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The Repair Method of Damaged H-shaped Steel Members and Experimental Study on Recovery after Repair

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Abstract

Recently, there have been many discussions about repairability for damaged building structures after severe disasters. In japan, a technical manual for repairing damaged buildings has been established; however, its repair abilities have not been reported sufficiently. In this study, the Box-Shaped Repair Method which has been suggested on Japanese technical guideline is adopted for the damaged steel members, and its applicability and feasibility are investigated experimentally. Herein, the damaged portion on steel member such as plastic hinge or local buckling occurrence is covered with steel plate by welding. So the loading test is performed as parameters with section size of steel members, thickness of cover plate and welding size during repair process, and loading path. The procedure of this study is as follows; the first, the damaged test specimens of H-shaped steel member with local buckling are reproduced by initial loading test. Next, the damaged specimens with plastic residual deformation are returned to the original position. Finally, the loading test is done after repair. From test results, it is confirmed that the fundamental structural performance such as the rigidity, maximum strength, and absorbed energy after repair are improved by comparison of original state. And also, this performance can be controlled by adjusting the thickness of cover plate and welding condition. Furthermore, from the observation of test results, the analytical model of repaired steel member is suggested. From the comparison of test results, it can be said that the proposed model shows good agreements both test results and theoretical figure.

Keywords: Box shaped repair method; H-shaped steel members; Local buckling; Repair ability; Seismic limit state; Ultimate

Introduction

Recently, there have been many discussions about repairability for damaged building structures after severe disasters. From these trends, new keyword "Resilience" which means revival potential or function maintenance of damaged structure is noticed. And in recent years, there are global environmental and resources problems. Considering these problems, the establishment and maintenance of technique and design method considering with the concept of resilience and repairability becomes increasingly important.

In Japan, a technical guideline for repairing damaged buildings has been established in the technical guideline for restoration by the Japan Building Disaster Prevention Association (2001, herein after referred to as "the restoration guideline"). But its repairabilities have not been sufficiently reported in past researches. Munemura H et al. [1] investigated the post-repair structural performance of H-shaped steel members, which the technical guidelines have suggested. The Moment-Rotation angle curve (M-Θ curve) is shown in Figure 1. Furthermore, the definition of the moment of member end M and rotation angle Θ

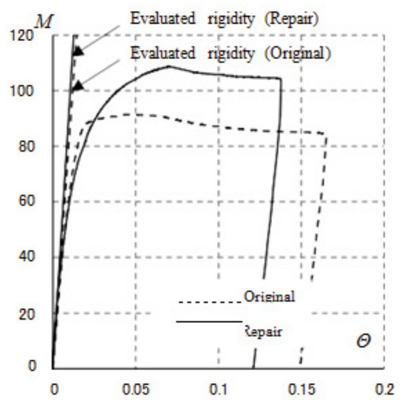

Figure 1: Structural performance of repaired member [1].

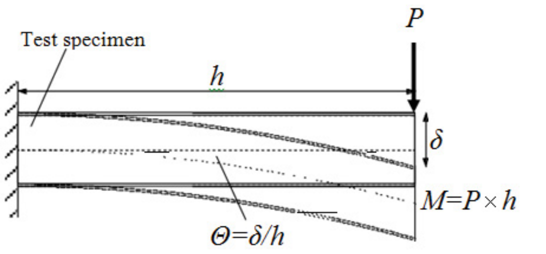

Figure 2: The definition of the moment-rotation *m* and rotation angle *Θ*.

are shown in Figure 2. The moment of member end and the rotation angle are obtained as Eq. (1) and Eq. (2).

$$M=P\times H \quad (1)$$

$$\Theta=\delta/H \quad (2)$$

From the test result, the strength and rigidity of the test specimens were improved. However, the crack was observed around the repaired area on member end. Furthermore, it is predicted that the moment capacity around member end is strengthened after repair. In case the crack occurs around the repaired area on member end, it is supposed that the likely failure modes are changed. Moreover, it could affect the seismic resistant performance of whole of framed structure after repair. This study aims to investigate the repairing condition with section size of steel members, thickness of cover plate and welding size. Moreover, it provides the adjustment method of strength and rigidity of repaired members.

