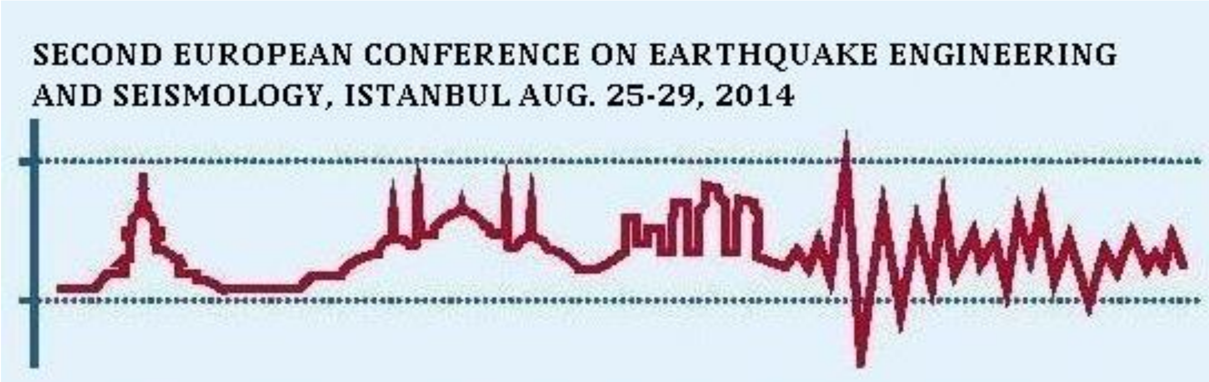


EXPERIMENTAL STUDY ON REPAIRABILITY AND RECOVERY OF STRUCTURAL PERFORMANCE FOR DAMAGED STEEL MEMBERS

Hiroka Munemura [1], Kenjiro Mori [2], Takeshi Matsumoto [3], Hanako Sato [4], Takumi Ito[5] and Changhoon Choi[6]

ABSTRACT

In this study, the repairability and recovery of the damaged steel structural members is investigated experimentally. On the H-shaped steel members, the local buckling and cracks would be generated in ultimate states after severe earthquake motions. In this paper, the experimental studies are conducted with variables as loading pattern, the existence/ nonexistence of scallop. At first, test specimens damaged with local buckling or cracks are reproduced by loading test. Next, the damaged test specimens with residual deformation are returned to the original position. Finally, the loading test is done to the test specimens after the damaged areas are repaired. From the test results, the evaluation and comparison with structural performance of the original states and that of the repaired states are investigated. It is confirmed that stiffness of the repaired test specimen is recovered to that of original state. And also, the maximum strength and ductility capacity are improved. Furthermore, the analytical simple model for strength and ductility is proposed by reference of test results. From the comparison of test results and analytical results, it shows good agreements with test results.

1. INTRODUCTION

In these days, there are a lot of discussions about the repairability for the damaged building structures after the event of disaster. A new keyword "Resilience" which means revival potential or functional maintenance capability of structures has been recently discussed (Architectural institute of Japan., 2012). Moreover, there are the environmental and resource problem in recent years, and the reuse and recycle of the old or used structural members are interested. Considering these trends, establishment and maintenance of techniques and design methods considering with the concept of resilience and repairability becomes important increasingly.

In Japan, the repair methods for the damaged structures have already been suggested, and it has been published in the technical manual for restoration by the Japan Building Disaster Prevention Association (herein after referred to as "the technical manual"). And it is reported that a lot of damaged building during past sever earthquake events were repaired by reference of this technical manual. However, there are various situations of the damaged building structures. It is necessary to examine the concrete and efficiently repair methods that take into account the residual performance

