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A Study on Ultimate Seismic States of Multi-story Horizontally Mixed Structural System and Feasibility on Connection Joints

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Abstract

This study is concerned with horizontally mixed structure system that an existing old R/C structure is seismically retrofitted by addition of exterior steel frame. This system is suggested as seismic retrofitting method in Japan. And some previous studies related to its seismic response mitigation effects were conducted analytically. This study focuses on ultimate seismic state on its multi-degree of freedom system, and the feasibility study of connection joint between exterior steel frame and existing R/C building is investigated. To determine the design point which estimates the ultimate seismic performance, monolithic load patterns considering seismic load effect are adopted on pushover analysis under structural design procedure. Herein, this composite system consists of two various structural systems, and it is assumed that the complicated elasto-plasticity behaviors are presented during inelastic response. So this study suggests the envelope curve model which approximates the inelastic seismic response domain, and the load pattern is obtained by reference of this model. From comparison of proposed model and seismic response analysis, the predicted design points are corresponded each other. And also, it is observed that the predominant failure mode is changed on original and retrofitted state. So this paper suggests the retrofitting strategy which overall failure mode formation is guaranteed. Moreover, the actual connection method between steel frame and R/C building has been suggested. Herein, the required strength is calculated by reference of design points, and ultimate strength of this proposed connection compares with the requirement. From comparisons, it is confirmed that this joint shows sufficient strength.

Keywords: Column-to-beam strength ratios; Connection joint; Design point; Envelope curve model; Horizontally mixed structural system; Load distribution

Introduction

It has been discussed that old R/C institutional buildings, such as government offices or school buildings, have poor seismic resistant performance. In Japan, "An Act on Promotion of Seismic Retrofitting of Buildings" was enacted in 1995.

In these trends, "the horizontally mixed structural system" that an existing old R/C structure is strengthen by new steel frames attached is suggested as one of the seismic rehabilitation methods by The Japan Iron and Steel Federation (Figure 1). It aims that the retrofitted composite structure can expand its floor space and acquires architectural changeability and flexibility (Figure 2). So in terms of the addition of flexibility and conversion for existing buildings, the concern over the horizontally mixed structural system has risen increasingly in future. Iwabuchi and Ito et al. and Chiyo and Fujii et al. [1] conducted analytical researches on the response mitigation effect of this system. These researches showed that the connection joint between the existing old R/C structure and the steel frames needs to possess sufficient rigidity and strength under an earthquake motion (Figure 3). However, it has not investigated the ultimate seismic states and the retrofitting effect of this system in elasto-plasticity behaviors. Then this paper investigates ultimate seismic states of the multi-story horizontally mixed structural system and suggests the load pattern adopted in pushover analysis. Moreover, this paper investigates whether the connection joint is effective in the ultimate seismic state [2].

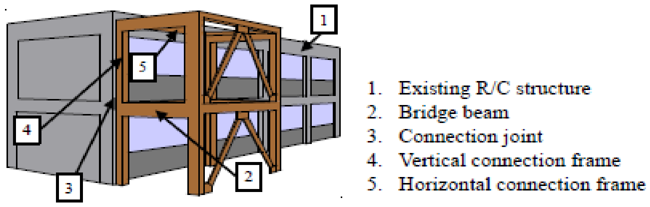

Figure 1: Horizontally mixed structural system.

(Images from www.mext.go.jp)

Figure 2: Architectural changeability.

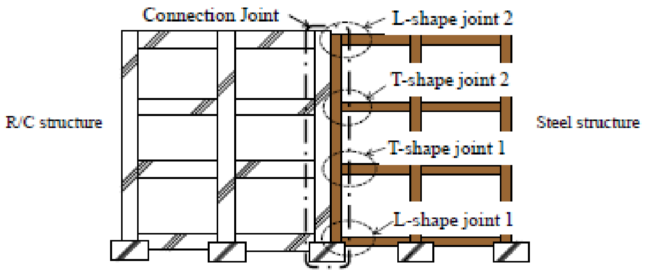

Figure 3: Connection joint.

