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Ultimate Seismic Limit State and Repairability of Multi-story Steel Frames Subjected to Severe Earthquake Loads

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Abstract

In the general seismic design, the building structures are required to have adequate strength to resist the applied loads. However, it has been reported that severe disasters, such as great earthquake, cause serious damage to a lot of building structures around the world. Based on these experiences, there are many discussions about resilience, repairability or recovery for damaged building structures.

It can be said that the criteria of the repairability for damaged building structures are estimated by the residual seismic resistant performance against an aftershock or future earthquake, the existence of reconstruction technique and its possibility under the damaged structures, economic loss or reasonable construction cost, and necessity and urgency of repair. Furthermore, in order to evaluate the structural performance on repaired building structures, the recovery on repaired members becomes essential index, while it is also important consideration that repairing damaged members may influence the performance of the whole of the building structure after repair.

In the case of steel structures, several studies have proposed repair methods for damaged steel members, and these studies have investigated the recovery of the structural performance on the repaired members. Based on these studies, a technical guideline and design procedure for repairing damaged building structures has been published in Japan. However, little study has been reported on investigating accurately the relationship between repair methods and the recovery of the structural performance on the repaired structures.

This study aims to clarify the repairability and recovery on steel framed structure. Therefore, the relationship between repair method and the seismic resistant performance on repaired steel framed structure is studied analytically, and it is try to evaluate the repairability and the recovery on steel framed structures.

In this paper, analytical study is conducted to investigate the repairability of multi-story steel frames by limit analysis and seismic response analysis, and the optimum repair strategy against future earthquakes is discussed.

First, the multi-story steel frame is designed according to Japanese Seismic Design Standard as analytical model. Second, the ultimate seismic limit state and structural damage which may occur under great earthquakes are calculated. Third, based on past research of repair methods, several repairing strategy are planned and the recovery of the structural performance of each strategy are calculated. Finally, the optimum repairing strategy is explored by comparing each strategy.

From the analytical results, it is observed that the structural performance of repaired steel framed model are enhanced if the adequate repairing strategy is adopted.

Keywords: Steel Frame, Repairability, Ultimate limit State

1. Introduction

In the general seismic design, the building structures are required to have adequate strength to resist the applied loads. However, it has been reported that severe disasters, such as large earthquake, cause a various type of terrible damage to building structures around the world. In recent years, based on these experiences, there are many discussions about new keywords such as “resilience”, “repairability” or recovery for damaged building structures.

Bruneau and Reinhorn [1] have mentioned the new concept of structural resilience (see Fig.1). And they have expressed a resilient system as follows: “1. Reduced failure probabilities, 2. Reduced consequences from failures, in terms of lives lost, damage, and negative economic and social consequences, 3. Reduced time to recovery (restoration of a specific system or set of systems to their “normal” level of functional performance)”.

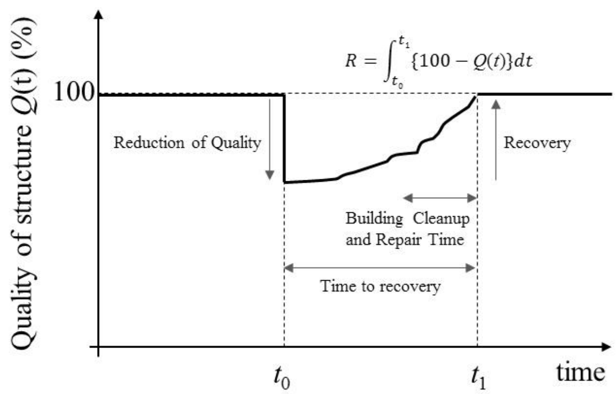


Fig. 1 – Seismic resilience concept (Bruneau and Reinhorn, 2006)

Considering the sustainable use of damaged building structures after severe earthquake shock, the building structures should keep sufficient structural performance and damaged members are repaired by using suitable repair methods.

It can be said that the criteria of the repairability for damaged building structures are estimated by the residual seismic resistant performance against to aftershock or future earthquake, the existence of reconstruction technique and its applicability to the damaged structures, economic loss or reasonable construction cost, and necessity and urgency of repair. Furthermore, in order to evaluate the structural performance on repaired building structures, the recovery of the structural performance of repaired members becomes essential index, while it is also important to consider that repairing damaged members may influence the performance of the whole of the building structure.

