Effect of Conventional Braces on Seismic Response of Steel Frames

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SUMMARY:
This research is concerned steel frames with conventional braces. Conventional steel braces have some problems in their behavior. For example, it cause buckling under compression and provide the behavior of slipping under tensile loads. This paper describes a hysteretic model of the braces with simplified expression for easy handling in numerical work and the validity of simplified model is verified. Moreover, the simplified model is compared with damper with respect to maximum inter-drift story angles by means of seismic response analysis with fishbone-shaped frame model. By comparing between the two kinds of frames, the effectiveness of the conventional braces is assessed.

Keywords: Seismic response, Steel brace, Maximum inter-drift story angle, Damper, Steel frame

1. INTRODUCTION

The conventional braces are widely used as the earthquake-resisting element in low and middle-rise frames, such as factories, warehouse and multi-story parking lot. Meanwhile, hysteretic dampers such as buckling-restrained braces are often used in the low and middle-rise frames. The dampers are selected by the fact that they have an advantage of replacement-free after a strong earthquake. On the other hand, the braces have complicated behavior and it is no easy to estimate damping performance under earthquake. They are the reasons for selecting not the braces but the dampers. The evaluation of earthquake-resisting element of the braces is generally low. Moreover, the braces are adopted for a means to secure the horizontal load-carrying capacity.

The restraint of displacement response of hysteretic dampers is lead by both shortening of period of vibration of the steel frames and hysteretic damping. This research aims to develop a methodology of utilization of the conventional braces as the seismic elements that can restrict the maximum inter-drift story angles.

The behavior of the conventional braces has been simulated with simplified restoring force characteristics, as well known. The characteristics are described with the load-deformation relationships with slipping under tensile load and certain post-buckling load under compressive load. However, it is not clarified how much reliable the simplified model is in simulating the practical braces. This research takes a couple of braces in two directions into account. Moreover, for simplification, an analytical model was made by means of idealized elements. They should behave as tensile elements with slipping relationship, compressive elements with post-buckling strength and with elasto-plastic relationship. The simplified frames with idealized hysteretic behavior and the frames with actual behavior of steel braces were investigated how much they close chose together with the result of analysis of seismic response. The verification of the fact that the both analytical results almost coincide by means of the simplified model and method was conducted in this research. Finally, it was clarified that the conventional braces are effective in performance of damping through the comparing analyses of the frames with seismic dampers.

2. SIMPLIFICATION OF RESTORING FORCE CHARACTERISTIC OF BRACE

2.1.Analytical Model

In this section, the outline of an analytical model is described. The model is a simplified and condensed frame from a multi-story and multi-bay frame with conventional braces as shown Fig.2.1 (a). Moreover, the model is expressed by a mathematical model as shown Fig.2.1 (b). θ is the angle between the beam and the brace. h is the height of the frame. The mathematical model consists of a stiffening member with elasto-plasticity rotational spring and a couple of braces. Load- deformation relationship of the spring is bilinear type under monotonic loading and hysteretic behavior of the spring is kinematic hardening relationship under cyclic loading. The steel frame with conventional braces is called "braced frame" after this.

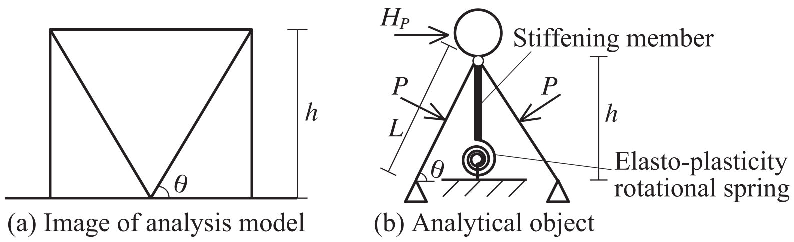

Figure 2.1. Analytical frame

The braces are analyzed by one-dimensional finite element method. The analysis can approximate complicated restoring force characteristics that have strength deterioration caused by buckling. The number of division along the axis of a member is 10 as shown in Fig. 2.2. The division rule of the member adopts Fibonacci sequence and the division starts from the center to the both ends of the member. Section of the brace is rectangle and it is divided into 20 layers. The load-deflection relationship of the brace is bilinear type under monotonic loading and is kinematic hardening relationship under cyclic loading. Before the main analysis, the brace is applied force P at the center of the element so that initial elastic deflection of 1/1000 to length of the element may cause buckling while the followed compression force on the brace increases in the analysis.