[1] Tokyo Univ. of Sci., 6-3-1, Niijuku, Katsushika-ku Tokyo, Japan, hero.m123@gmail.com
[2] Tokyo Univ. of Sci., 6-3-1, Niijuku, Katsushika-ku, Tokyo, Japan, spy54tv9@theia.ocn.ne.jp
[3] Tokyo Univ. of Sci., 6-3-1, Niijuku, Katsushika-ku, Tokyo, Japan, nyan_tea0304@yahoo.co.jp
[4] Tokyo Univ. of Sci., 6-3-1, Niijuku, Katsushika-ku, Tokyo, Japan, hanapoo321@gmail.com
[5] Tokyo Univ. of Sci., 6-3-1, Niijuku, Katsushika-ku, Tokyo, Japan, t-ito@rs.kagu.tus.ac.jp
[6] Tokyo Univ. of Sci., 6-3-1, Niijuku, Katsushika-ku, Tokyo, Japan, musasi73@rs.tus.ac.jp

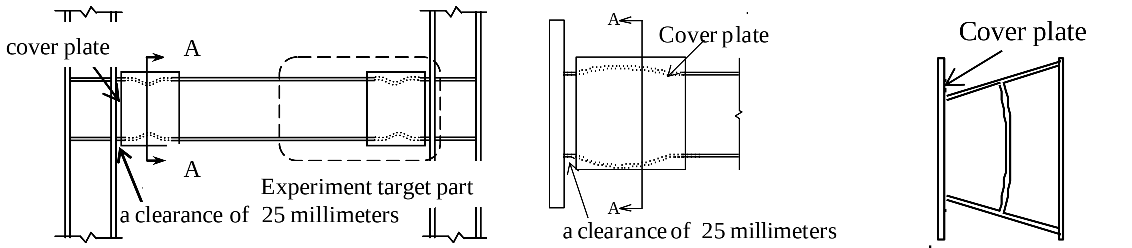
and damage condition, post-repair performance. For repairability of the steel structures, it is necessary to investigate how the steel members that strength are decreased by crack, local buckling and break should be repaired, and how many post-repair performances are recovered. According to the technical manual, when repairing for local buckling, post-repair strength returns to the original strength and it is supposed that the ductility capacity improve to some degree. This is based on the results of a past framework test (Tanaka A et al., 1990). However, a scale and frame form of actual buildings is different. It is necessary to clarify a relation between the repair methods for steel members and post-repair performances. So, it is necessary to improve the design method and construction technology about repairability.

Matsumoto T et al., (2013) investigated the post-repair performances of the H-shaped steel members which have the scallop, and the applicability and validity of the repair methods were verified. In this paper, the experimental study of repairability and recovery on the post -repair performances of H-shaped steel members manufactured by the non-scallop construction methods is conducted.

2. REPAIR METHODS FOR DAMAGED STEEL MEMBERS

2.1 Repair methods for local buckling

In this study, the damaged area around the flange local buckling of H-shaped steel members is repaired by cover plates (herein after referred to as “Box-shaped repair method”) as shown in Fig.1. First, residual deformation of the damaged test specimens should be almost returned to original position on each test specimens. By reference of the technical manual, a clearance of 25mm is opened between the end plate and the edge of cover plates. And, the thickness of cover plates is equal to that of flange plate of H-shaped steel members.

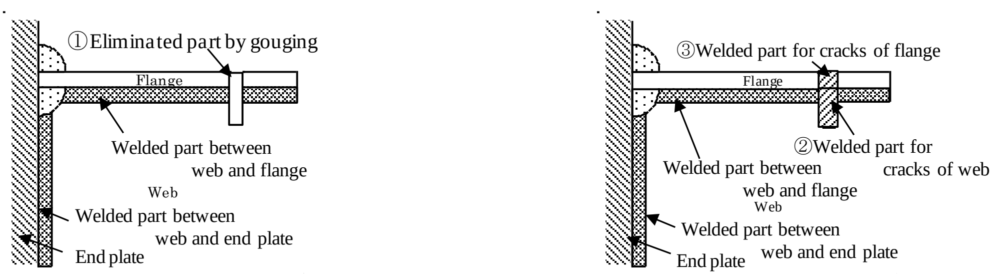


(a) Repairing method for local buckling (b) Elevation (c) A-Section

Figure 1. Box-shaped repair method

2.2 Repair methods for crack

The technical manual is mentioned that when the cracks are generated, the affected area is generally replaced with renewal member. However, it is considered that the local buckling and residual deformation would disturb it. Matsumoto T et al., (2013) studied the repair methods for the cracks generated around scallop. This paper suggests the repair methods for the cracks that are generated around the intersection part of flange and web. The outline of the repair methods for the damaged members that the cracks generated is shown in Fig.2.