Tanaka et al [2] have proposed repair methods for damaged steel members, and have investigated the recovery of the structural performance on the repaired members experimentally. Based on these studies and other past researches, a technical guideline and design procedure for repairing damaged building structures has been published in Japan [3]. However, little study has been reported on investigating accurately the relationship between repair methods and the recovery of the structural performance on the repaired structures.

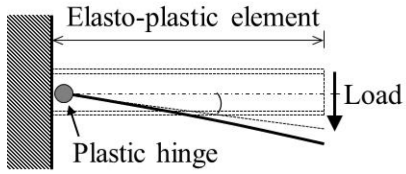
Authors have been investigating the effectiveness of existing repair methods for damaged steel members. Mori et al [4] have clarified experimentally the seismic performance of repaired steel members and have proposed an analytical model of repaired steel members. Furthermore, analytical study has been conducted to evaluate the structural repairability of low-rise moment resisting steel frame after severe earthquake shock [5]. As a result of analytical study, a concept of the structural repairability evaluation method has been suggested.

In this paper, analytical study is conducted to investigate the ultimate seismic limit state of repaired multi-story steel frame. First of all, a method to ultimate seismic limit state of multi-story steel frame, which has suggested in previous study, is presented. Second, the multi-story steel frame is designed according to Japanese Seismic Design Standard as analytical model. And the ultimate limit state and structural damage which may occur under earthquake response are analytically calculated. Third, by means of the repair methods and the analytical model of repaired steel frames which has suggested in previous research, several repairing strategy are planned and the recovery of the structural performance of each strategy are calculated. Finally, the optimum repairing strategy is discussed by comparing the strategies.

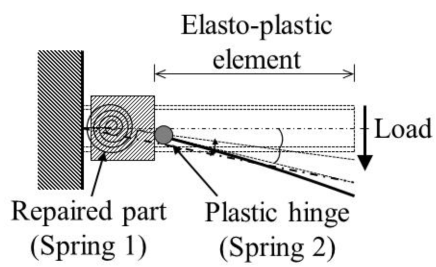
2. General description of ultimate seismic limit state of repaired steel frames

2.1 Analytical model for repaired steel members and frames

Previous report [4] has investigated the applicability and the recovery of a repair method for damaged steel members as an example of actual technique which is proposed in Japanese repair guideline. This research has also suggested an analytical model of the repaired steel member (see Fig.2 (b)). This analytical model has two springs; one spring expresses the behavior of repaired part (Spring 1), the other spring expresses the inelastic behavior of the elasto-plastic element (Spring 2). This model can evaluate the ultimate strength of repaired model. And also this analytical model can simulate the inelastic behavior.



(a) Original state



(b) Repaired state

Fig. 2 – A repair method of steel members and analytical model [4]

Previous report [5] has suggested an analytical method to simulate the inelastic behavior of steel frame by using above analytical model (see Fig.3). This report also has outlined the ultimate seismic limit state of repaired low-rise steel frame and has suggested the evaluation method of the recovery (below mentioned).

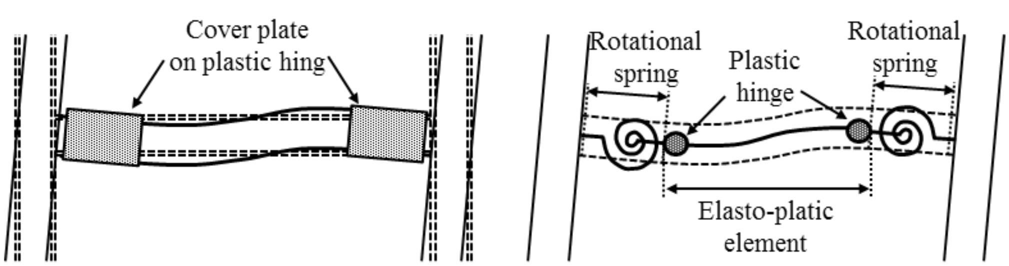


Fig. 3 – Modeling of repaired steel frame [4]

