

Repair Method of Damaged Steel Framed Structures and Ultimate Seismic State of Repaired Steel Frames

Takumi Ito* and Kenjiro Mori

Department of Architecture, Tokyo University of Science, Japan

Abstract

Recently, a lot of building structures have been experienced severe natural disasters, and it was reported that various types of terrible collapse mode were occurred. And also, there are many discussions about repairability and recovery on damaged buildings over the world. In particular, there has been focused on new keyword as Resilience in any field including structural engineering. In Japan, a technical guideline for repairing damaged buildings has been established. However, the applicability and feasibility of repair method and recovery has not been well reported. Herein, to investigate the recovery and ultimate seismic state of repaired steel framed structures, experimental and analytical studies are conducted. Herein, the actual repairing technique for steel framed structure is suggested. During experimental study, the damaged steel member is reproduced by loading tests with consideration of past reports of mega-earthquake disasters. The next, the damaged portion is repaired by proposed method by use of steel-cover plate technique. After this repair process, the loading test is done again. And the recovery of structural performance is estimated by comparison of original and repaired state. From the test results, it is confirmed that the strength and ductility are improved after repair. Furthermore, the analytical model and restoring force characteristics of repaired steel member are suggested by observation of ultimate behavior during loading test. Here, the purpose on seismic design is to guarantee the overall failure mode formation on frames. So, the structural demand of strength and rigidity and column-to-beam strength ratio on repaired state are discussing analytically.

Keywords: Restoration method; Repairability; Seismic ultimate state; Steel frame

Introduction

In Japan, a lot of building and infrastructure have been experienced severe earthquake disaster since the dawn of history. Recently, there are many discussions about repairability and recovery for these damaged building structures, in particular, after 2011 Great East Japan Earthquake. There has been focused on the new keyword "Resilience", which presents the revival potential or function maintenance of damaged structures and Bruneau and Reinhorn [1] have mentioned the concept of structural resilience, and high resilience system is 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. The technical guideline [2] has been published to repair the various kinds of structures in Japan. Particularly for steel structures, it suggests a repairing method based on the past experimental researches [3], however the number of such past researches was restricted. And also, few past research on repairability and recovery of steel structures limit to Japan have been conducted. Furthermore, authors have done the experimental studies to investigate the repairability of repaired H-shaped steel members [4] and also, an analytical model of repaired H-shaped steel member has been proposed. Its analytical model can evaluate the fundamental performance and hysteresis behavior.

General Description of Damaged Steel Frames and Restoration Method

Failure mode of steel frames after severe earthquake motions

In Japan, the various kinds of failure mode on building structures have been observed and reported during past earthquake disasters in Japan, such as the Great Hanshin-Awaji Earthquake 1995, the Great East Japan Earthquake 2011. And then, the Japanese technical guideline [2] has been published, and which suggests the estimation method of damage and restoration method for damaged members. Herein, the restoration method of damaged steel framed structures is explained.

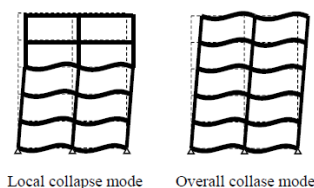
Restoration method of steel members

Outline of restoration method for damaged steel members:

When the great earthquake motions occur, a various kind of failure mode is generated on the steel framed structures as shown in Figure 1. After the plastic hinge or local buckling is formed on the members, it is desirable to repair this damaged portion. And the example of restoration method on Restoration Manual is summarized as shown in Figure 2.



(a) Example of damaged steel frames (the Great Hanshin-Awaji Earthquake, Japan, 1995)



(b) Failure mode of steel frame

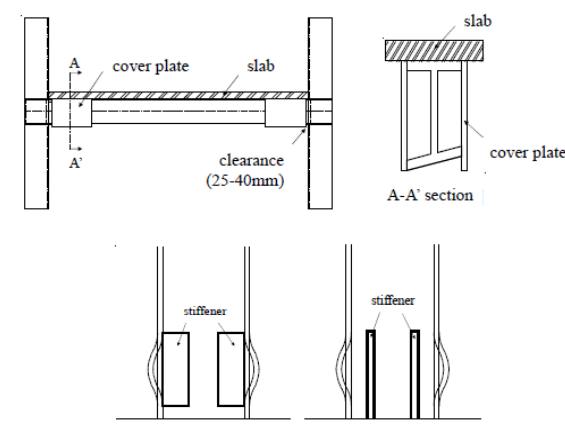
Figure 1: Failure mode of steel frames during earthquake.