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Detail of Repair Method for Local Buckling

Based on the restoration guideline

The restoration guideline has suggested a repair method mentioned that the damaged area around the flange local buckling of H-shaped steel members is repaired by cover plate (herein after referred to as "Box- shaped repair method") as shown in Figure 3. Before repaired by this method, residual displacement of damaged H-shaped members should be almost zero as same as original position. The damaged area around the flange local buckling is repaired by welding cover plate, and a clearance of 25 mm is provided between the end plate and the edge of the cover plate. The thickness of the cover plates is equal to that of the flange of the H- shaped steel member.

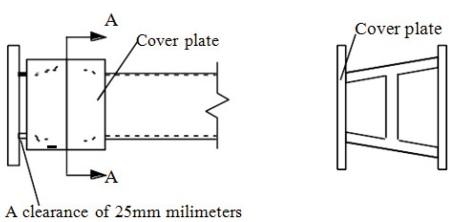
Proposal of repair method

Herein, based on original Box-shaped repair method, this study suggests a modified repair method to adjust the strength and rigidity of repaired members. That is, it is assumed that the strength and rigidity of repaired members can be adjusted by changing either of the following:

1. The welding condition on repaired area

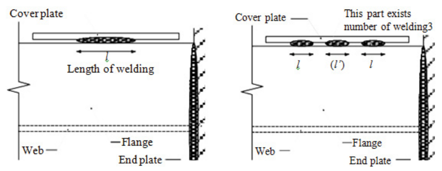
2. The thickness of cover plate

Authors have studied the affectivity and feasibility of the former repair method experimentally. Herein, the effects of welding condition as parameters with the number of welding and length are investigated (Figure 4). Table 1 shows the list of test specimens of monotonic loading test. The number of welding and length is based on Matsumoto T et al. [4]. The number of welding is 2 or 3 point. In case the number of welding is 2 point, the welding length (*l*) is 20 mm, 40 mm or 60 mm. On the other hand, in case the number of welding is 3 point, the welding length (*l*) is 20 mm, and the medium welding length (*l'*) is 20 mm or 40 mm. Figure 5 shows an elevation view of the test specimens. Test specimens are set as cantilever. The ultimate state of the normalized Moment-Rotation angle curve (*M-Θ* curve) and the test specimens with loading pattern are shown in Figures 6 and 7. Where *Mp* is full plastic moment of the specimen, *Θp* is the rotation angle when the load reaches *Mp* on monotonic curve. Moreover, Table 2 shows the comparison of the maximum strength (*Mm*) and the energy absorption capacity when load reaches maximum strength (*cηm*). From the test results, the strength and the energy absorption capacity after repair show almost same with original state; however, the ultimate behavior is unstable. From the comparison of test results, it can be said that the fundamental structural performance such as the strength and the energy absorption capacity after repair depend on the damage condition of welding between cover plate and the damaged area around the flange local buckling. This study aims to provide the adjustment method of strength and rigidity of repaired member by changing the thickness of cover plate experimentally. The test specimens are repaired by cover plate which is half or 3/4 thick of the flange.



(b) Elevation (c) A-Section

Figure 3: Detail of box-shaped repair method.



(a) Number of welding: 1 (b) Number of welding: 2, 3

Figure 4: Method of welding on cover plate.

Name	Steel grades and section	Thickness of cover plate (mm)	Welding condition (*l-l'*)
NS150-NR-M	-	-	-
NS150-IR1-M	-	-	20
NS150-IR2-M	-	-	40
NS150-IR3-M	-	-	60
NS150-IR4-M	SM490 180×150×6×6	-	20-20
NS150-IR5-M	-	6	20-40

Table 1: Test specimen list (based on Matsumoto T et al. [4]).

Outlines of Experimental Study

General description

At first, test specimens which are damaged local buckling, and that residual deformation are reproduced by loading tests. Next, the damaged test specimens are returned to the original position (herein after referred as "Returning"). Then, the damaged area around the local buckling is repaired by the method described in chapter 2. Finally, the loading tests are done after repair, which the loading programs are same as initial loading tests. The evaluation and comparison with performance of the original states and that of the repaired states are examined.