(a) Eliminate cracks (b) Repair cracks by welding

Figure 2. Repair method for cracks

3. OUTLINE OF EXPERIMENTAL ABOUT REPAIR EFFECT

3.1 General description

At first, test specimens which are damaged with local buckling or cracks, 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 and cracks is repaired by the methods described in Chapter2. Finally, the loading tests are done to the test specimens repairing construction again, 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.

3.2 Test specimens and mechanical properties of materials

In this paper, the name of test specimens with scallop and non-scallop are called as S150 and NS150 specimen respectively. NS150 specimens are composed by welding of steel plates. Test specimens names and loading patterns are summarized in Table.1. Herein, NS150 specimen is shown in Fig.3. In Fig.3, drawing of repaired test specimen is also shown. Mechanical properties of steel are summarized in Table.2. According to Japanese seismic resistant codes, NS150 specimens are classified as FC-rank.

3.3 Test set up and loading test methods

Fig.4 shows an elevation view of the test specimens. 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 plates. The monotonic and cyclic Loading patterns are shown in Fig.6 along with test results.

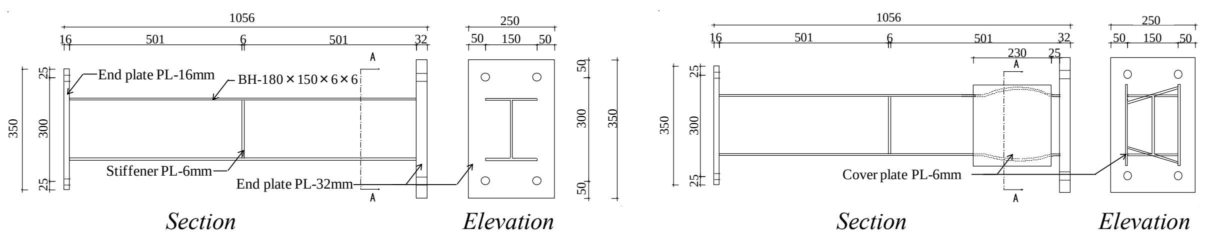
Table 1. Test specimens list

Name	Steel grades※	Repair	Loading pattern
NS150-NBM	SM490	unrepair	monotonic
NS150-RBM		repair	monotonic
NS150-RB1			cyclic1
NS150-RB2			cyclic2
NS150-RB3			cyclic3
S150-NBM	SM490	unrepair	monotonic
S150-RBM		repair	monotonic
S150-RB4			cyclic4
S150-RB5			cyclic5
S150-RB6			cyclic6

※Grade of JIS (Japanese Industrial Standards)

Table 2. Mechanical properties of material

Parts	Size	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Young's modulus (kN/mm^2)
Webs and Flanges	PL-6mm	390	544	217



(a) Before repair (b) After repair

Figure 3. Layout of test specimen

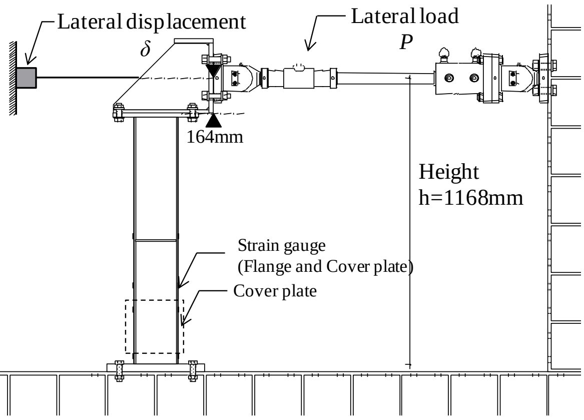


Figure4. Elevation of test set up and location of sensors

4. RESULTS OF TEST STUDY

4.1 Test results of before and after repair

4.1.1 Test results of monotonic loading

The normalized *M*-*Θ* curves of monotonic loading tests are shown in Fig.5. And, photo of the test specimens are shown in Fig.6. From the test results in Fig.5 (a), following things were observed. On the loading test before repair (First Loading), the local buckling was observed on the flange at the compression side after reaching M_p. After the maximum strength, the local buckling of the web progressed and the strength was deteriorated.