*Corresponding author: Takumi Ito, Department of Architecture, Tokyo University of Science, Japan, Tel: +81 3-3260-4271; E-mail: t-ito@rs.kagu.tus.ac.jp

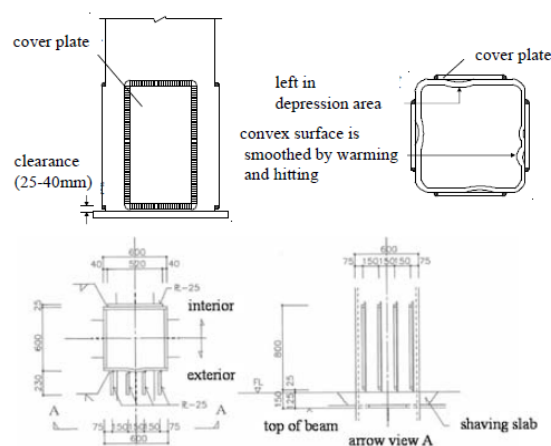
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(a) H-shaped section steel members



(b) Box-type steel members

Figure 2: Examples of restoration method of damaged steel members.

Restoration method and repairing process on damaged H-shaped steel members: From the Restoration Manual, some repair methods for damaged H-shaped steel members are indicated as shown in Figure 2a. Herein, the diagram of actual repair method is illustrated in Figure 3. This method is as follows; the damaged portion is repaired by welding cover plates to the flanges with local buckling, and a clearance of 25 mm is opened between the end plate and the edge of the cover plates. The thickness of the cover plates is equal to that of the flange plate of the H-shaped steel members.

Restoration method and repairing process on damaged Box-shaped steel members: From the Restoration Manual, some repair methods for damaged box-type steel members are indicated as shown in Figure 2b. This method is as follows; the surface of damaged portion is corrugated, and this convex surface is smoothed by warming and hitting. The cover plates are attached by welding, and a clearance of 25 mm is opened between the end plate and the edge of the cover plates. The thickness of the cover plates is equal to the box type steel member.

Analytical Method for Repaired Steel Member and Frame

Analytical model of steel member after repair

H-shaped steel member: The authors have conducted the experimental

study to investigate the applicability and reparability of the restoration method for damaged H-shaped steel member as shown in Figure 3. From the test results, the ultimate states of test specimens were observed as shown in Figure 4. And the test results of moment-angle relation were obtained as shown in Figure 5, which compares the original state and repaired member. From the test results, the ultimate state behavior was observed as follows; on the repaired steel member, the plastic hinge were formed to the side of cover plates, and the repaired portion with cover plate behaved as rocking of rigid body. And also, the strength and ductility of repaired member were improved by

Comparison with original state and damaged member without repair. From these considerations, the analytical models of H-shaped steel member of original and repaired state were established as shown in Figure 6. And also, the hysteresis models during inelastic cyclic loading were applied with Skeleton Shift Model as shown in Figure 7. And the comparison of test results and analytical results are presented in Figure 8, and it can be said that the proposed analytical model can chase the test results well.