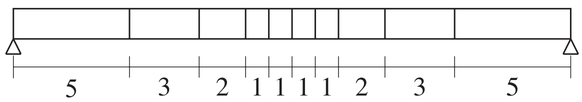

Figure 2.2. Mesh division along the axis of braces

2.2.Analytical Parameters

In this section, the conditions in analysis of the model and the prepared mathematical parameters are showed.
a) The steel grade of the braces is SN400, Young's modulus (E) is 2/5000N/mm^2 and yield strength (σ_y) is 235 N/mm^2.
b) The ultimate loading capacity (H_P) is sum of the strength of the steel frame, yield strength of the brace (N_y) on tensile side, and post-buckling strength of the braces (N_u) on compression side.
c) The ratio of shear force of the braces to that of the overall frame (β) is 0.5.
d) The natural period of the overall frame (T) takes 0.4s, 0.8s and 1.2s.
e) The flexural frame yields with 1/100 of inter-drift story angle. The braces yield with 1/400 of inter-drift story angle.
Moreover, the analyses are conducted with slenderness ratio of the brace (λ_B), which is 0.5, 1.0 and 1.5. N_u can be derived from Eqn. 2.1.

$$N_u = \frac{N_y}{\sqrt{1 + \dfrac{\pi^2 \lambda_B^2 E}{200\,\sigma_y}}} \qquad (2.1)$$

2.3.Simplification of Hysteretic Characteristics

It is needed that simplification of hysteretic characteristics of the braces is prepared for many numbers of calculations of the frame to conduct a numerical work. The braces should be simple and easy handling for the work. They behave as both tensile elements, which yield at specified strength with slipping relationship, and compressive elements, which have post-buckling strength with elasto-plastic relationship under cyclic loading. Moreover, the elastic stiffness of the braces under compressive load is provided the following two models (called “simplified models”).
Model (1): Elastic stiffness of a brace under compressive load is assumed the same as that of a tensile element.
Model (2): Both horizontal displacement of a compressive element and that of elastic limit of a tensile element are the same.
Model (1) has the same natural period as the braced frame. However, Model (1) cannot absorb hysteretic energy because it yields within small range of deformation under compression and effect of its hysteretic may occur excessively. Therefore, Model (2) is prepared for prevention against the weak points. It can absorb much energy after large deformation occurs in the element.

3. EXAMINATION OF SIMPLIFIED CHARACTERISTICS

In this chapter, validity of the simplified model is investigated. Analytical procedure of one-dimensional finite element method is assumed that it can explain the behavior of the braced frames almost exactly. In other words, seismic response of the braced frame, which is expressed with simplified model, represents the result obtained by one-dimensional finite element method. The ground motions used in the FEMA/SAC project were used for the seismic response analysis of all the frames. The ground motion data consists of two sets of 20 records that represent the probabilities 10% and 2% in 50 years in the Los Angeles area of the United States, which are denoted as the 10/50 and 2/50 record sets, respectively. The durations and the maximum value of accelerations of these waves are used source waves as they are. The time increment is set less than 1/500 of the natural period of each frame and the damping factor is 0.01 in analysis.

Fig. 3.1 shows the comparison between the maxim inter-drift story angles of the braced frames and the simplified models. These are summarized by every natural period. A plotted data on the solid line, which has an inclination of 45 degrees in the coordinate system of the graph, means that the result of the maxim inter-drift story angles of the braced frame is equal to that of the simplified model. The seismic response results in Fig. 3.1 are plotted at near places to the line. Therefore, the both simplified models of Model (1) and Model (2) can approximate the behavior of the braced frame.

