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REPAIRABILITY AND RECOVERY OF REPAIRED STEEL FRAMED STRUCTURES EXPERIENCING ULTIMATE STATE

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Recently, there are many discussions about repairability and recovery for damaged buildings after severe disasters, and new keywords such as "Resilience" and "Redundancy" have been closed-up. This paper investigates the repairability of damaged steel building structures which experienced severe disasters such as earthquake input motions. At first, the analytical model for repaired steel member is explained, and also its applicability is represented by comparison with past test results. The next, the ultimate states of steel framed model of original state and repairing state under seismic loads are calculated by limit analysis. Herein, an analytical frame model is designed that the whole story collapse mode is predominated in original state. And also, to adjust the failure mode of frame after repair, a various strategy of repairing portion in frame is assumed. From the analytical results, it is observed that the strength and energy absorption are enhanced if the adequate repairing strategy is adopted to generate the whole collapse failure mode. That is, it can be said that these repaired frame has high repairability and resilience.

Keywords: Repair method, Limit analysis, Collapse failure mode.

1 INTRODUCTION

Recently, there are many discussions about repairability and recovery methods for damaged building structures, particularly after 2011 Great East Japan Earthquake. The discussion has focused on the new keyword "Resilience", which presents the revival potential or functional maintenance of damaged structures. The concept of structural resilience and high resilience system (Bruneau and Reinhorn (2006)) is as follows: 1) reduced failure probabilities, 2) reduced consequences from failures, and 3) reduced time to recovery.

Japan's Technical guideline (2001) suggests a repairing method based on the past experimental researches (Tanaka *et al.* 1990). Also, research has been done on repairability and recovery of steel structures by Asami, et. al. (2011) and Kozaki, et. al. (2014) and experimental studies to investigate repairability (Matsumoto *et al.* 2014, Mori *et al.* 2015).

In this paper, the repairability and recovery on steel framed structures after repair are studied analytically. Furthermore, the limit analysis on multi-story steel framed model is performed to estimate the ultimate seismic performance before and after repair.

2 OUTLINE OF REPAIR METHOD AND ANALYTICAL MODEL

2.1 Repair Method for Steel Member with Local Buckling

From enormous past reports about earthquake disasters in Japan (1995 Kobe, 2011 Tohoku), the local buckling of steel members have been observed in damaged steel framed structures. And also, the Japanese technical guideline (2001) has suggested a method for repairing the damaged area caused by local buckling of H-shaped steel members. In this method, the damaged area is repaired by welding cover plated to the flange, as shown in figure 1. And also, this study adopts two types of welding on cover plate, continuous welding (CW) and intermitted welding (IW).

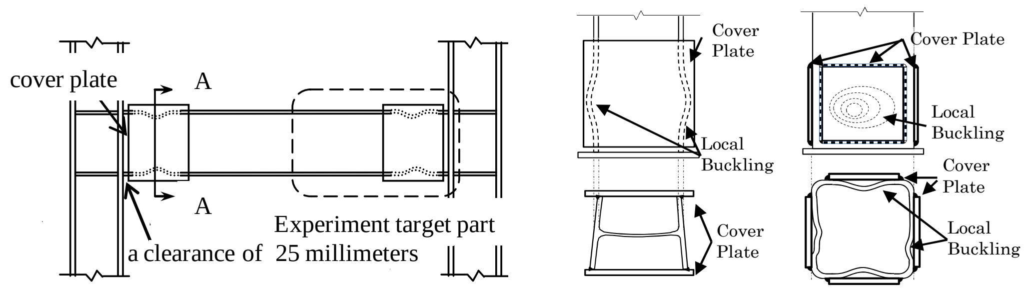


Figure 1. Repair method of damage steel structures (Japanese guideline, 2001).

2.2 Summary of Previous Experimental Study

The authors have conducted the experimental studies to estimate the effectivity of the above-mentioned repairing technique (2014, 2015).