Test setup and loading test methods

Figure 5 shows an elevation view of the test specimens. This is as same as previous study which examined by changing the number of welding and welding length on repaired area. Test specimens are set as cantilever. The top of the test specimen was laterally loaded to produce the bending moment at the base of the H-shaped steel members. Test specimens were instrumented with sensors for measuring below items: lateral displacement at the top of the test specimens, strain of flange and cover plate.

Test specimens

In this paper, the name of test specimens with non-scallop are called as NS150 and these specimens are composed by welding of steel plates. Herein, the configuration of test specimen is illustrated in Figure 8. The name of test specimens and loading patterns are summarized in Table 3. NS150-6C-M is the non-scallop test specimen repaired by the cover plate which thickness is equal to that of the flange of the H-shaped steel members, and investigated in Munemura H et al. [1]. In this study, 3.2 mm and 4.5 mm thick of cover plate means half or 3/4 thick of the flange respectively.

Mechanical properties of materials

Mechanical properties of steel are summarized in Table 4. According to Japanese seismic resistant codes, NS150 specimens are classified as FC-rank. This is as same as previous study which examined by changing the number of welding and welding length on repaired area.

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Results of Test Study

Test results of original state and after repair

The ultimate state of the test specimens and the normalized Moment-Rotation angle curve (M-Θcurve) with loading pattern are shown in Figures 8 and 9 respectively. Table 3 shows the comparison of the maximum strength (Mm), the energy absorption capacity when load reaches maximum strength ($c\eta m$), and failure mode of each specimen. The results in case of 6.0 mm thick of cover plate are also shown in the same table [2].

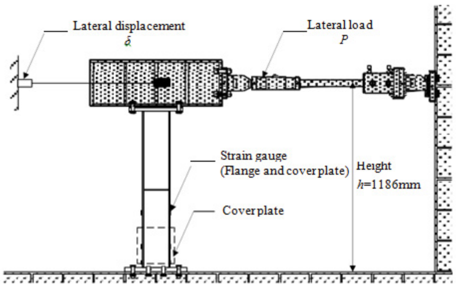


Figure 5: Elevation of test set up and location of sensors.

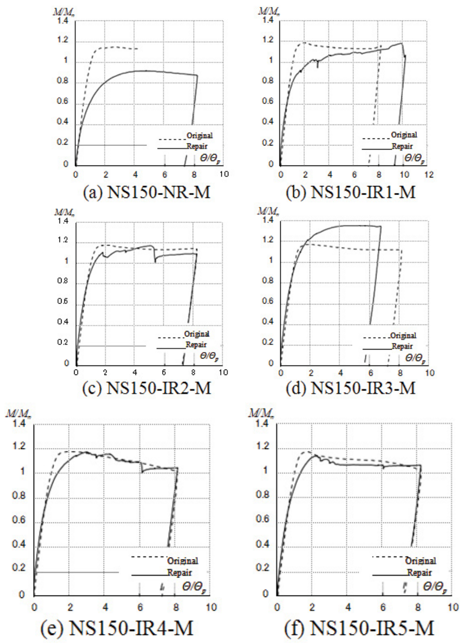
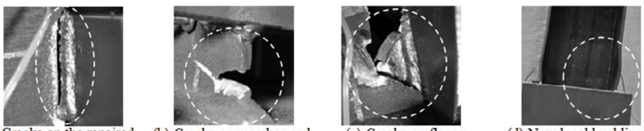


Figure 6: Test results of normalized M-Θ curves (based on Matsumoto T et al. [4]).



(a) Cracks on the repaired area of welding (b) Cracks on member end (c) Cracks on flange (d) New local buckling

Figure 7: Photographic observations of damage condition (based on Matsumoto T et al. [4]).