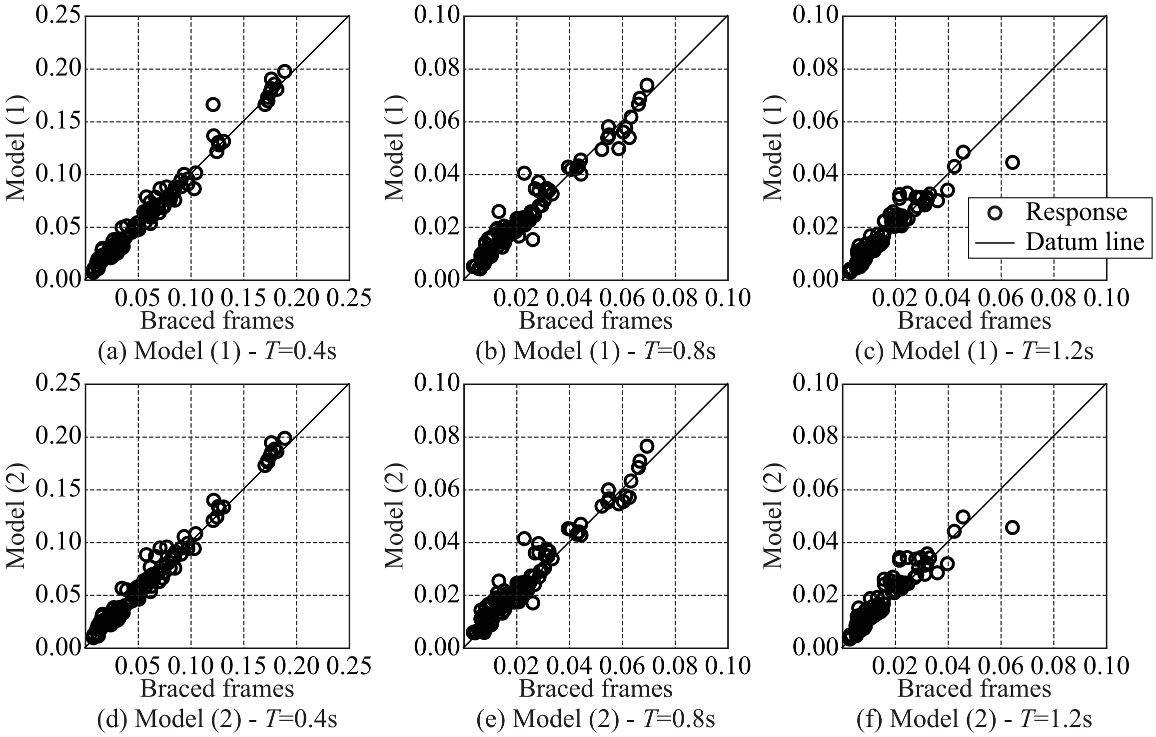

Figure 3.1. Comparison between maximum inter-drift story angles of two simplified models

The ratio of mean value and standard deviation of the maximum inter-drift story angles between the braced frames and the simplified models are shown in Fig. 3.2. λ_B is changed every 0.1 from 0.3 to 1.5. From Fig. 3.2, the simplified models tend to overrate the maxim inter-drift story angles. The results of Model (1) is much closer to the maximum inter-drift story angles of the braced frame than Model (2) with respect to all the value of λ_B. In addition, the standard deviations of the ratio of the maximum inter-drift story angles of Model (1) are smaller than those of Model (2). From this investigation, it should be judged that Model (1) is appropriate for the simplified model. The cause of the adoption is that the maximum displacement is greatly influenced by the natural period and the value of the natural period of Model (1) is almost equal to that of the braced frame.