2.2 Evaluation of ultimate limit state

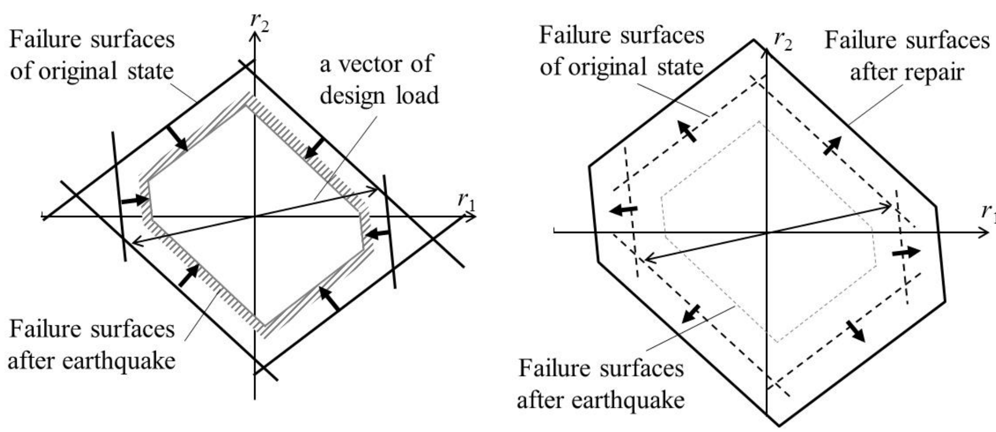
Ultimate seismic limit state of steel building structures is influenced by various variables, such as strength, stiffness, vibration characteristics, and the stress distribution generated under seismic loads. Then, in this paper, the recovery of structural performance after repair is discussed by comparing plastic failure surfaces and load distribution.

Plastic failure surfaces of each collapse failure mode which may occur under severe earthquake, such as whole story collapse and local story collapse, are calculated by the plastic hinge analysis as following:

$$\Sigma f_i d_i = \Sigma M_k \theta_k \tag{1}$$

where, f_i and d_i are the restoring force and displacement of the i-th story, M_k and θ_k are the moment carrying capacity of the k-th plastic hinge.

Fig.4 shows an example of plastic failure surfaces versus a load distribution. When plastic hinge and local buckling are formed at the members end with the strength deterioration, the failure surfaces shift to the inside and the safety of the building structure reduces against seismic load (see Fig.4 (a)). Considering sustainable use of these damaged building structures, it is necessary to repair the damaged members. Fig.4 (b) illustrates an outline of the failure surface after repair. Failure surfaces shift to the outside and the safety of the building structure increases because the strength recovers by the repair. By using this evaluation method of ultimate seismic limit state, by comparing with failure surfaces and seismic load distribution, the appropriate repair strategy can be discussed.



(a) Original state and Damaged state (b) After repair

Fig. 4 – Plastic failure surface vs. Load distribution

3. Recovery of structural performance on multi-story steel frame

To investigate the efficacy and applicability of the above method, the repairability and the recovery of multi-story moment resisting frame is evaluated by the method.

3.1 Model setup

Detail of frame model and member sizes are shown in Fig.5. This model has constructed with reference to Japanese Limit State Design guideline [6]. The cross sections of all beams are assumed to be H section, and the cross sections of all columns are assumed to be rectangular hollow section. The moment carrying capacity of beams are less than the one of columns, therefore, it is expected that plastic hinges will form at beams end around each beam-to-column connection, and beam yielding collapse mechanism will generate. Herein, the yield strength of steel is assumed to be 235 MPa