Box-type steel member: The authors have conducted the experimental study to investigate the applicability and reparability of the restoration method for damaged Box type steel member as shown

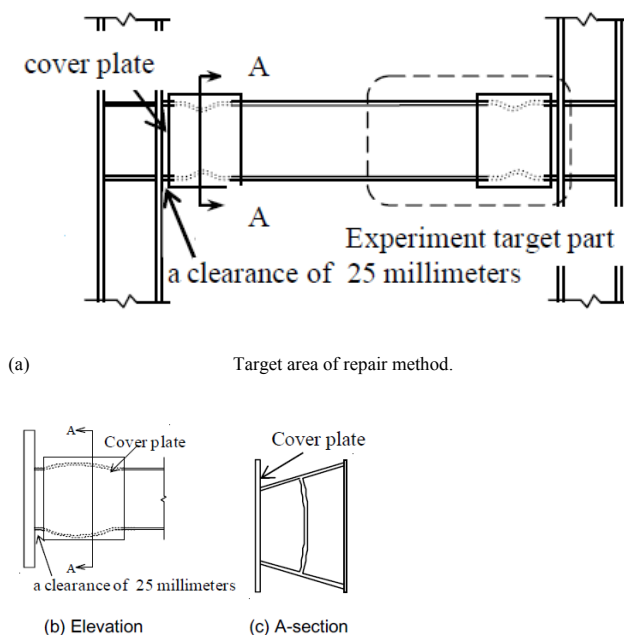


Figure 3: Diagram of restoration method of damaged H-shaped steel member.

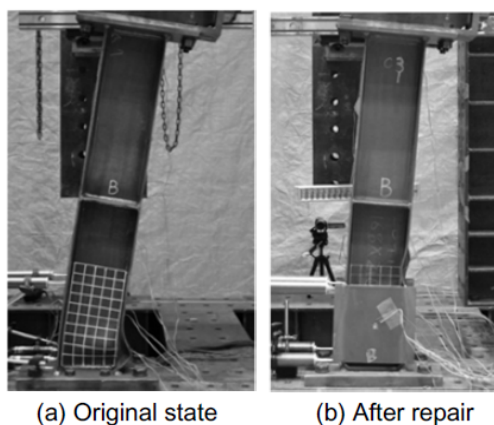


Figure 4: Ultimate state of test specimen.

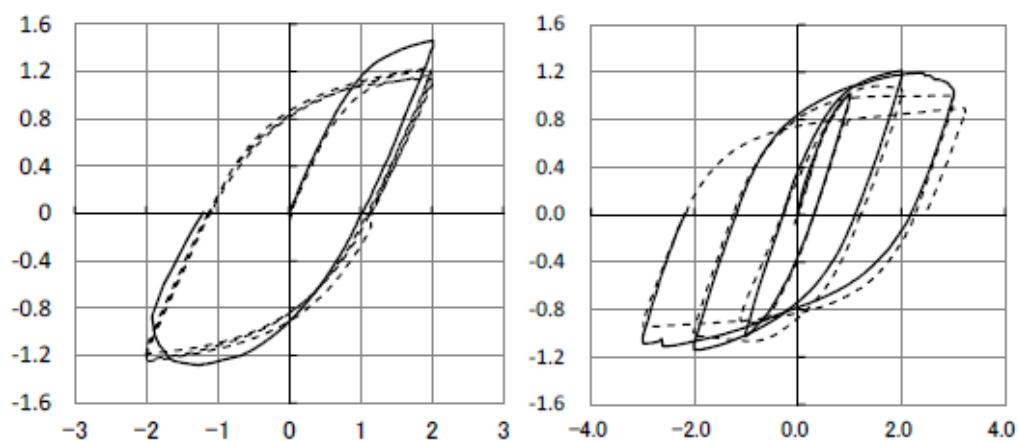


Figure 5: Comparison of test results.

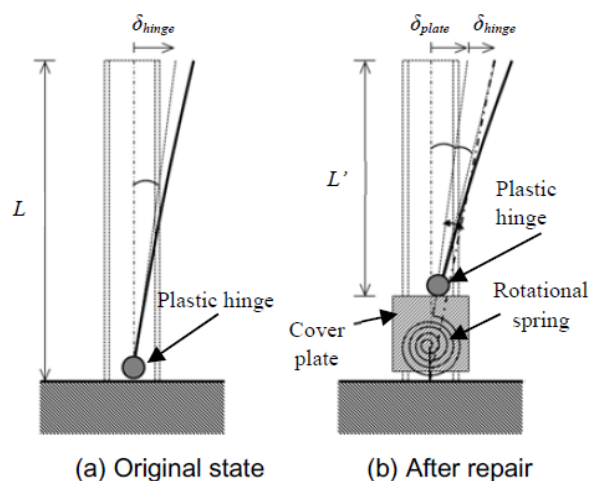


Figure 6: Assumption of analytical model.