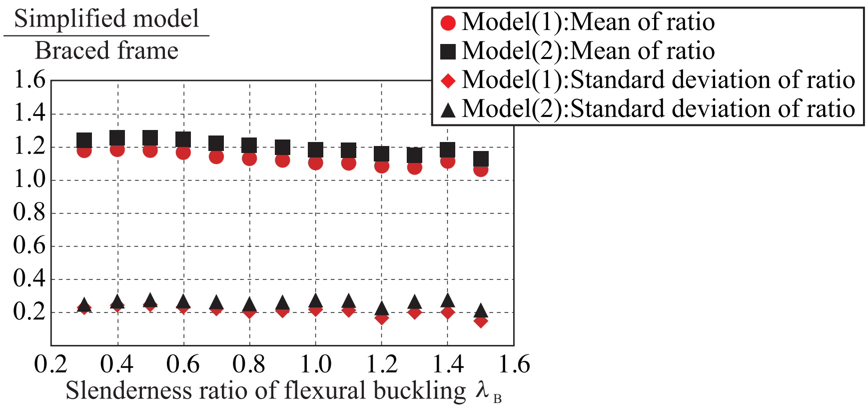

Figure 3.2. Relationship between λ_B and ratio of maximum inter-drift story angles

Moreover, as to almost case, the behaviors of the simplified models are similar to that of the braced frames with each λ_B become longer. Figure 3.3 show the relationship between shear force and inter-drift story angle of Model (1) and the braced frame. When the value of λ_B becomes larger, the behaviors that the braced frames burden tensile force are more approach than the behaviors of slipping relationship. It is the reason that the behaviors of simplified models approach those of the braced frames with each λ_B that becomes larger. For the result stated above, the simplified model is judged appropriating the model to use analyses of seismic response.

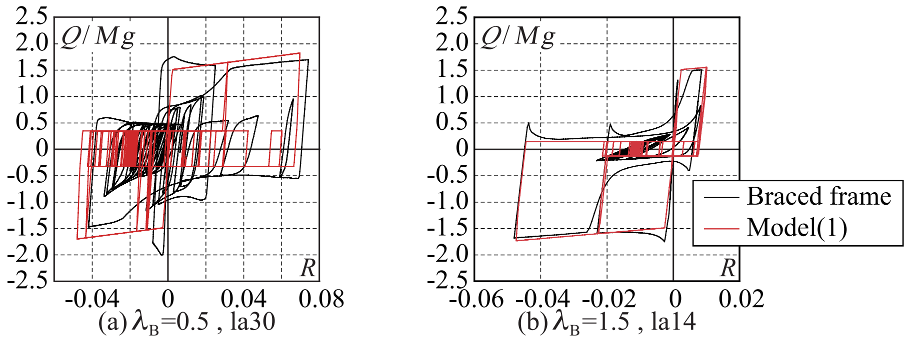

Figure 3.3. Behavior of braces and Model (1)

4. COMPARISON OF SEISMIC CONTROL BETWEEN BRACES AND DAMPERS

Comparison of the effect of seismic control of braces and dampers is discussed in this chapter. The braces in an analytical model are the simplified models specified above. The analytical model is adopted fishbone-shaped frame, which can approximate seismic response of a multi story frame as shown in Fig. 4.1. The details of the model are explained in another paper of this proceeding that the authors wrote. The full plastic moment of the beams in the frame is the floor moment at the story of the original frame, and the strength of the column of the frame is the sum of the strengths of all columns in the original frame. Thus, this model can almost exactly simulate the behavior of the model up to collapse stage and the behavior of 3D steel moment frames under strong seismic excitation. Two kinds of analytical frame were prepared other the braced frame for numerical study. The one is the steel frame without brace (called "non-braced frame"), and another one is the steel frame with dampers (called "damper frame"). The braces and dampers are represented by shear springs, which play an important role of the response of the inter-drift story angles.