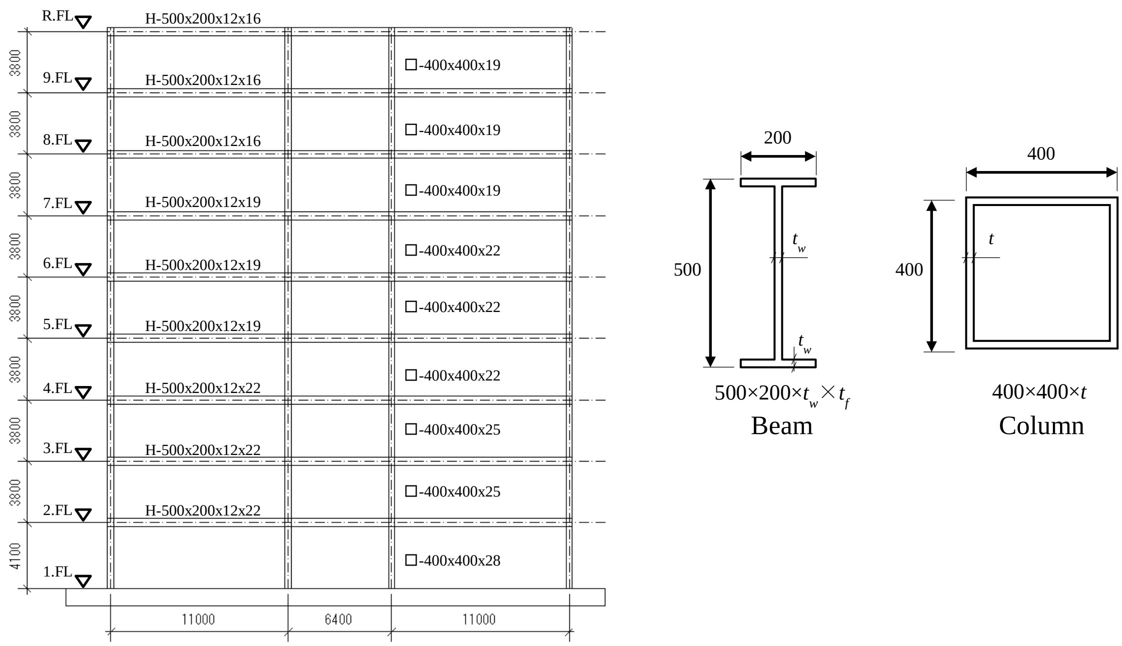


Fig.5 – Model building: 9 story steel frame

Table 1 – Description of analytical model

<table>
<tr><th rowspan="2">Story</th><th rowspan="2">Height [m]</th><th rowspan="2">Weith [kN]</th><th colspan="2">Cross section [mm]</th></tr>
<tr><th>Column</th><th>Beam</th></tr>
<tr><td>1</td><td>4.1</td><td>857</td><td>400×400×28</td><td>-</td></tr>
<tr><td>2~3</td><td rowspan="6">3.8</td><td>844</td><td>400×400×25</td><td rowspan="2">500×200×12×22</td></tr>
<tr><td>4</td><td>844</td><td rowspan="2">400×400×22</td></tr>
<tr><td>5~6</td><td>844</td><td rowspan="2">500×200×12×19</td></tr>
<tr><td>7</td><td>844</td><td rowspan="2">400×400×19</td></tr>
<tr><td>8~9</td><td>1190</td><td rowspan="2">500×200×12×16</td></tr>
<tr><td>R</td><td>-</td><td>-</td><td>-</td></tr>
</table>

Table 2 – Vibration characteristic

Mode	Modal mass [%]	Vibration period [s]
1	79.5	2.19
2	10.6	0.72
3	4.2	0.40
4	2.2	0.26
5	1.4	0.19
6~9	(omitted)	

Table.1 and Table.2 show the properties of the analytical model. Herein, modal mass means effective mass of each vibration mode, and Table.2 shows the ratio of modal mass to total mass of the frame. In case of this model, the first-order vibration mode and second order vibration mode occupies most of the total mass. Therefore, in this paper, analytical study has conducted by first-order and second-order vibration mode on behalf of all vibration modes.