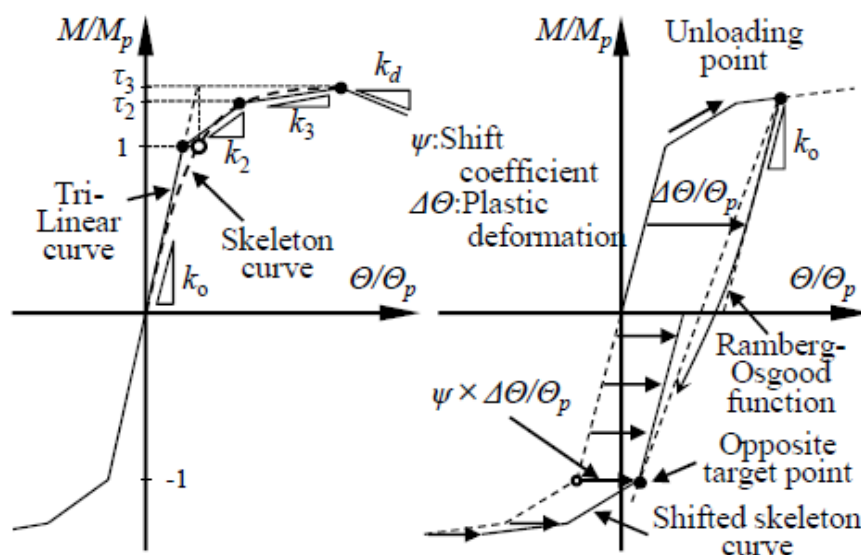


Figure 7: Hysteresis model during cyclic loading, called "Skeleton Shift Model".

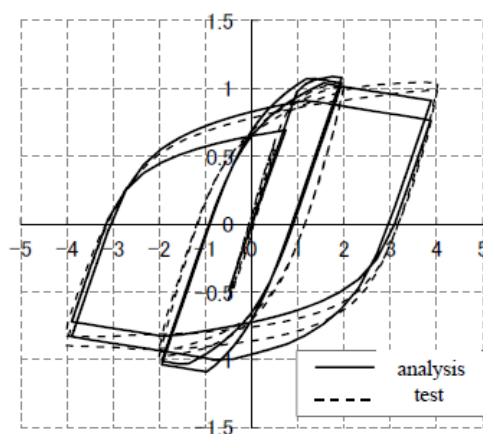


Figure 8: Comparison of test and analytical results.

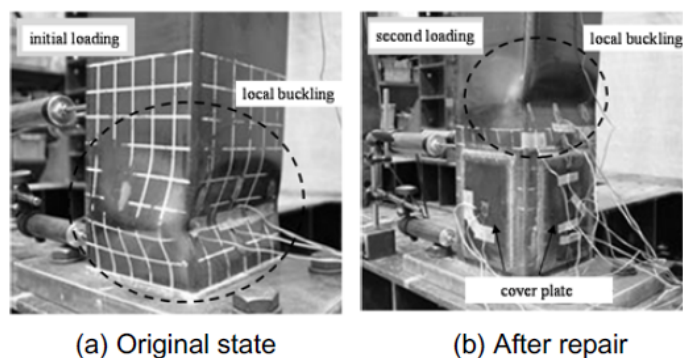


Figure 9: Ultimate state of test specimen.

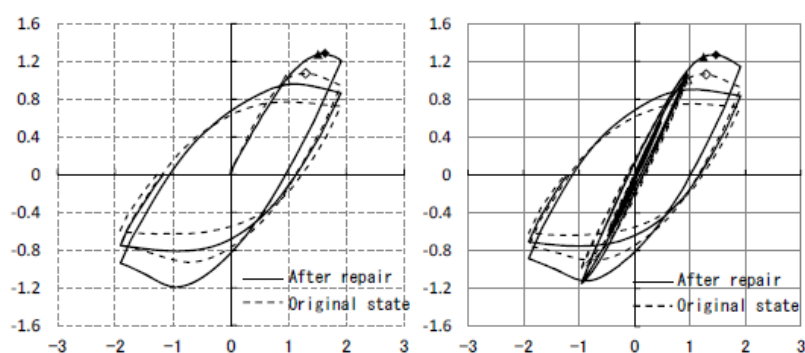


Figure 10: Comparison of test results.