Table 1 summarizes the list of test specimen, and Table 2 lists the mechanical properties of steel member. Figure 3 shows the test results of normalized moment-rotation angle curve. The moment M is normalized by the fully plastic moment, and the angle Θ is normalized by the rotation angle at which the load reaches plastic moment. Table 1 compares the test results before and after the repair process. M_m is the maximum strength, η_m is the energy absorption capacity up to the maximum strength.

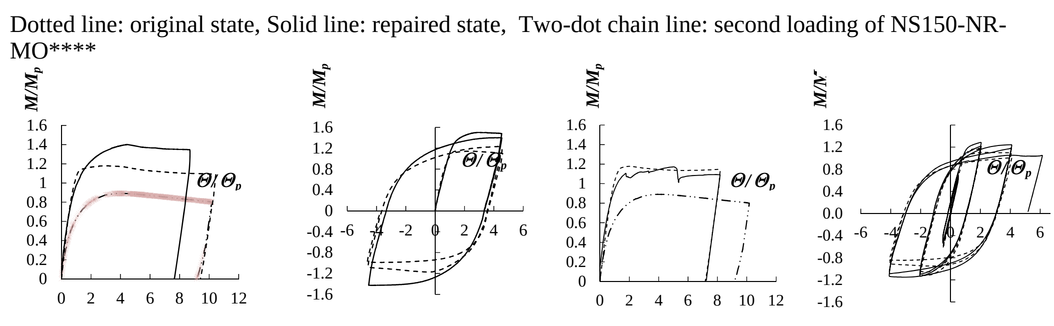


Figure 3. Comparison of normalized M-Θ curve of loading test.

From the figure 3 and Table 1, it is verified that the maximum strength in case of continuous welding has increased after repairing compared with the original state. And also, the maximum strength in some case of intermitted welding almost become same. That is, the maximum strength can be adjusted by welding conditions. Furthermore, the energy absorption capacity is usually recovered, except in the case of a few specimens.

2.3 Analytical Model for Steel Member after Repair

Figure 4 shows the photographs of the deformation at the ultimate state of test specimens. As shown in figure 4 (a), the area that underwent local buckling before at original state has rotated. As shown in figure 4 (b), both the area covered by the plate and the upper area of the cover plate have rotated. From the observations, the analytical models of steel member before and after repair are proposed as shown in figure 5. This analytical model after repair consists of plastic hinge and rotational spring. The skeleton curve is approximated as tri-linear, and the "skeleton shift model" (K. Mori *et al*, 2015) as shown in figure 6 is adopted for hysteresis rule. The hysteresis loops of test results vs. analytical results are compared in figure 7. From the comparison, there is good agreement between the analytical results and the test results. It can be said that the proposed analytical method and model can effectively evaluate the inelastic behavior repaired steel member.

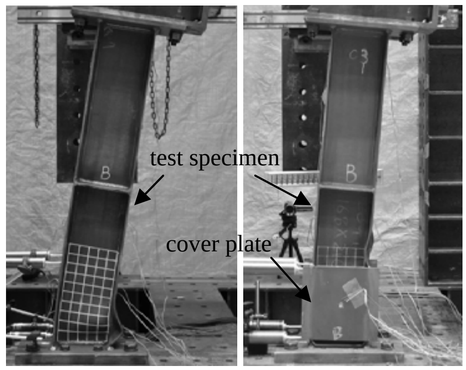
Table 1. List of test specimen and test results.

Specimens***	Steel grades*	b/t_f**	d/t_w**	Maximum strength (normarized by M_p)		Energy absorption capacity	
				Original	After repair	Original	After repair
NS150-NR-MO	SM490	12.0	28.0	1.17	0.89****	2.57	2.47****
NS150-CW-MO	SM490	12.0	28.0	1.18	1.40	2.40	4.51
NS150-CW-C1				1.16	1.36	6.39	16.5
NS150-CW-C2				1.23	1.50	4.07	2.75
NS150-IW1-MO	SM490	12.0	28.0	1.18	1.17	1.45	4.42
NS150-IW2-MO				1.17	1.36	1.35	5.87
NS150-IW1-C3				1.18	1.29	1.32	1.58
NS150-IW2-C3				1.16	1.31	1.29	1.68

* Grade of JIS (Japanese Industrial Standards)
** b/t_f is the width-thickness ratio of flange, d/t_w is the width-thickness ratio of web
*** NS: non-scallop, 150: width of flange, NR: non-repair, CW/IW: repair, MO: monotonic, C1-3: cyclic

Table 2. Mechanical properties of steel member.