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Envelope Curve Model

Design point and load distribution

This study adopts modal load coordinate in order to investigate the design point and the load distribution in elasto-plasticity response behaviors (Figure 4). Forces in normal coordinate are transformed into forces in modal load coordinate by Equation 1.

$$\{f\} = \left[\Phi^{T}\right]^{-1}\{r\} \tag{1}$$

Where,

{f }: restoring force vector in normal coordinate.

[Φ]: participation matrix.

{r}: restoring force vector in modal load coordinate.

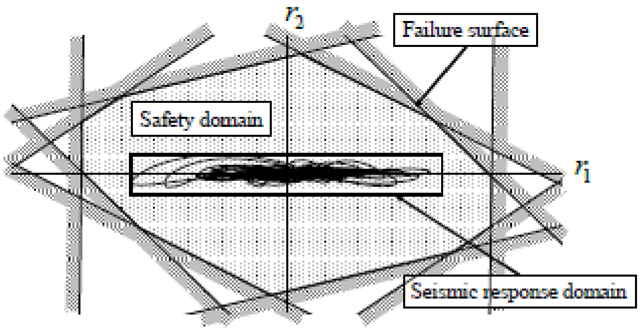


Figure 4: Failure mode in modal load coordinate.

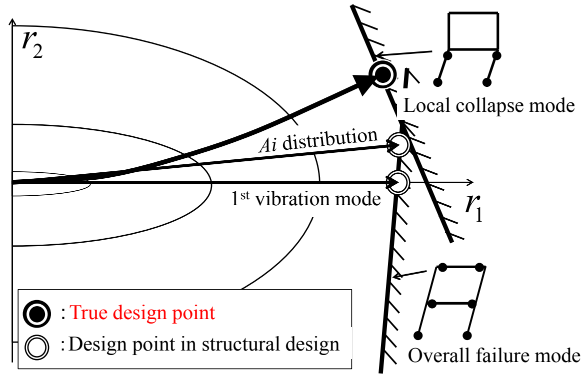


Figure 5: Conceptual diagram of design points.

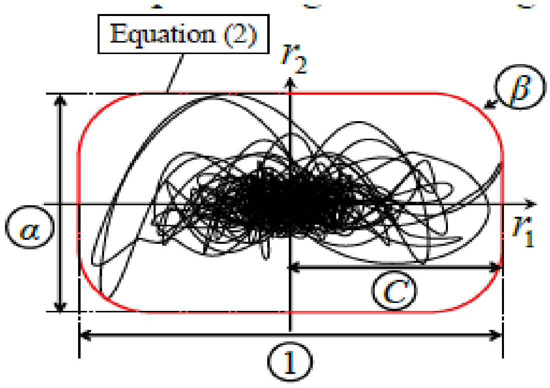
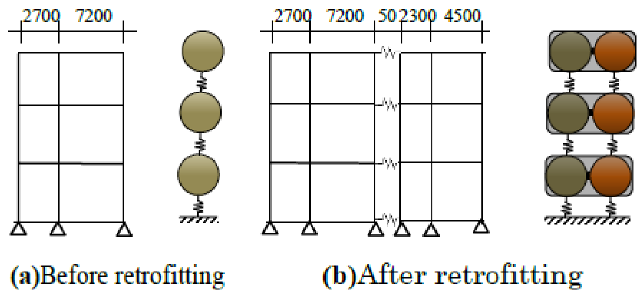


Figure 6: Conceptual diagram of envelope curve model.



(a)Before retrofitting (b)After retrofitting

Figure 7: Analytical model.

In normal structural seismic design, the pushover analysis is often performed, and a monolithic load pattern such as Ai distribution is adopted. However, in the horizontally mixed structural system, it is assumed that the complicated inelastic behavior is presented because both the hysteresis characteristics of R/C and steel structure exist simultaneously. So it is likely that this effect is considered on load pattern adopted on limit state analysis during limit state design procedure (Figure 5) [3].