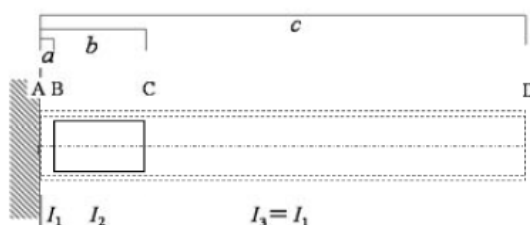


Figure 11: Assumption of analytical model.

in Figure 4. From the test results, the ultimate states of test specimens were observed as shown in Figures 8 and 9. And the test results of moment-angle relation were obtained as shown in Figure 10, which compares the original state and repaired member. From the test results, the ultimate state behavior were observed as follows; on the repaired steel member, the plastic hinge were formed to the side of cover plates, and the repaired portion with cover plate behaved as rocking of rigid body. And also, the strength and ductility of repaired member were improved by comparison with original state and damaged member without repair. From these considerations, the analytical model of box type steel member of original and repaired state was established as shown in Figure 11. And also, the hysteresis model during inelastic cyclic loading was applied with Skeleton Shift Model as shown in Figure 8 too. And the comparison of test results and analytical results are presented in Figure 12, and it can be said that the proposed analytical model can chase the test results well.

Analytical model of repaired steel frame

Most steel moment resisting frame (rahmen frame) consists of

H-shaped steel girder and Box type steel column. Generally, the failure mode of ultimate seismic state after large seismic input are formed as shown in Figure 13, in which the plastic hinges are generated on the end of most girder and few column end. The restoration method above mentioned (see 5.1) is adopted on this plastic hinge, the frame after repair is illustrated as shown in Figure 13a, and also the analytical model of the frame can be given as Figure 13b. Furthermore, the restoring force characteristics model of this repaired member can be referred with model as shown in Figures 7, 8 and 11.

Analytical study and considerations

Herein, by use of proposed analytical model above mentioned, the ultimate seismic behavior and seismic resistant performance of repaired steel frame are discussed. A 3-story 2-bay steel moment-resisting frame shown in Figure 14 is studied hereafter. The member properties are as follows; moment of inertia, beam = $9.28 \times 10^8 \text{ mm}^4$, column = $7.56 \times 10^8 \text{ mm}^4$, plastic moment capacity, beam = 1,182 kN m, column = 682 kN m, and floor weights are 0.29M (2nd, 3rd), 0.42

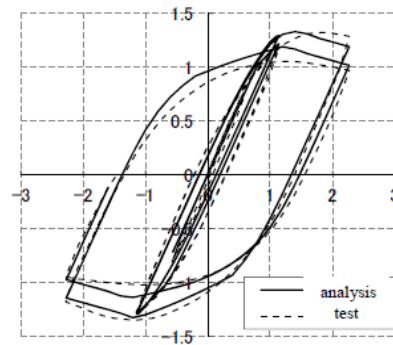
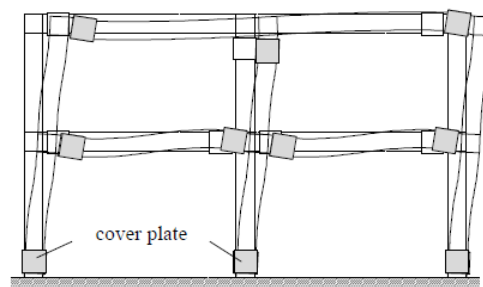
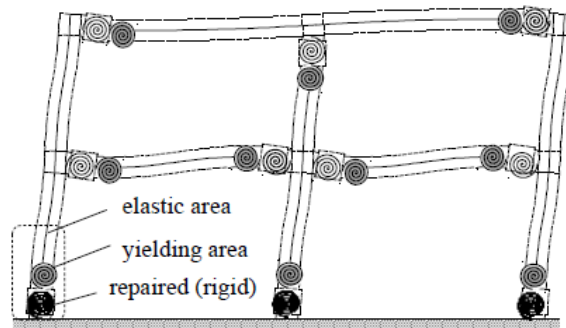


Figure 12: Comparison of test and analytical results.