Test results of monotonic loading: The normalized M-Θ curves of monotonic loading tests are shown in Figure 8. On the loading tests before damaged (first loading), the local buckling was observed on the flange at the compression side after reaching Mp. After reached the maximum strength, the local buckling of the web progressed and the strength was deteriorated. On the second loading test of NS150-NR-M specimens (Non-repair) after Returning, rigidity lowered by the existence local buckling. Furthermore, the maximum strength was deteriorated, and the maximum strength stopped at 0.88 Mp. In case of NS150-3.2C-M specimen (repaired by 3.2 mm thick cover plate), initial rigidity after repair became almost equal to initial rigidity before damaged. The maximum strength improved compared with test specimen before damaged. The damage process is described below. When the moment reached around 1.75Θp, the welding on the repaired area was cracked and the rigidity lowered. Then, the crack around the repaired area on member end was observed when the moment reached around 1.11 Mp. After new local buckling is observed in the upper cover plate at the compression side, the maximum strength was reached.

Test results of cyclic loading: The normalized M-Θ curves of cyclic loading tests are shown in Figure 8. During the first loading, the local buckling was observed on the flange at the compression side after reaching Mp. After the local buckling of the flange progressed, the maximum strength was reached and the strength was deteriorated. This result is almost same with the results of monotonic loading. On the second loading test of NS150-3.2 C-C specimen, after the shape of cover plate is changed, the welding on the repaired area was cracked. After the maximum strength, the local buckling was observed in the upper cover plate at the compression side. Then, the crack around the repaired area on member end was observed. In case of NS150-4.5C-C specimen, after the welding on the repaired area was cracked around 1.0Θp, the maximum strength was reached and the crack around the repaired area on member end was observed. Then, new local buckling is observed in the upper cover plate at the compression side [3,4].

Examination of the test results

The maximum strength: The recovery of performance is compared by the difference of the thickness of cover plate. The results are shown in Figure 10. The maximum strength of every repaired test specimen is experimentally improved. However, it is assumed that the reason why the maximum strength of NS150-3.2C-M was larger than that of NS150-4.5 C-M is due to the early cracks around the repaired area on member end. From the observation of test results, the analytical model

	First Loading			Second Loading			Ratio (after/before)	
Name	Mm	cηm	The determinant of maximum strength	Mm	cηm	The determinant of maximum strength	Mm	cηm
NS150-NR-M	1.15	1.88	- -	0.92	3.11	The existence Local Buckling	0.8	1.66
NS150-IR2-M	1.18	1.45	-	1.17	4.42	Cracks on the repaired area of welding	1	3.06
NS150-IR3-M	1.17	1.35	-	1.36	5.87	Cracks on flange	1.16	4.33
NS150-IR4-M	1.17	1.32	-	1.17	2.17	Cracks on the repaired area of welding	1	1.64
NS150-IR5-M	1.17	0.84	Local Buckling	1.14	1.23	Cracks on the repaired area of welding	0.97	1.46

Table 2: Comparison of test results (based on Matsumoto T et al. [4]).

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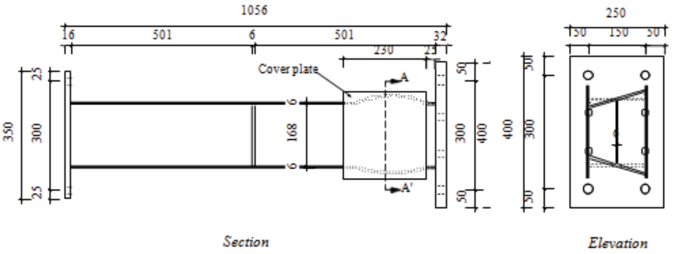

Figure 8: Configuration of test specimen after repair.

Name	Steel grades and section	Thickness of cover plate(mm)	Welding condition	Loading pattern
NS150- NR-M	SM490 180×150×6×6	-	-	Monotonic
NS150- 3.2C-M		3.2	Continuous	Monotonic
NS150- 4.5C-M		4.5		
NS150- 3.2C-C		3.2		Cyclic
NS150- 4.5C-C		4.5		
NS150- 6C-M		6.0		Monotonic

Table 3: Test specimen list.

	Yield strength (N/mm2)	Tensile strength (N/mm2)	Young's modules (GPa)	Elongati on (%)
SM490 (t=6.0 mm)	436	573	206	32
SS400 (t=3.2 mm)	354	438	198	31
SS400 (t=4.5 mm)	298	445	208	35

Table 4: Mechanical properties of material.