On the second loading test of NS150-NAM specimens (Non-repair), stiffness lowered by the existence local buckling. And, the maximum strength stopped at the 0.89 M_p.

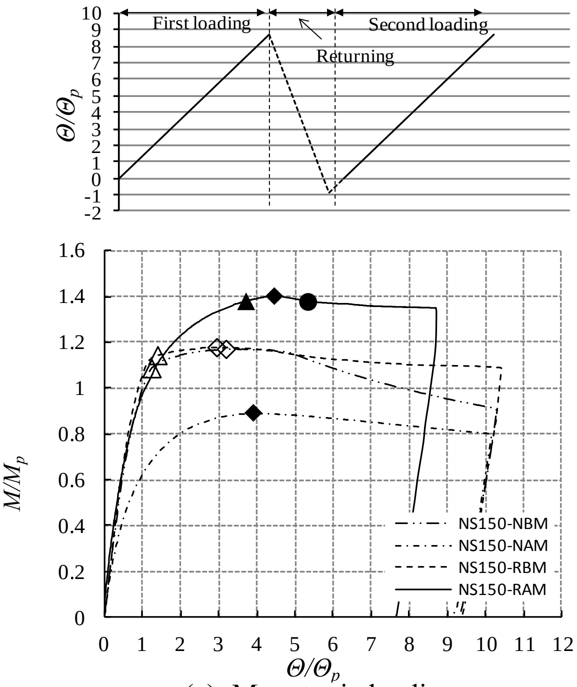
On the second loading test of NS150-RAM specimens (Repair), initial stiffness after repairing became almost equal to initial stiffness before damage. The maximum strength improved compared with test specimen before repairing. The damage process is described below. When the moment is reached around 1.4 M_p, new local buckling was observed in the upper part of cover plates. Then, the crack was observed on the edge of the flange in the lower part of cover plates at the tension side, and the maximum strength was reached. The initial local buckling did not advanced by the restraint of the cover plates. After the maximum strength, the cracks progressed and the strength declined.

4.1.2 Test results of cyclic loading

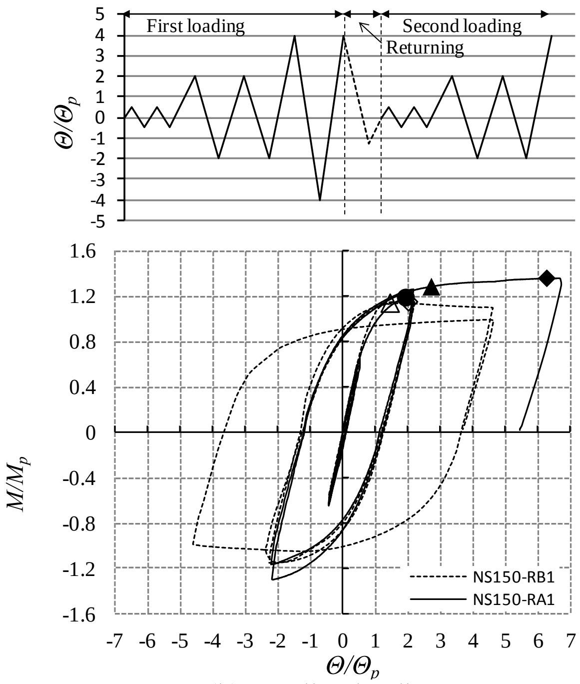
From the test results in Fig.5 (b) (c) (d), following things were observed. On the loading test before repair (First Loading), local buckling was observed on the flange at the compression side after reaching M_p. After the maximum strength, local buckling was observed on the web. In NS150-RB2 specimens, the cracks as shown in Fig.6 (c) were generated around the intersection part of flange and web by local buckling at the time of Returning. In NS150-RA3 specimens, the maximum strength and ductility capacity are higher than other specimens, because the both sides of flange at the compression side are deformed inside as shown in Fig.6 (d).