(a) Steel frame after repair.



(b) Analytical model of repaired frame

Figure 13: General diagram of steel frame after repair.

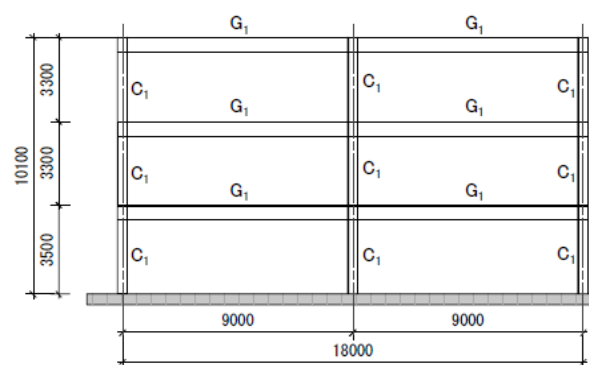


Figure 14: Analytical model of 3-story 2-bay steel frame.

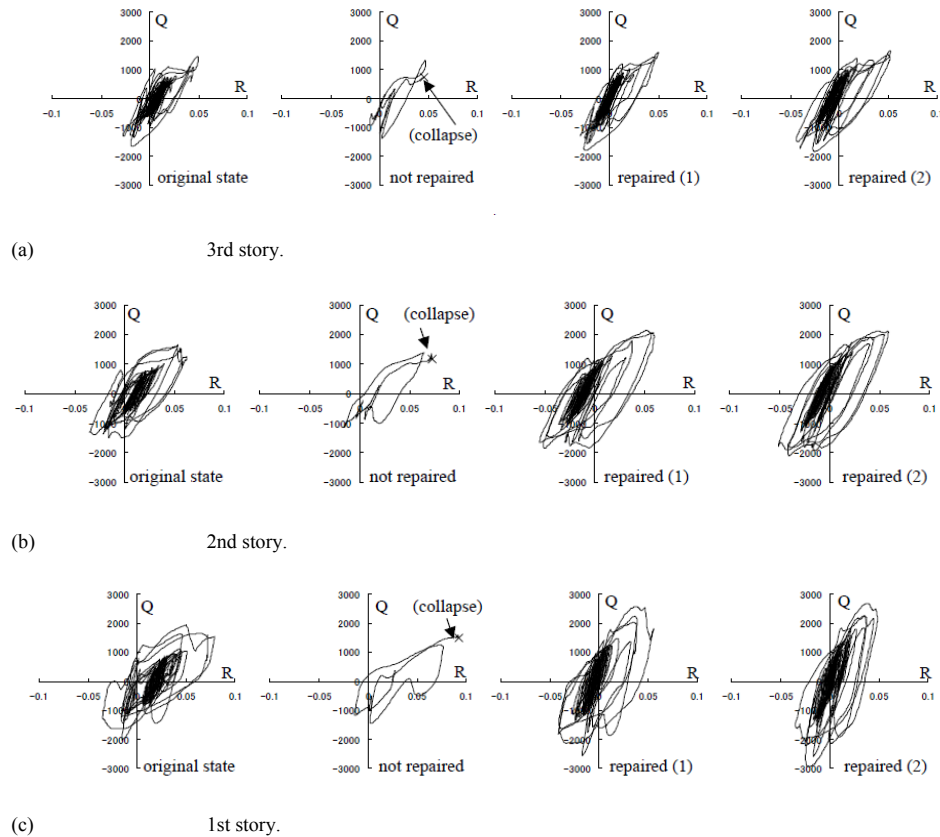


Figure 15: Hysteresis loops of story shear – story drift (vertical axis = shear Q (kN), horizontal axis = story drift R (rad)).