Definition of envelope curve model

This study suggests the envelope curve model which approximates the inelastic seismic response domain. This model is described by Equation 2.

$$r_1^{\beta} + \left(\frac{r_2}{\alpha}\right)^{\beta} = C^{\beta} \tag{2}$$

Where,

α: ratio of 2nd mode component to 1st mode component.

β: constant representing roundness of the curve.

C: length of major axis.

The input level of seismic waves is assumed gradually from a range of elastic to a range of forming failure mechanisms. The values of α and β are determined so that the envelope curve model for each seismic wave can describe (Figure 6).

Outline of seismic response analysis

The analytical model is the 3-story horizontally mixed structural system composed of the R/C structure and exterior steel frame, assuming 3-degree of freedom system (Figure 7). Here, the connection joint possesses sufficient rigidity and strength, and R/C structure and connection frame behave in a unified fashion. And it is assumed that the mass of each floor is sum of R/C structure and steel frame. The restoring force characteristics of R/C structure and steel structure are Takeda model and perfect elasto-plasticity model respectively (Figure 8). Considering aging deterioration, this study regards concrete strength as small value: F_c = 18 N/mm². The weight and vibration characteristics of this model building and the seismic waves adopted in this analysis are summarized in Table 1. The sum of 1st mode effective mass and 2nd mode effective mass in the analytical model is more than 90% of the total, so this study excludes 3rd mode component from consideration [4-6].

Analytical results

The six failure modes are expected in the analytical model frame as shown in Figure 9. The transitions of the value of α and β in each input wave level are shown in Figures 10 and 11.

Figure 12 shows an example of the load path obtained from seismic response analysis and the plastic surface in modal load coordinate. Plastic surfaces in Figure 12 and failure modes in Figure 9 correspond respectively, and the seismic response domain under seismic response reaches plastic surface (Figure 13).

This study adopts large input level (120 kine) that was observed at The South Hyogo Prefecture Earthquake in 1995. From the results of Figures 10a and 11a, α tends to rise as input level becomes large and converge at about 0.25 in all kinds of seismic waves. Comparing the result of the R/C structure before retrofitting and the horizontally mixed structural system under same input level, there is little difference between two values of α. Therefore, it is confirmed that there is little effect of higher vibration mode on retrofitting state. From the results of Figures 10b and 11b, the relation β under the elastic response is not confirmed; however, β under the elasto-plasticity response takes averagely about 3.0. From the above, the seismic response domain of the horizontally mixed structural system in the ultimate seismic state can be described by the envelope curve model using α =0.25, β =3.0, and the design point is identified by determination of value of C.

Investigation of Design Point

Comparison of design point and failure mode

Figure 14a shows the load path during seismic response in case of El Centro NS (100 kine) on original state (Figure 7a). Figure 14b shows the load path during seismic response in case of same input wave

Members and weight of building

Structure	Members	Sectional shape	Material	Weight of the building [t]		
				1st story	2nd story	3rd story
R/C	Column	550×550 (12-D19)	Reinforcing bar: SD345	33.9	36.5	36.5
	Beam	300×600 (10-D19)				
	Footing Beam	300×1200 (12-D19)				
Steel	Column	□-300×300	BCP235	4.2	9.3	9.3
	Connection frame	H-300×300×12×15	SN400			
	Beam	H-400×200×7×11				
	Footing Beam	H-600×200×11×17				