On the second loading test of NS150-RA1 specimens, after the cracks was observed on the edge of the flange in the lower part of cover plates at the tension side, new local buckling was observed in the upper part of cover plates. Then, the fracture surface of flange as shown in Fig.6 (e) touched the welding beat, and the strength and stiffness improved near $4\Theta_p$. Although strength declined near $6\Theta_p$, loading was ended because the cover plate became touching the end plate.

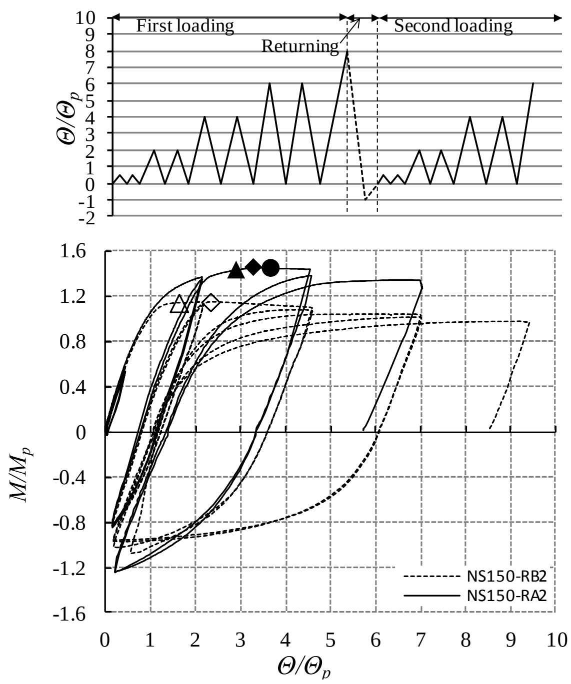
On the second loading test of NS150-RA2 and NS150-RA3 specimens, new local buckling was observed in the upper part of cover plates. Local buckling advanced and the maximum strength was reached. Then, the crack generated from the edge of flange and the strength declined because the cracks advance.