3.2 Analytical results

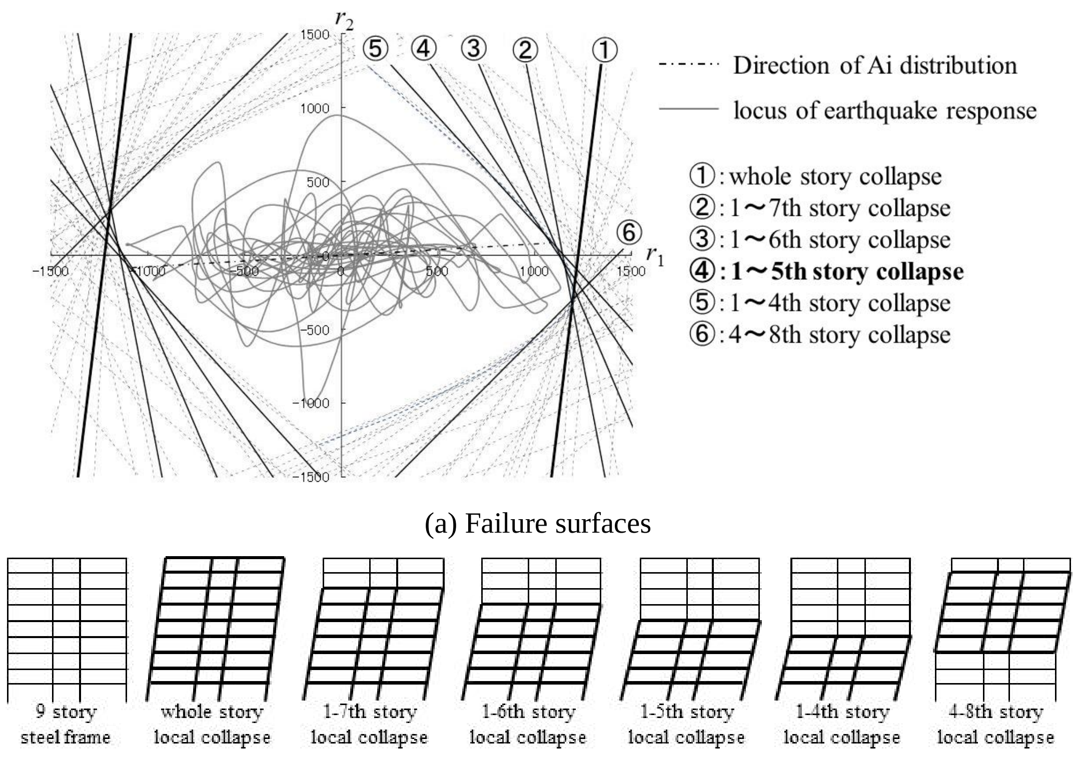
3.2.1 Failure mode of original state

Fig.6 shows the failure surfaces of each collapse in modal space. Herein, r_1 means the modal restoring force of first-order vibration mode, r_2 means the modal restoring force of second-order vibration mode, the restoring forces can be transformed to the modal restoring force as following equation:

$$\{r\} = [\Phi^T]\ \{f\} \tag{2}$$

Where, $\{f\}$ is the restoring force vector, $\{r\}$ is the modal restoring force vector, Φ is modal participation matrix which is obtained from the modal analysis. This figure also shows an example of a locus of restoring force under earthquake response, and shows the distribution of design load, which called “Ai distributed lateral load pattern” in Japanese Seismic Design Code.

Although the analytical frame has been designed in accordance with a strong column-weak beam approach, the five-story local collapse mode predominates under Ai distribution and the distribution based on first-order vibration mode (the direction of lateral axis) as shown in Fig.6.



(a) Failure surfaces

(b) Collapse modes

Fig.6 – Failure surfaces in modal space and Collapse modes

3.2.1 Failure mode after repair

From the result of the previous section, it has been observed that 5-story local collapse mode predominates during severe earthquakes. In this mechanism, plastic hinges form at the ends of the columns of 1st and 5th floor, and at the ends of the beams between 1st and 5th floor. Therefore, the analytical model of repaired frame is modeled as shown in Fig.7.

In the case of this repaired frame, the ultimate strengths of each repaired member increases based on the shift of the position where plastic hinges form (refer Fig.2 and 3). Herein, the lengths of the repair part at each beam are determined according to a method which estimates the length of local buckling of H-shaped steel members (276mm), and the lengths of the repair part at the column are assumed to be equal with the flange width (400mm). The following strategies are the parameter of analytical study;

i) The bending stiffness of the repaired parts is equal to original member. And the plastic hinges don't form at the repaired parts.

ii) The bending stiffness of the repaired parts becomes larger than the original state: the repair parts become rigid. And the plastic hinges don't form at the repaired parts.