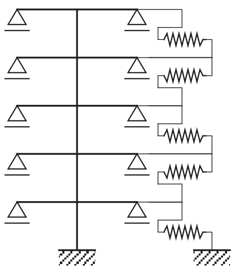

Figure 4.1. Fishbone-shaped frame

The outlines of analytical frame are shown below.
a) The number of stories is N.
b) Every story height is fixed to 4 m.
c) The design story-shear force (Q_i) at the ith story is obtained from Eqn. 4.1.

$$Q_i = C_0 R_t A_i \alpha_i W_t = C_0 R_t \sqrt{\alpha_i} W_t \tag{4.1}$$

Where W_t is the total weight of the frame and α_i is the ratio of the weight from the top through the ith story (W_i) to W_t. R_t is determined by means of the seismic design code of Japan. A_i is the value concerned with the story-shear force coefficient of ith story, which is expressed by Eqn. 4.2.

$$A_i = \frac{1}{\sqrt{\alpha_i}} \tag{4.2}$$

d) The ratio of lateral shear force of the braces and damper to that of over-all frame is given by β.
e) The column-to-beam strength ratio is 1.5.
f) The steel frame without brace or damper keeps elastic within the range of the inter-drift story angle of 1/100, and has the kinematic hardening rule, and the column-to-beam strength ratio to 1.0.
g) The damper keeps elastic within the range of the inter-drift story angle of 1/400, and has the kinematic hardening rule.
h) The braces under tensile force keep elastic within the range of the inter-drift story angle of 1/400, and behave with the slipping phenomena.
i) The braces under compressive force behave with elasto-plastic relationship. The elastic stiffness under compression is the same as that of under tension.
Moreover, the analyses were conducted with variation of λ_B, which takes 0.5, 1.0 and 1.5. P-Δ effect is considered and the viscous damping is Rayleigh type, whose both the damping factor of first and second is 0.01.

5. OUTLINE OF THE SUPPRESSIVE EFFECT OF DISPLACEMENT RESPONSE

5.1. Summary of The Analysis

The fundamental natural periods of the analysis frames are shown Table 5.1. They mainly depend on β. The fundamental natural period becomes shorter when β becomes larger. Besides, when λ_B becomes larger, the fundamental natural period becomes shorter because the ratio of lateral shear force of the brace under tensile force becomes large. The input ground motions are used intact waves as mentioned in chapter 3.

Table 5.1. Fundamental Natural Periods (s)

		Non-braced frame	Damper frame			Braced frame								
	β		0.2	0.5	0.8	0.2			0.5			0.8		
	λ_B					0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5
Fundamental natural period	4-story	1.10	0.9	0.7	0.6	0.8	0.8	0.8	0.60	0.6	0.6	0.5	0.5	0.5
	8-story	1.59	1.3	1	0.9	1.1	1.1	1.1	0.9	0.8	0.8	0.7	0.7	0.7
	12-story	2.30	1.8	1.5	1.3	1.6	1.6	1.5	1.2	1.2	1.1	1	1	0.9

Notations about the seismic response of models are referred below.
1) ${}_{\mathrm{R}}R_{\max}$: The maximum value among maximum inter-drift story angles of all stories of the non-braced frame.
2) ${}_{\mathrm{D}}R_{\max}$: The maximum value among maximum inter-drift story angles of all stories of the damper frame.
3) ${}_{\mathrm{B}}R_{\max}$: The maximum value among maximum inter-drift story angles of all stories of the braced frame.

5.2. Results of The Analysis

The relationships between ${}_{\mathrm{D}}R_{\max}$ and ${}_{\mathrm{R}}R_{\max}$ and the other ${}_{\mathrm{B}}R_{\max}$ and ${}_{\mathrm{R}}R_{\max}$ are shown in Fig. 5.1. They are collated with the results of analysis by means of all 40 waves. Fig. 5.1 shows that both the maximum inter-drift story angles of the damper frame and the braced frame do not differ extremely from those of the non-braced frames. Moreover, the maximum inter-drift story angles of the braced frames tend to larger than those of the non-braced frames when their values become large. The damper frames have the same tendency, however it is not conspicuous.

