]. Given these information, here was established the criterion that the maximum story drift angle of steel-framed houses against seismic waves with an intensity of level 2 should be held within 1/50 rad. The experimental results of the steel-framed wall specimen shown in Fig. 2 indicate that the wall still retains sufficient strength at 1/50 rad. This supports that the 1/50-rad criterion assures satisfactory seismic safety. The seismic design methods for the steel-framed houses described in Chapter 2 are developed using this maximum story drift criterion, based on the seismic response analyses.

Fig. 21 shows the change in the seismic response in the span direction of a steel-framed house in Chapter 8 as the wall length on the first floor is gradually reduced to the minimum required wall length. **Fig. 22** shows the cyclic response given by the analysis when the wall length on the first floor is the minimum limit required.

In Fig. 21, the ratio of the actual wall length to the minimum wall length on the first floor is plotted along the horizontal axis, and the maximum story drift angle produced by seismic response analysis is plotted along the vertical axis. In the seismic response analysis, the wall length on the second floor is reduced at the same rate as the wall length on the first floor. The lower horizontal axis in Fig. 21 also includes the corresponding base shear factor C_0 for allowable design. The maximum story drift angle increases with decreasing the wall length. When the wall length is the minimum required limit given by the design methods described in Chapter 2 (i.e., ratio = 1 and C_0 = 0.2), the maximum story drift angle is about 1/60 rad. This shows that the 1/50-rad criterion is satisfied. Since the wall length has a direct impact on the magnitude of the maximum story drift

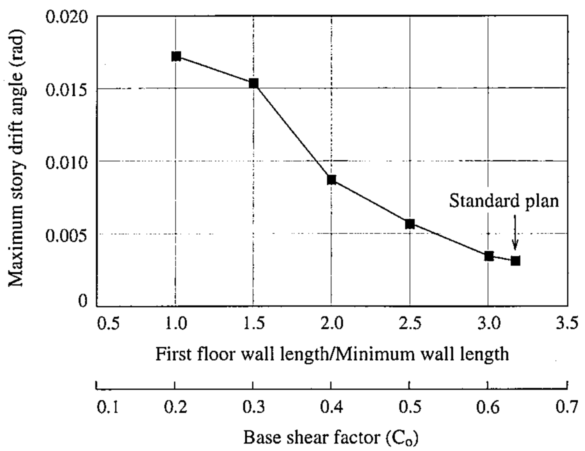
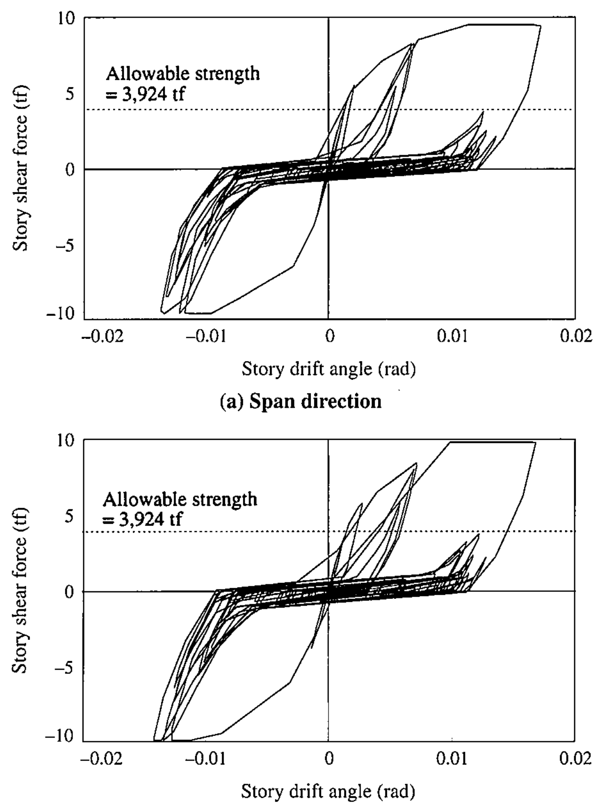


Fig. 21 Relationship between wall length and maximum story drift angle



(a) Span direction

(b) Ridge direction

Fig. 22 Seismic response of first floor of steel-framed house with minimum wall length

angle, providing the necessary wall length is most important in assuring the seismic safety of steel-framed houses.

10. Conclusions

This report outlined the results of studies conducted by the Kozai Club on the seismic resistance of steel-framed houses and quantitatively discussed the seismic resistance. The findings obtained are summarized as follows:

1) The design methods of steel-framed houses were proposed based on the direct evaluation of seismic resistance by the seismic response analyses. Holding the maximum story drift angle to 1/50 rad in a severe earthquake was proposed as a criterion for steel-framed houses.
2) For proper evaluation of the seismic resistance, a hysteresis model was developed that properly reflects the hysteretic characteristics of steel-framed houses. The model appropriately considers the pinching behavior of a steel-framed house in the cyclic hysteresis portion. The validity of the model was verified by comparison with the shaking table test results of load-bearing walls.
3) Vibration test of an actual steel-framed house was conducted at three stages of construction. The damping ratio was found to exhibit a relatively large value due to the influence of interior and exterior finishes. According to the results of the vibration test, the damping ratio was set at 6% for the seismic response analyses of steel-framed houses.
4) The response of a standard steel-framed house was analyzed to seismic waves of level 2. The steel-framed house exhibited a story drift angle of about 1/300 rad as maximum response to severe earthquakes and indicated that it had high seismic performance. When the steel-framed house was provided with the minimum required wall length, its maximum response was about 1/60 rad and was smaller than the established criterion of 1/50 rad.