Specimens	Parts	Steel grades (Grade of JIS)	Thickness	Yield strength	Tensile strength	Young's modulus
NS150-NR, NS150-CW	Flange, Web	SM490	6mm	390 N/mm^2	544 N/mm^2	217 GPa
	Cover plate	SS400	6mm	398 N/mm^2	461 N/mm^2	202 GPa
NS150-IW	Flange, Web	SM490	6mm	402 N/mm^2	551N/mm^2	211 GPa
	Cover plate	SS400	6mm	334 N/mm^2	421N/mm^2	210 GPa



(a) original state. (b) after repair.

Figure 4. Ultimate state of test specimen.

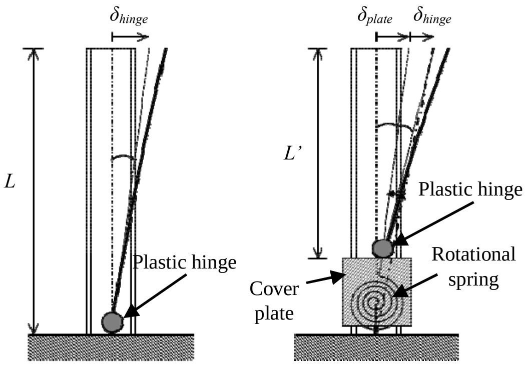


Figure 5. Analytical model of member.

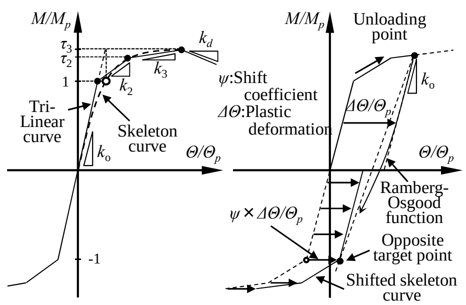


Figure 6. Restoring force characteristics and skeleton shift model for hysteresis rule.

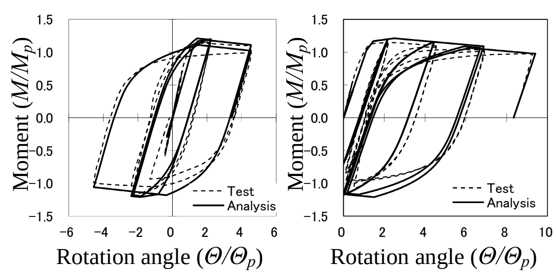


Figure 7. Comparison of normalized M-Θ curve of test and analytical result.

3 LIMIT ANALYSYS ON FRAME MODEL BEFORE AND AFTER REPAIR

3.1 Analytical Model of Low-rise Steel Frame

To investigate the ultimate seismic resistant performance of steel framed structure of original state and repairing state, the limit analysis is performed.

Herein, low-rise steel framed structure as shown in figure 8 is analyzed. The analytical frame is designed that the whole story collapse mode is predominated in original state. Herein, the load pattern of Japanese seismic resistant design code is adopted on limit analysis as shown in figure 8. This frame consists of H-shaped steel columns (C_1: H-414×405×18×28) and beam (G_1: H-600×200×11×17) of SN400 (grade of JIS, the nominal yield strength is 235N/mm^2), herein, the analytical study is performed on the strong axis of section of column and beam.

The result of limit analysis is presented in figure 8 (b). As the reference, if the plastic hinge with local buckling is not repaired, the base shear deteriorated by 80% and the energy absorption deteriorated 20%.