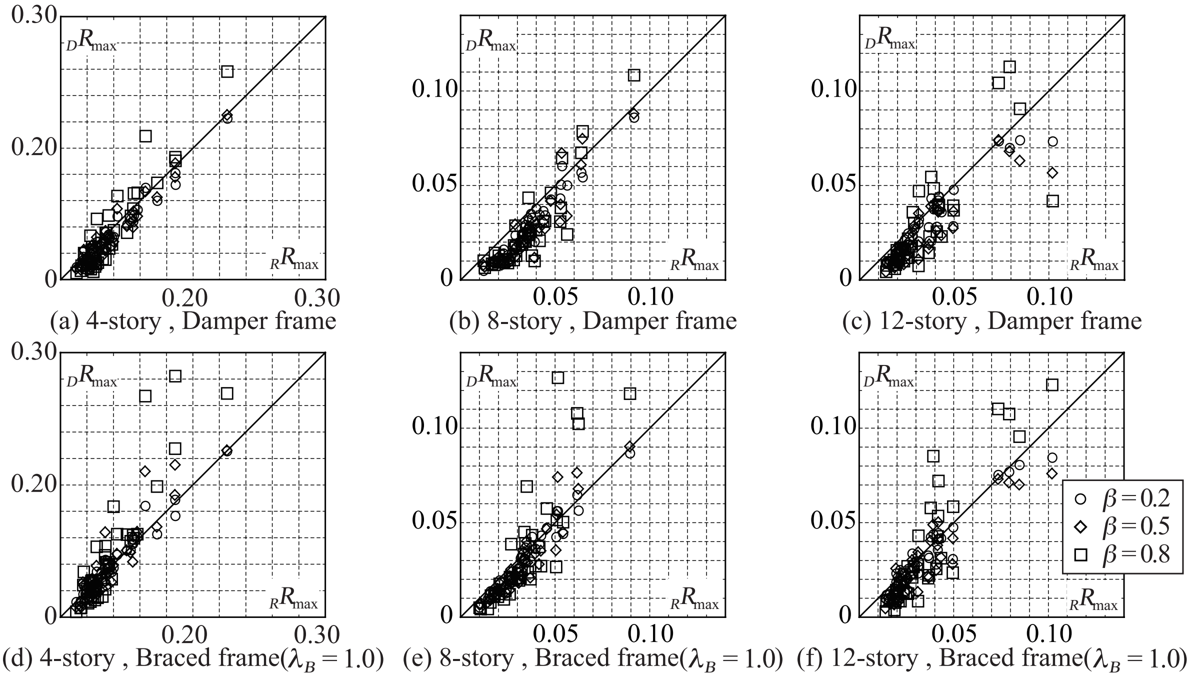

Figure 5.1. Comparison of maximum inter-drift story angles

The percentage of frames in case that the response of the braced frames or the damper frames become larger than that of the non-braced frames are shown in Table 5.2. They are summarized with respect to ${}_{R}R_{max}$ under three conditions that the value of ${}_{R}R_{max}$ is less than or equal to 0.03, more than 0.03 or in the whole range. The number of results that the maximum inter-drift story angle of both the damper frames and the braced frames are larger than that of the non-braced frames tends to be larger in condition that ${}_{R}R_{max}$ takes more 0.03 than in condition that ${}_{R}R_{max}$ takes 0.03 or less, whatever the other parameters change. This tendency is particularly remarkable at the frame that β = 0.8 or λ_B = 1.5.

Table 5.2. Percentage Of Frames Whose Responses Exceed Non-braced Frames (%)

		Damper frame			Braced frame								
	β	0.2	0.5	0.8	0.2			0.5			0.8		
	λ_B				0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5
Percentage	Whole	10.83	12.50	25.83	28.33	25.00	33.33	25.83	25.00	34.17	33.33	34.17	38.33
	${}_{R}R_{max}$=0.03 or under	8.55	10.51	13.99	20.10	17.51	17.51	14.83	15.07	15.52	19.62	16.83	17.27
	Over ${}_{R}R_{max}$=0.03	13.62	14.79	37.27	34.87	36.20	49.16	34.87	33.29	52.06	44.40	49.69	58.41