The research work on steel-framed houses was carried out at the Kozai Club as a joint effort by six steel companies (Kawasaki Steel, Kobe Steel, Nippon Steel, Sumitomo Metal Industries, Nisshin Steel, and NKK). The seismic resistance studies reported here were condected cooperatively by Nippon Steel and NKK.

Acknowledgments

The authors would like to thank Professor Kazuo Inoue of Kyoto University, Professor Koji Ogawa of Kumamoto University, Professor Nobuo Fukuwa and Lecturer Riei Nishizaka of Nagoya University, and Chief Researcher Naoto Kawai of the Building Research Institute, Ministry of Construction, for their guidance in the present work. They are also indebted to Osaka Gas for providing the seismic wave data of Fukiai-x 1995.

References

1) Housing Bureau, Ministry of Construction: Guidelines for Structural Calculation of Wood-Framed Buildings, 1992. Japan 2×4 Home Builders Association, 1992, 645p.
2) Housing Construction Material Subcommittee, Kozai Club: Guidelines for Structural Calculation of Steel-Framed Houses. Kozai Club, May 1997
3) Housing Construction Material Subcommittee, Kozai Club: Steel-Framed House Structure and Durability Research Report, Vol. 1. Kozai Club, October 1997, 315p.
4) Housing Construction Material Subcommittee, Kozai Club: Steel-Framed House Structure and Durability Research Report, Vol. 2. Kozai Club, October 1997, 211p.
5) Housing Construction Material Subcommittee, Kozai Club: Steel-Framed House Structure and Durability Research Report, Vol. 3. Kozai Club, June 1998, 155p.
6) Steel House Office Committee, Kozai Club: Steel-Framed Houses: For People Planning to Design and Build Steel-Framed Houses (technical pamphlet). Kozai Club, 1998, 16p.
7) Steel House Office, Kozai Club: Kozai Club Standard for Building Structural Coated Light-Gauge Steel Shapes. Kozai Club, July 1997, 21p.
8) Steel House Office, Kozai Club: Kozai Club Standard for Steel-Framed House Self-Drilling Screws. Kozai Club, June 1997, 26p.
9) Aoki, H.: Technical Regulations for Structural Resistance Performance of Low-Rise Structural Steel-Framed Buildings. Building Letter, 23-38 (July 1995)

10) High-Rise Building Appraisal Committee: Earthquake Ground Motions for Dynamic Analysis of High-Rise Buildings. Building Letter, 49-50 (June 1986)
11) Hanya, K., Kanno, R.: Study on Screw Connections between Thin Steel Plates and Plywood, Parts 1 and 2. Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, August 1995
12) Sakamoto, I., Ohashi, Y.: Seismic Response Analysis of Representative Wooden Dwellings - Model of Standard Conventional Housing. Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, October 1984, p.2651-2652
13) Ohashi, Y., Sakamoto, I.: Seismic Response Analysis of Representative Wooden Dwellings, Part 2, - Using Non-linear Model Based on Racking Tests. Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, October 1985, p.1237-1238
14) Smith, H.A. et al.: Model to Incorporate Architectural Walls in Structural Analysis. J. Struc. Engrg. ASCE, 122 (4), 431-438 (1996)
15) Ogawa, K.: Manual for shearms.f Ver. 1.2. Environmental System Engineering Department, Faculty of Engineering, Kumamoto University, 1997
16) Kunnath, S.K. et al.: Analytical Modeling of Inelastic Seismic Response of R/C Structures. J. Struc. Engrg. ASCE, 116 (4), 996-1017 (1990)
17) El-Tawil, S., Kanno, R., Deierlein, G.G.: Inelastic Models for Composite Moment Connections in RCS Structures. Composite Construction in Steel and Concrete III. ASCE, 1997, p.197-210
18) Takahashi, H. et al.: A Study on Dynamic Characteristics of Steel House Based on Vibration Tests. Proceedings of Annual Meeting of Tokai Branch, Architectural Institute of Japan. 1998, p.181-184
19) Building Research Institute, Japan 2×4 Home Builders Association: Joint Research Report on Experiments of Full-Scale, Three-Story 2×4 House. March 1988
20) Fukuwa, N. et al.: A Study on the Eigen Property of 3 Story Steel House Based on Vibration Test. Journal of Structural Engineering, 41B, 279-288 (1995)
21) Kanno, R. et al.: Shaking Table Test of Steel Framed Walls, Study on Various Performance on Steel Framed Houses, Part 7. Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, September 1998
22) Committee on Preparation of Standards for Seismic Resistance Guidance of Structures and Buildings, Yokohama City: Vibration Analysis Manual, Appendix 2, Preparation of Standard Waves
23) Kawai, Y. et al.: Analytical Investigation on Seismic Behavior of Steel-Framed Houses, Study on Performance Properties of Steel-Framed Houses, Part 6. Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, September 1998