3.2 Strategy of Repair for Damaged Frame

In this paper, the damaged member of plastic hinge formation is repaired by use of repairing method as shown in figure 1. And also, it is assumed that the restoring force characteristics show the above-mentioned model as shown in figures 4, 5.

Herein, the strategy for repairing to damaged member is assumed as follows, 1) all damaged member of plastic hinge formation is repaired, and its member is fully strengthened, 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 as shown in figure 8 (d).

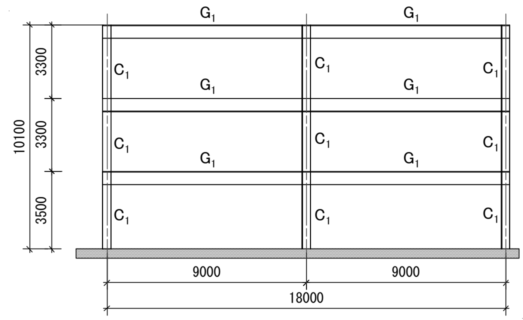
3.3 Results of Limit Analysis and Observations

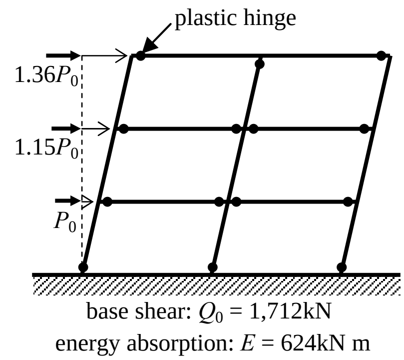
The results of limit analysis are shown in figure 8. From figure 8 (c), the local story collapse mode after repair has occurred, because the repaired member was strengthened excessively. On the other hands, from figure 8 (d), it is confirmed that the whole story collapse mode has occurred, and the base shear has increased by 38%. For calculating the plastic energy absorption, *E,* it is assumed that the ductility of plastic hinge is 0.05rad (original state) and 0.075rad (after repair) by reference to test results. It is confirmed that the energy absorption is improved after repaired.

4 CONCLUSION

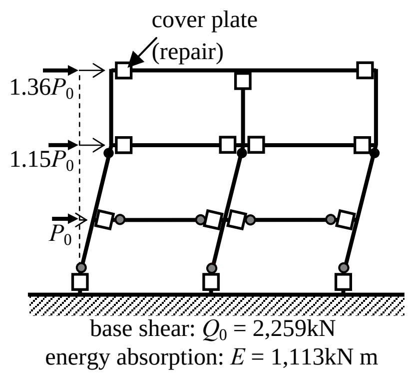
In this paper, the analytical method to estimate the repairability and recovery of damaged steel framed structures is suggested. At first, the previous study on repair method is summarized, and an analytical model is explained. Its applicability is represented by comparison with test results. Furthermore, the restoring force characteristics and performance after repair are summarized.

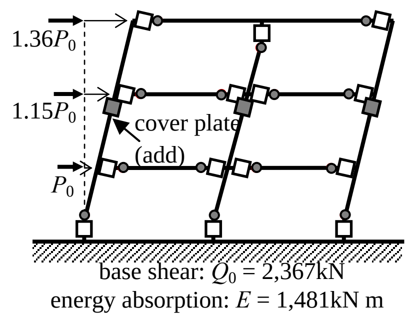
The next, the ultimate states of steel framed model of original state and repairing state have been calculated by limit analysis. Herein, to adjust the failure mode of frame after repair, a various strategy of repairing portion in frame have been assumed. From the analytical results, it has been observed that the strength and energy absorption have been enhanced if the adequate repairing strategy has been adopted to generate the whole collapse failure mode.





(a) Analytical model of 3story-2bay frame (uint: mm). (b) Failure mode of original state.





(c) Failure mode after repair in case of 1). (d) Failure mode after repair in case of 2).

Figure 8. Low-rise steel analytical frame model and results of limit analysis.

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