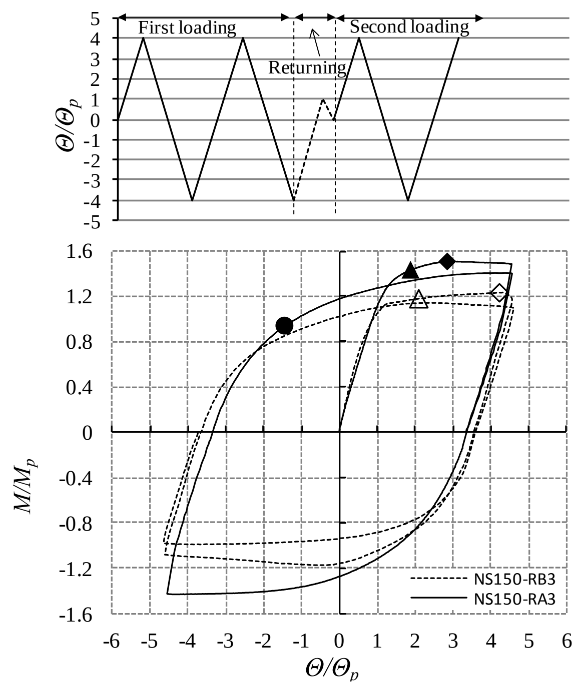
(a) Monotonic loading



(b) Cyclic1 loading

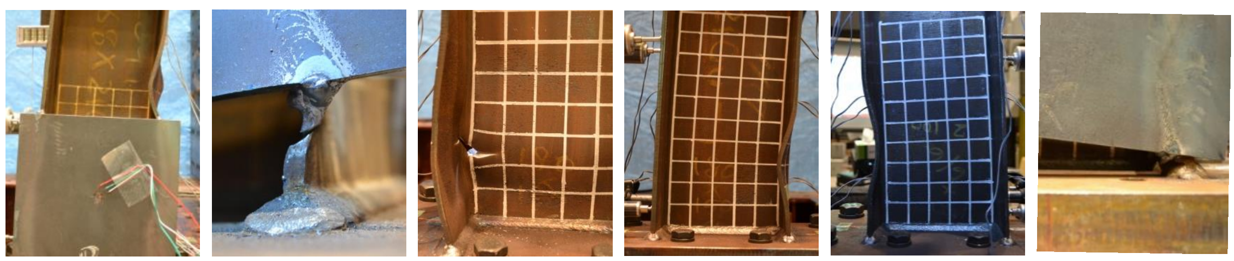


(c) Cyclic2 loading



(d) Cyclic3 loading

Figure 5. *M-Θ* curves and loading patterns



(a) (b) (c) (d) (e)

Figure 6. Photographic observations of damage condition

4.2 Verification of repair effect

From the hysteresis loops of test results before and after repair of cyclic loading, the skeleton curve and cumulative deformation curve is abstracted. And the strength, deformation and energy absorption capacity are considered. The results before and after repair of the maximum strength (M_m) and the normalized cumulative plastic deformation ($_c\eta_m$) until it reaches the maximum strength is shown in Table.3. And also, the ratio (ξ) of before $_c\eta_m$ / after $_c\eta_m$ is shown in Table.3.

From the Table.3, the recovery of strength and ductility are recognized. In NS150-RB3, the situations of deformation differ as Chapter 4.1.2 is described. This specimen has reached the maximum strength by the first loop. The state of deformation assumes that it is the same as the results of monotonic loading, so it uses the energy absorption capacity of monotonic loading before repair. As a result, ξ is 1.15. So, it can be summarized that the repair effect was acquired.

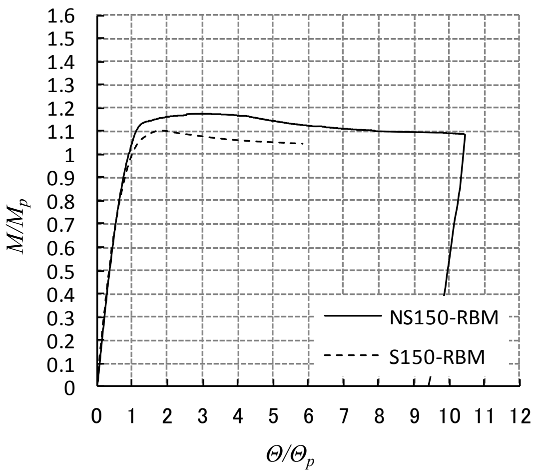
Table3. Comparison of the performance to the maximum strength

	NS150-NAM		NS150-RAM		NS150-RA1		NS150-RA2		NS150-RA3	
	M_m	$_c\eta_m$	M_m	$_c\eta_m$	M_m	$_c\eta_m$	M_m	$_c\eta_m$	M_m	$_c\eta_m$
First loading	1.17	2.57	1.18	2.40	1.16	6.39	1.15	3.09	1.23	4.07
Second loading	0.89	2.47	1.40	4.51	1.36	16.5	1.45	4.24	1.50	2.75
ratio	0.76	0.96	1.19	1.88	1.17	2.58	1.26	1.37	1.22	0.68