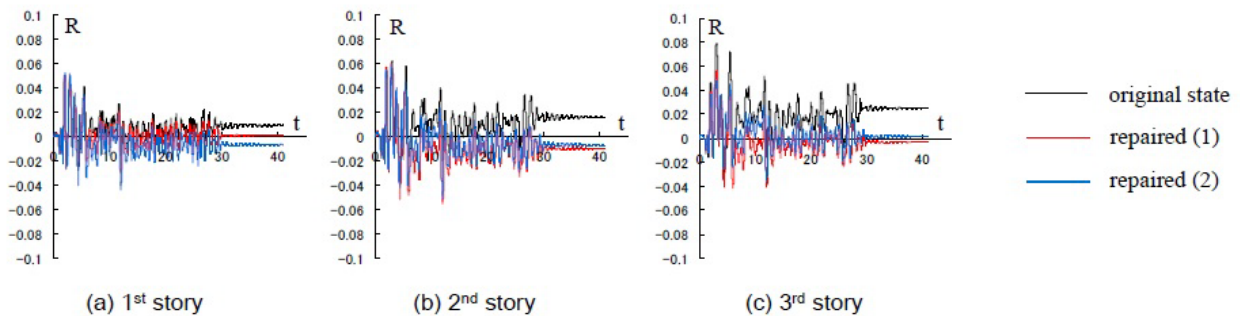


Figure 16: Time history of story drift (vertical axis = story drift R (rad), horizontal axis = time t (sec)).

M (roof), here M is total mass of frame. A constant modal damping ratio of 2% is considered. The elastic vibration periods are 0.866sec (1st mode), 0.225 sec (2nd mode), and 0.110 sec (3rd mode). In this paper, the effect of slab or interior/exterior material is not considered. This frame is analyzed for the ground acceleration records of El Centro 1940 NS (Imperial Valley Earthquake, here, PGV = 111 m/sec). The time history response analysis is performed on original state, and the results of story shear – story drift are presented in Figure 15, time history of story drifts are shown in Figure 16.

In this paper, the damaged member of plastic hinge formation is repaired by use of repairing method as shown in Figures 3 and 4. Furthermore, the strategy for repairing to damaged member is assumed as follows, strategy 1) all damaged member of plastic hinge formation is repaired, and its member is fully strengthened, strategy

2) to prevent the excessive increment of strength in specific member around beam-column-connection, the non-damaged member which remains within elastic is repaired alternatively. And then, the time history response analysis is performed on repaired state again, and the results of story shear – story drift and time history of story drift are presented in Figures 16 too. Furthermore, the frame without repair after failure mode formation is analyzed.

From the response analysis results,

1. On the frame which is not repaired after failure mode formation on original state, it is observed that the response of story drift becomes large, and the strength and rigidity become small. Finally, the frame is collapsed completely. It means that the damage frame does not have enough seismic resistant performance against aftershock,

2. However, the repaired frames have high strength comparing with original state. And also, the response of story drifts becomes smaller than original state. It means that the repaired frame has enough seismic resistant performance; furthermore, the seismic reinforcement effect is obtained.

Conclusion

In this paper, the restoration method and its repairability for damaged steel frames are focused on. In Japan, the restoration guideline has been published, and it was actually referred and availed during past earthquake disasters. And also, the various kinds of restoration method are developed and suggested. This paper summarizes the outline of restoration method for H-shaped steel member and box type steel member. And also, the past experimental studies are explained, furthermore, the proposed analytical model are presented. By use of these proposed analytical model, the time history response analysis are performed on low-rise steel frame. Herein, to investigate it's effectively and effect to damage frame, a various strategy of repairing portion in

frame has been assumed. From the response analysis results, the frame which is not repaired after failure mode formation on original state, the frame is collapsed completely. It means that the damage frame does not have enough seismic resistant performance against aftershock. However, the repaired frames survive against aftershock. And also, the repaired frame has enough seismic resistant performance; furthermore, the seismic reinforcement effect is obtained.

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