The maximum inter-drift story angles of each stories (R_{max}) of β = 0.8 are shown in Fig. 5.2. In other words, the median is calculated by means of the exponential function. Furthermore, 84% limit is the exponential function, which is the sum of the value and the standard deviation. On this occasion, the value is assumed that it the maximum inter-drift story angles of all stories become lognormal distribution. Besides, these three values are found as the exponential function of the value after the logarithm of the maximum inter-drift story angles of all stories are found. Moreover, the lognormal distribution is assumed in this report because the maximum inter-drift story angles are distributed at only positive domain. According to Fig. 5.2, the maximum inter-drift story angles of the damper frames and the braced frames are smaller than those of non-braced frames when the seismic response using 10/50 record sets that the maximum inter-drift story angles are comparatively small. Consequently, the braced frames demonstrate the same the restrain effects of displacement responses as the damper frames. On the other hand, both the maximum inter-drift story angles of the damper frames and the braced frames tend to large at the substratum when the seismic response using 2/50 record sets, which is the maximum inter-drift story angles are comparatively large. These are causes that ${}_{D}R_{max}$ and ${}_{B}R_{max}$ are larger than ${}_{R}R_{max}$.

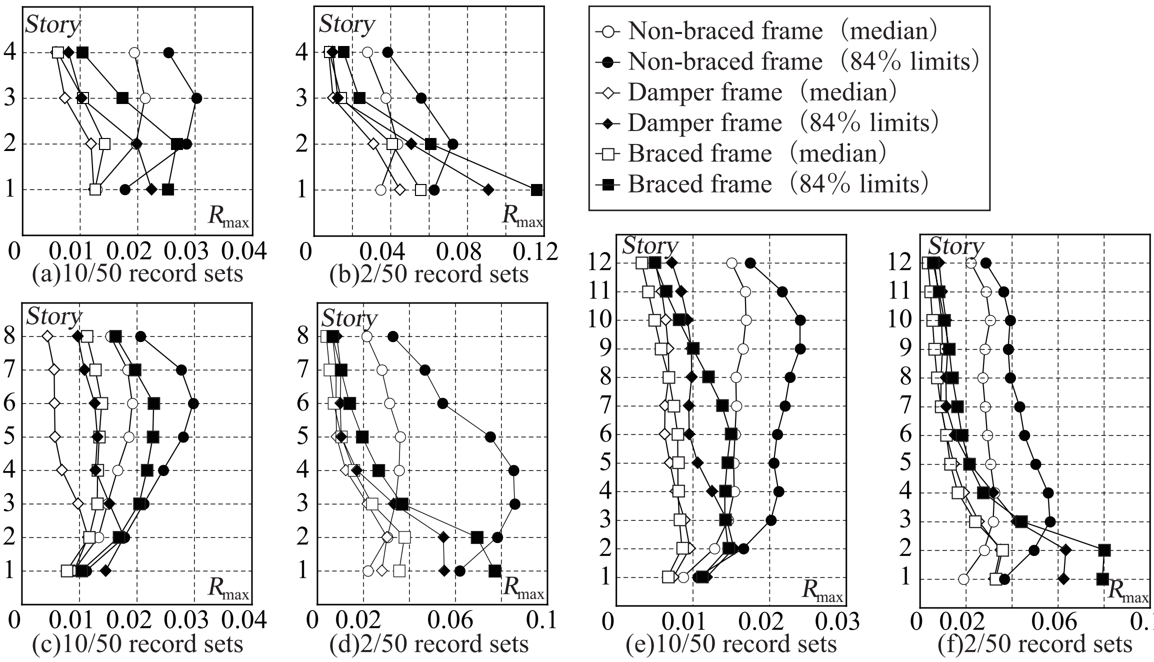

Figure 5.2. Maximum inter-drift story angles of all stories

The non-braced frames, which is adopted this report, secures the column-to-beam strength ratio at 1.5 and has the effect, which deal with the maximum inter-drift story angles of all stories equally. However, the frame, which is small the strength shearing ration, is susceptible to displacement concentration any stories. As a result, according to Fig. 5.2, the damper frames and the braced frames, which are $\beta = 0.8$, cause displacement concentration at near the substratum through a large number of analysis. Moreover, the maximum inter-drift story angles become larger at $\lambda_B = 1.5$ because the effect of slipping phenomenon, which can not expected to absorb energies with cyclic behavior, is estimated to strongly appear. It seems that this is observed when ${}_{B}R_{max}$ is larger than ${}_{R}R_{max}$, which is over 0.03.