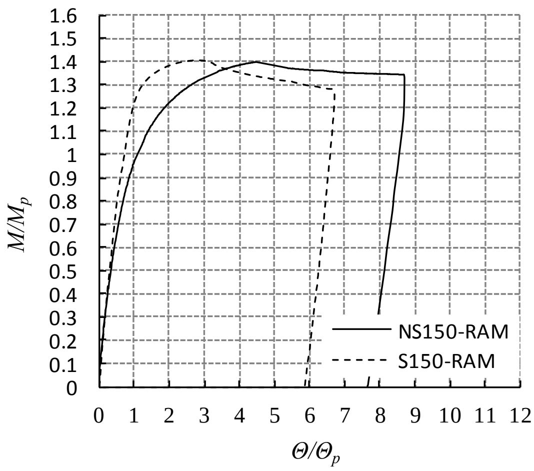
4.3 Comparison of the existence/ nonexistence of scallop

4.3.1 Test results of monotonic loading

The recovery of performance by the difference of the existence/ nonexistence of scallop is compared. The results are shown in Fig.7 and Table.4. By the comparison of the test results of S150 and NS150 specimens before repair, the maximum strength is about 1.1 times and the ductility factor ($_s\mu_m$) is about 1.6 times. In the case of non scallop specimens, the maximum strength and deformation capacity are improved. On the loading test after repair, the maximum strength is equal in general independently of the existence/ non existence of scallop. The reason is that the crack of flange plate has determined the maximum strength of the specimens. This can be paraphrased as collapse mode was the same.



(a) Before repair



(b) After repair

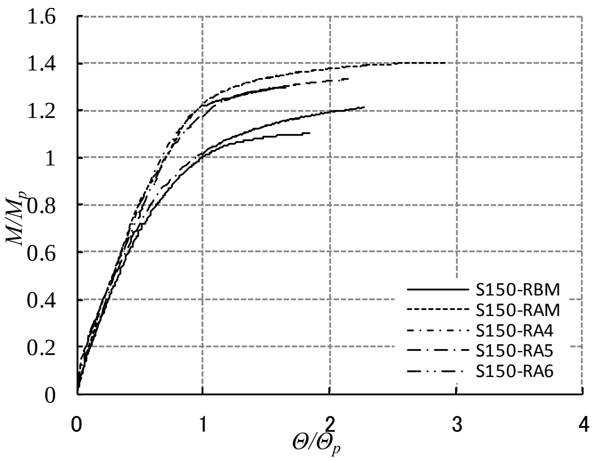
Figure 7. Test results of monotonic loading

Table 4. Comparison of the performance of the existence or non existence of scallop

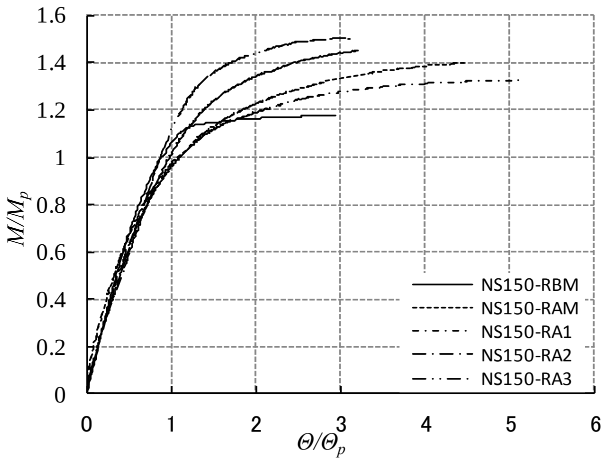
	S150-RBM	NS150-RBM	S150-RAM	NS150-RAM
M_m	1.10	1.18	1.41	1.40
$_s\mu_m$	1.72	2.68	2.67	4.00

4.3.2 Comparison of skeleton curves

The skeleton curves are abstracted from the hysteresis loops of NS150 and S150 specimens, and it is shown as Fig.8. In addition, about the skeleton curves before repair, the monotonic loading curve is shown in Fig.8 since the every skeleton curves were compatible with. The energy absorption capacity (${}_s\eta_m$) and the ratio (before ${}_s\eta_m$ / after ${}_s\eta_m$) are shown in Table.5. The ${}_s\eta_m$ of S150-RBM before repair is 1.16 and the ${}_s\eta_m$ of NS150-RBM before repair is 2.40. The post-repair performance of the S150 specimens and NS150 specimens has exceeded the original state. However, about S150-RA6, the post-repair performance is comparable as the original state because the cracks which generate from the repaired part of the cracks again make the ductility factor small. The ${}_s\eta_m$ of the NS150 specimens is larger than that of the S150 specimens.