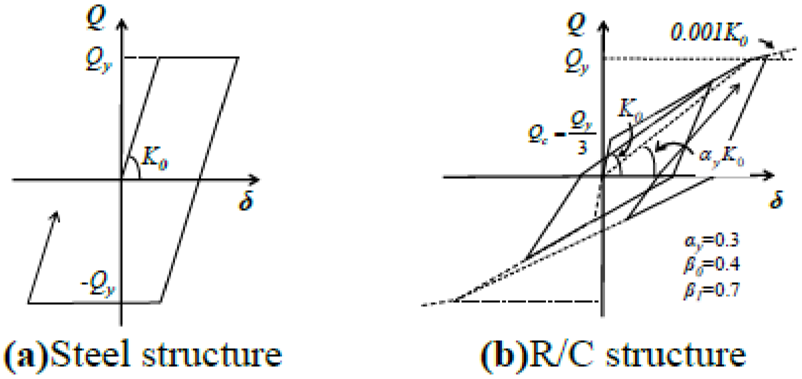
Vibration characteristics

Mode	Before retrofitting		Horizontally mixed structural system	
	Effective mass [t]	Natural period [s]	Effective mass [t]	Natural period [s]
1	91.3	0.289	111.4	0.282
2	11.3	0.111	13.5	0.109
3	4.2	0.078	4.9	0.078

Input of seismic waves

No	Seismic waves	Maximum acceleration [gal]	Duration time [s]
1	El Centro 1940 NS	314.7	30.0
2	El Centro 1940 EW	210.1	
3	Taft 1952 NS	152.7	
4	Taft 1952 EW	175.9	
5	Tohoku 1978 NS	258.2	
6	Tohoku 1978 EW	202.5	
7	JMA Kobe 1995 NS	818	
8	Fukiai 1995 NS	804.6	
9	Hachinohe 1968 NS	225	
10	Hachinohe 1968 EW	182.9	

Table 1: Detail of analysis.



(a)Steel structure (b)R/C structure

Figure 8: Restoring force characteristics.

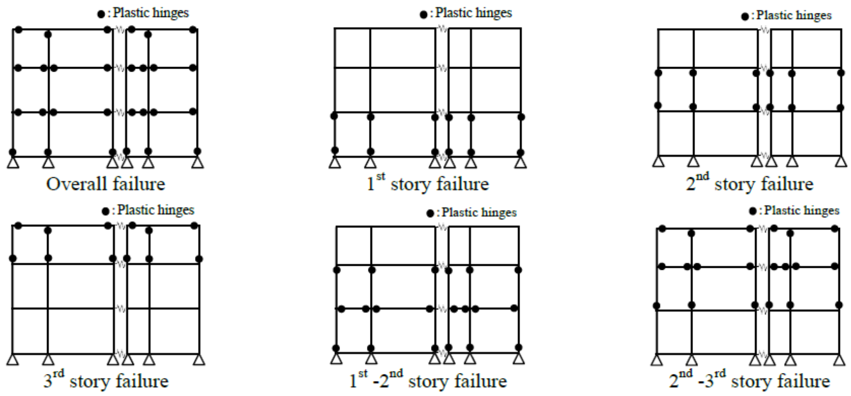


Figure 9: Failure mode.

(a)Value of α. (b) Value of β

Figure 10: Transition of constants before retrofitting.

Figure 11: Transition of constants after retrofitting.

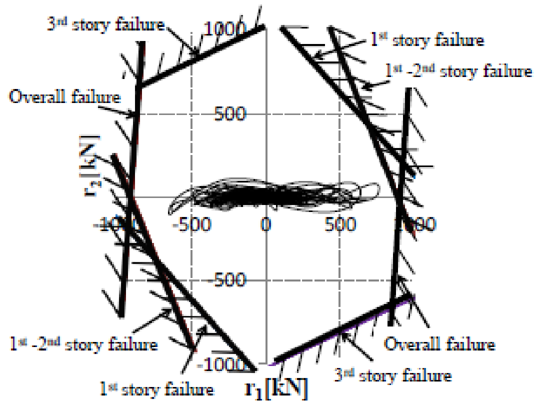


Figure 12: Load path and failure surface (40 kine).