However, the tendency is not approved with 10/50 record sets in condition that ${}_{D}R_{max}$ or ${}_{B}R_{max}$ is larger than ${}_{R}R_{max}$ as shown in Fig. 5.2 and ${}_{R}R_{max}$ is equal to 0.03 or less as shown in Fig. 5.1. Therefore, the seismic responses of the damper frames and the braced frames tend to become smaller than that of the non-braced frames in condition that ${}_{R}R_{max}$ is equal to 0.03 or less. Moreover, the braces and the dampers in earthquake-resistant design oriented to control of the maximum inter-drift story angle should not positively used in the condition that ${}_{R}R_{max}$ takes more than 0.03. In these circumstances, the seismic responses in condition that ${}_{R}R_{max}$ is equal to 0.03 or less are examined with respect to shown below.
1) ${}_{D}R_{max}/{}_{R}R_{max}$: the ratio of the seismic response of the non-braced frames to the damper frames.
2) ${}_{B}R_{max}/{}_{R}R_{max}$: the ratio of the seismic response of the non-braced frames to the braced frames.
The medians with respect to the lognormal distribution are show in Table 5.3. According to Table 5.3, the maximum inter-drift story angles tend to become smaller that the structure is not the non-braced frames but the braced frames because the all values of ${}_{B}R_{max}/{}_{R}R_{max}$ are smaller than 1.0. Viewing overall, ${}_{B}R_{max}/{}_{R}R_{max}$ tends to become larger than ${}_{D}R_{max}/{}_{R}R_{max}$ and the restraint the effects of displacement responses of the braced frames are inferior to the damper frames. The effects of the braces are larger, when λ_B becomes smaller and β becomes larger. In these conditions, the braces can demonstrate the effect equivalent to the dampers to set up the domain of proper parameters.

Table 5.3. Median Of $_{D}R_{max}/_{R}R_{max}$ And $_{B}R_{max}/_{R}R_{max}$

(a) 4-story frame

		Damper frame	Braced frame			
			λ_B			Average
			0.5	1.0	1.5	
β	0.2	0.795	0.949	0.979	0.993	0.974
	0.5	0.655	0.774	0.835	0.867	0.826
	0.8	0.615	0.697	0.772	0.806	0.759
Average		0.688	0.807	0.862	0.888	0.853

(b) 8-story frame

		Damper frame	Braced frame			
			λ_B			Average
			0.5	1.0	1.5	
β	0.2	0.623	0.692	0.718	0.741	0.717
	0.5	0.555	0.599	0.667	0.715	0.660
	0.8	0.584	0.557	0.601	0.664	0.607
Average		0.588	0.616	0.662	0.707	0.662

(c) 12-story frame

		Damper frame	Braced frame			
			λ_B			Average
			0.5	1.0	1.5	
β	0.2	0.691	0.806	0.845	0.861	0.837
	0.5	0.536	0.582	0.638	0.687	0.635
	0.8	0.607	0.540	0.577	0.604	0.573
Average		0.611	0.642	0.686	0.717	0.682

(d) Put data of 4-story, 8-story and 12-story frame

		Damper frame	Braced frame			
			λ_B			Average
			0.5	1.0	1.5	
β	0.2	0.703	0.816	0.847	0.865	0.843
	0.5	0.582	0.652	0.713	0.756	0.707
	0.8	0.602	0.598	0.650	0.691	0.647
Average		0.629	0.688	0.737	0.771	0.732

6. CONCLUSIONS

1. The model with simplified restoring force characteristics of that elastic stiffness of compressive element is the same as that of tensile element can appropriately represents the behavior of the actual braces.
2. The restraint effects of displacement responses of the braces tend to be conspicuous when the shear strength ratio becomes large or the slenderness ratio of buckling becomes small.

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