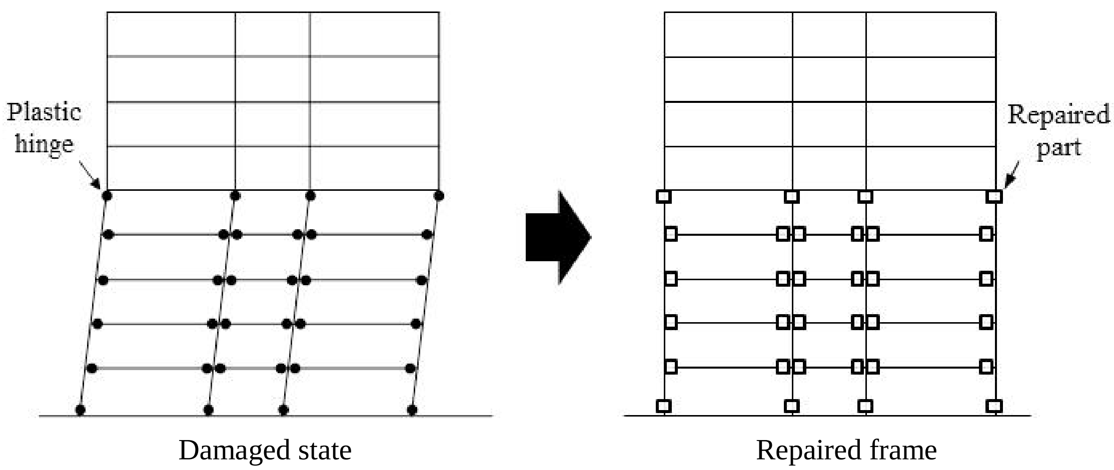
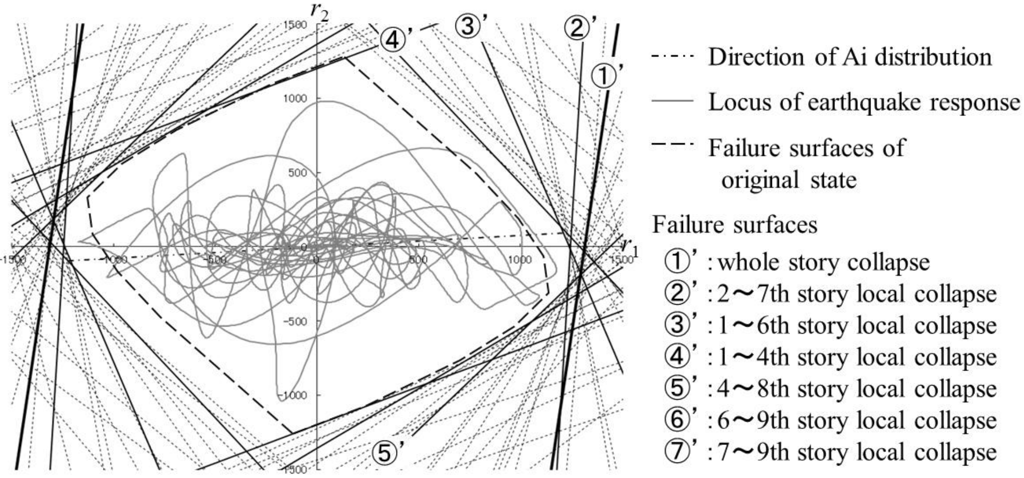