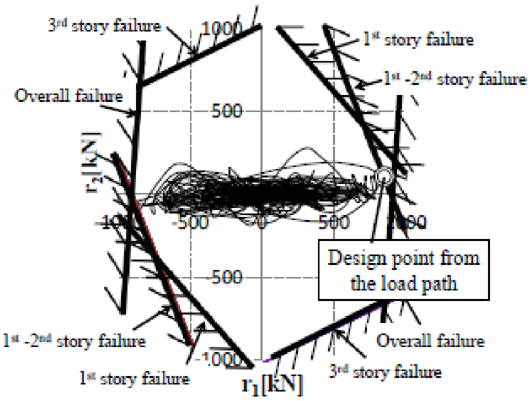
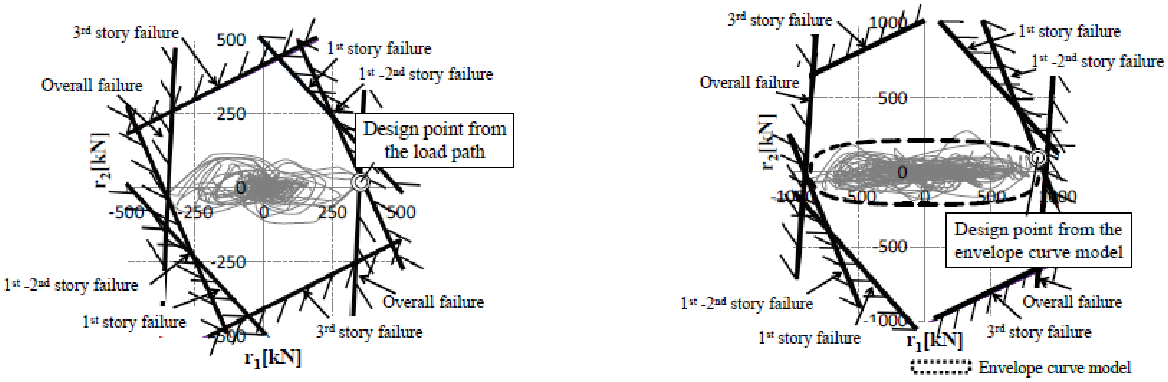


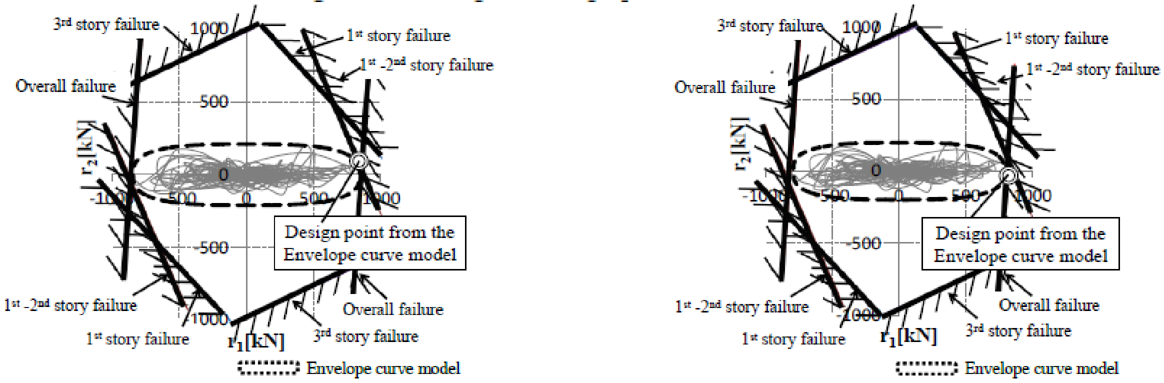
Figure 13: Load path and failure surface (150 kine).



(a)Before retrofitting

(b)After retrofitting

Figure 14: Change of design point and failure mode.



(a) Column-to-beam strength: 1.50

(b) Column-to-beam strength: 1.75

Figure 15: Relationship between column-to-beam strength ratios and design points.

for the horizontally mixed structural system. Comparing two cases, it is confirmed that these design point does not correspond with each other. And also, in case of other seismic input, these transitions of failure mode are confirmed. From these results, it can be said that the predominant failure mode moves by retrofitting with the horizontally mixed structural system.

Retrofitting plan of steel structure

Now in the seismic design, it is desirable that buildings form overall failure mechanism in the ultimate seismic state. Then the required performance of the exterior steel structure for forming the overall failure mechanism after retrofitting is investigated.