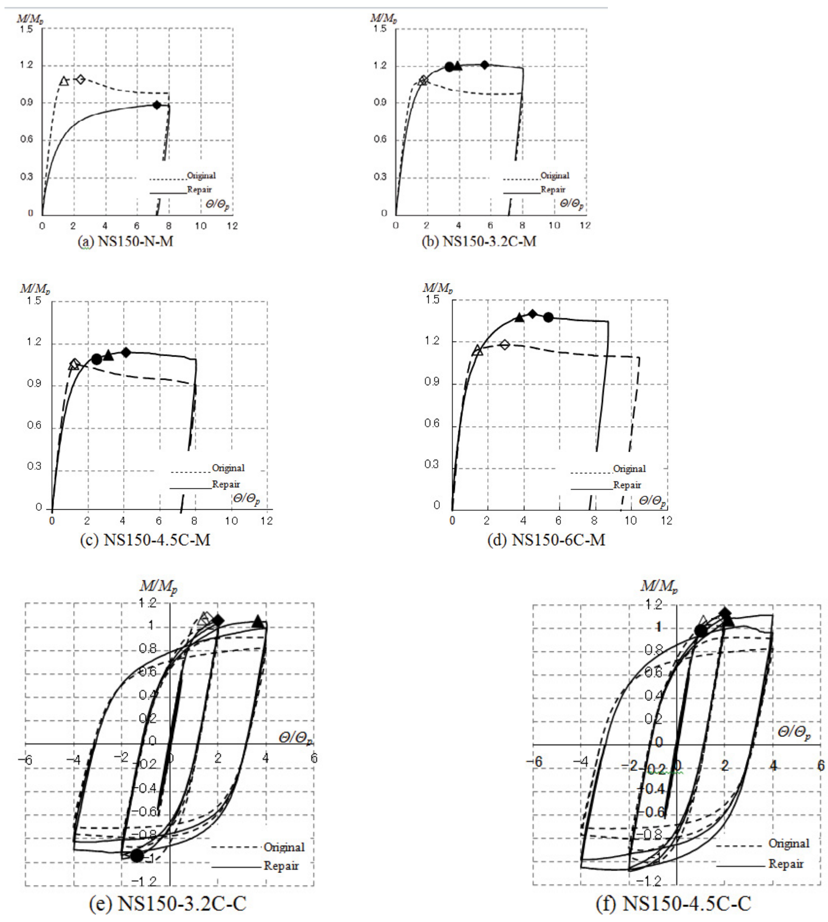

Figure 9: Comparison of test results of normalized M-Θ curves on original state and repaired state.

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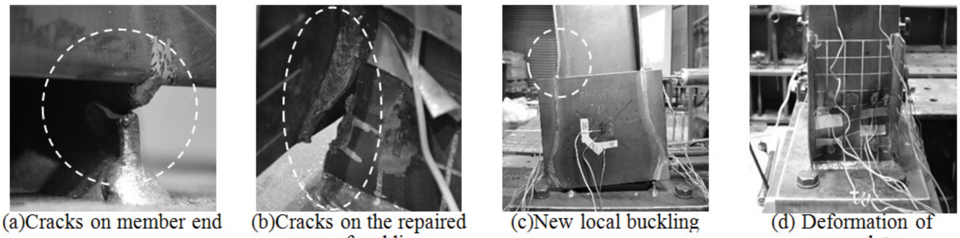

(a)Cracks on member end (b)Cracks on the repaired area of welding (c)New local buckling (d) Deformation of cover plate

Figure 10: Photographic observations of damage condition.

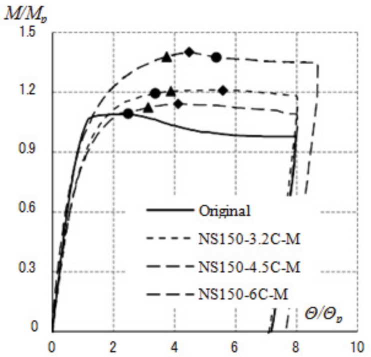

Figure 11: Comparison of test results of monotonic loading.