Fig.7 – Detail of damaged frame and analytical model of repaired frame

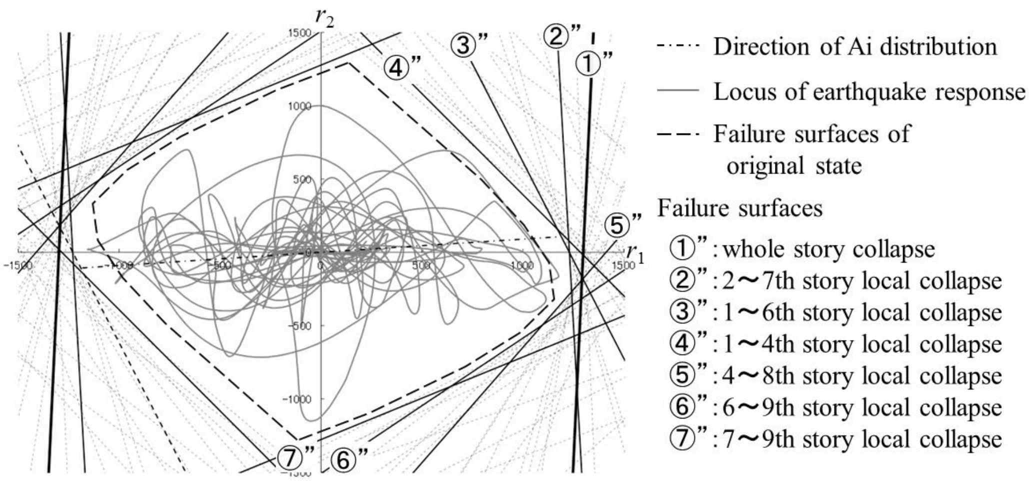
Fig.8 shows the failure surfaces of repaired frame in modal space and illustrates the possible failure modes under severe earthquake. From the results of Fig.8 (a), in the case of strategy i), the failure surfaces which are related with the repaired members shift to the direction of the outside, and the safe zone enclosed by failure surfaces extend. However, under the influence of strengthening the members, it tends to generate more local collapse than original state: it can be confirmed that 4-story collapse mode predominates.

From the results of Fig.8 (a), in the case of strategy ii), the failure surfaces which relate to the repaired members, shift to the direction of the outside, while it can be confirmed that the slope of the failure surfaces are changed because the modal participation matrix is changed, which caused by the change of the stiffness distribution in the repaired frame. In this case, it is considered that the estimation of the failure mode which generates under severe earthquake becomes harder than the strategy i).

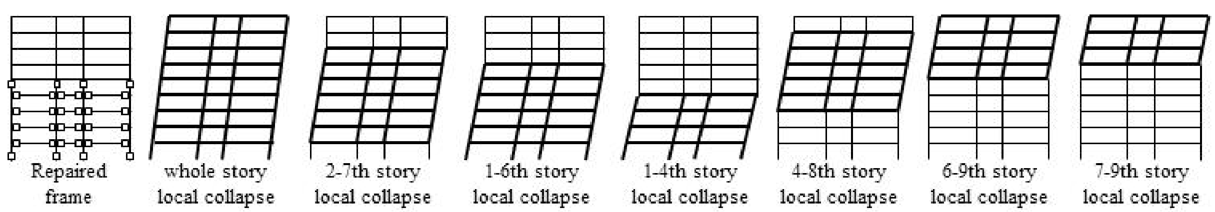
Although the load carrying capacity of the repaired frame is recovered by the repairs, in both cases, it can be said that to choose appropriate strategy of the repair is important because the frame which the local story collapse occurs typically has poor energy absorption capacity compared with the frame which the whole story collapse occurs.



(a) Failure surfaces in Strategy i)



(b) Failure surfaces in Strategy ii)



(c) Collapse modes

Fig.8 – Failure surfaces of the repaired frame in modal space

4. Conclusions

This paper outlines a concept of the method to estimate the ultimate limit state of multi-story moment resisting steel frame under severe earthquake, and suggests the method to evaluate the structural performance of repaired frames after earthquake. This suggested method can visualize the ultimate limit state of the original frame and the repaired frame in modal space by using plastic hinge analysis, and the strategies of repair plans can be discussed according to the ultimate limit state with load distributions.

To investigate the influence caused by repairing damaged members on the ultimate limit state of the repaired frame, an analytical study has been conducted against the 9 story moment resisting steel frame by using suggested method. The results of analytical study have indicated that collapse modes which have not been expected in original frame may generate to the repaired frame under severe earthquakes because of the change of the failure surfaces and the load distributions. Furthermore, the change of the failure surfaces also depends on the vibration characteristic after repair, therefore it can be said that when the strategies of the repair plan are discussed, it is important to investigate the influence caused by repairing damaged members.

7. References

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