This paper focuses on the relationship between the design points and the plastic surfaces when the column-to-beam strength ratio of steel structure changes. This investigation sets two column-to-beam strength ratios: 1.50 and 1.75 by changing only the beam's strength. Figure 15 shows the result of the seismic response analysis in case of column-to-beam strength ratios 1.50 and 1.75. From these results, in

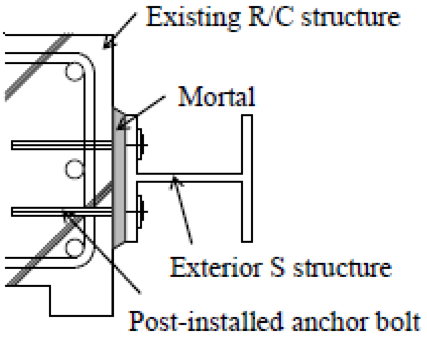


Figure 16: Direct-connection technique.

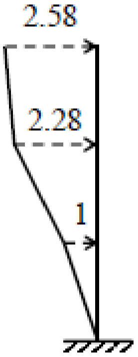


Figure 17: Load distribution.

Parameter		T-shape connection Joint	L-shape connection Joint
Tensile force on post installed anchor bolts [kN]		63.1	118.2
Tensile strength [kN]	Axial-yield of anchor bolts	197.7	
	Cone-type failure	548.4	
	Adhesion section failure	208.6	
Joint coefficient *αc*		3.13	1.67

Table 2: Value of tensile forces on connection joint.

case of column-to-beam strength ratios 1.50, the design point is on the 1st -2nd story failure. On the other hands, in case of column-to-beam strength ratios 1.75, the design point is on the overall failure.

From the above, it can be said that adjusting the column-to-beam strength ratios of steel structure can control the failure mechanism of the horizontally mixed structural system in the ultimate seismic state.

Feasibility Study of Connection Joint in Ultimate Seismic States

Outline of investigation of connection joint

Mitomi et al. suggested the concrete connection joint techniques, and the effectiveness of this method is shown experimentally. However, it is likely that the stress on the connection in the ultimate seismic state is very complicated. Therefore, pushover analysis is performed for investigating whether the connection joint is effective in the ultimate seismic state. Herein, the load distribution is calculated from the design point by the envelope curve model.

Outline of the connection joint

In this analysis, H-300×150×7×11 (SS400) is used for the beams in the exterior steel structure; the other members are the same as the analytical model (Figure 7b). The direct-connection technique (Figure 16) is adopted for the connection joint between the R/C structure and the steel structure, and D19-SD345 is adopted for post-installed anchor bolts.

The seismic response analysis is performed for this analytical model, and the collapse load and the load distribution is gained as shown in Figure 17. The pushover analysis for the investigation of the connection joint is adopted in these conditions of the ratios and design points.

Result of the pushover analysis

From the results of the pushover analysis, the maximum tensile force at the each bridge beam (Figure 2) is calculated as shown Table 2, following the evaluation method suggested by Mitomi et al. The tensile strength of the three collapse mode with post-installed anchor bolts is also shown in Table 2. It is confirmed that the joint coefficient αc is more than 1.5 in each joint. Therefore, the connection joint has sufficient strength.

Conclusions

This study investigates the design point and the load distribution of the multi-story horizontally mixed structural system, and the feasibility of the connection joint in the ultimate seismic state. The main conclusions are shown below:

1. The envelope curve model that approximates the inelastic seismic response domain in the horizontally mixed structural system is suggested. Moreover, by identifying the design in the ultimate seismic state from this model, the failure mechanism and the load distribution are investigated.

2. It is shown that the failure in the ultimate seismic state mode can move after retrofitting. Adopting the relevant column-to-beam strength ratios of the steel structure, the failure mechanism can be controlled.

3. The feasibility of the connection joint in the ultimate seismic state. Herein, adopting the load distribution at the design point, pushover analysis is done. Then it is shown that the connection joint technique suggested by Mitomi et al. can be effective in the ultimate seismic state.

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