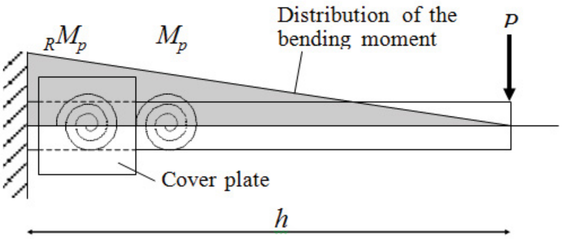

Figure 12: The analytical model of repaired steel.

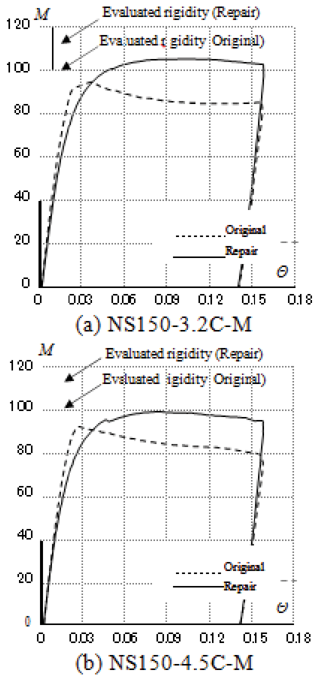

Figure 13: Comparison of the results of theoretical initial rigidity and M-θ curves.

	First Loading			Second Loading			Ratio (after/before)	
Name	*Mm*	*cηm*	The determinant of maximum strength	*Mm*	*cηm*	The determinant of maximum strength	*Mm*	*cηm*
NS150-NR-M	1.09	1.61		0.88	-4.99	The existence Local Buckling	0.81	-3.09
NS150-3.2C-M	1.09	0.91		1.21	5.21	Cracks on the repaired area of welding	1.11	5.73
NS150-4.5C-M	1.06	0.39		1.14	3.44	The crack on member end	1.08	8.74
NS150-3.2C-C	1.07	0.82		1.05	1.24	Cracks on the repaired area of welding	0.98	1.5
NS150-4.5C-C	1.09	1.28		1.13	1.31	the crack on member end	1.04	1.02
NS150-6C-M	1.18	2.4	Local Buckling	1.4	4.51	New flange local Buckling	1.19	1.88

Table 5: Comparison of test results.

of repaired steel member composed of $_RM_p$ (repaired area occurred plastic deformation or rigidity rotation) and M_p (the elastoplastic element occurred local buckling) could be suggested. The analytical model of steel member is shown in Figure 11. From the theoretical results, it is predicted that the cracks on the repaired area of welding and the crack around the repaired area on member end was observed in the specimens repaired by 3.2 mm thick and 4.5 mm thick cover plate respectively. And also, it is also predicted that the crack around the repaired area on member end was observed in the specimens of 6.0 mm thick of cover plate. However, the crack around the repaired area on member end was not observed in case of repaired by 3.2 mm thick cover plate. This is due to the influence area of the welding heat. From the above, it was predicted that the proposed model shows good agreements both test results and theoretical figure.

The rigidity: The experimental and theoretical results of initial rigidity in the specimens of 3.2 mm thick and 4.5 mm thick of cover plate are shown in Figures 12 and 13. From these results, it is confirmed that initial rigidity could be controlled by changing the thickness of cover plate. Furthermore, initial rigidity after repair in this study became almost equal to initial rigidity before damaged.

The absorbed energy: From test results shown in Table 5, it is confirmed that the absorbed energy after repair was improved by comparison of original state.

Conclusion

In this study, the experimental and theoretical study about recovery of H-shaped steel members is performed. The main conclusions are shown below:

1. It is confirmed that the fundamental structural performance such as the rigidity, maximum strength, and absorbed energy after repair are improved by comparison of original state.

2. These performances can be controlled by adjusting the thickness of cover plate and welding condition.

3. From the observation of test results, the analytical model of repaired steel member is suggested.

4. From the comparison of test results, it can be said in Figure 10 that comparison of test results of monotonic loading that the proposed model shows good agreements both test results and theoretical figure.

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