(a) S150 specimens



(b) NS150 specimens

Figure 8. Comparison of skeleton curve

Table 5. The energy absorption capacity

	S150-RAM	S150-RA4	S150-RA5	S150-RA6
${}_s\eta_m$	2.82	1.83	1.75	1.10
ratio	2.43	1.58	1.51	0.95
	NS150-RAM	NS150-RA1	NS150-RA2	NS150-RA3
${}_s\eta_m$	4.51	7.19	2.67	2.75
ratio	1.88	3.00	1.11	1.15

5. ANALYTICAL STUDY

5.1 Analytical model

The analytical simple model for strength and ductility is proposed by test results. From the test results, it was observed that the plastic hinge was formed at the member's end in case of before repair, and the plastic hinge was formed at the upper part of cover plates in case of after repair. From these observations, the simple analytical model shown as Fig.9 is assumed.

5.2 Comparison with strength and ductility

The maximum strength' ratio of after repair to before repair is the ratio of h to h'. Where h is the height from a fixed end to loading point, h' is the height from a fixed end to the upper part of cover plates. In this paper, h/h' is 1.28. This ratio is good agreement with experiment results when the maximum strength is determined by local buckling. However, if the cover plates become long, the moment in the lower part of cover plates increase. It is thought that the crack generated easily by reaching ultimate strength. About the ductility before and after repair, when a plastic hinge is formed at the upper part of cover plates, the equation of the plastic rotation angle is shown (1), (2).

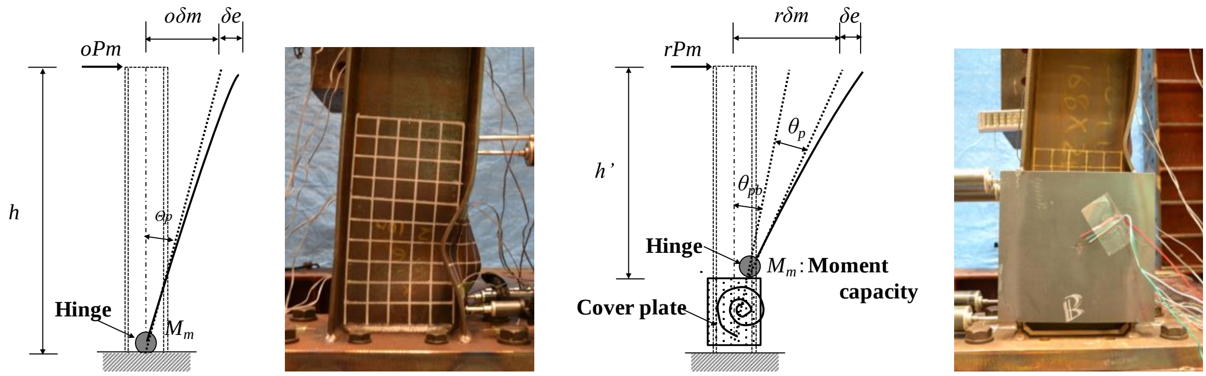
The rotation angle Θ_p is obtained as Eq. (1).

$$\Theta_p = {}_o\delta_m/h \tag{1}$$

In the case of the hinge occurred in the upper part of cover plates in second loading, the rigid rotation θ_{pb} is obtained as Eq. (2).

$$\theta_{pb} = {}_r\delta_m/h-(h'/h)({}_o\delta_m/h) \tag{2}$$

Where ${}_o\delta_m$ is lateral displacement of maximum strength in first loading, ${}_r\delta_m$ is lateral displacement of maximum strength in second loading. The rate of θ_{pb} to the ${}_r\delta_m/h$ was calculated. The plastic deformation in the end parts of the member is equal to the plastic deformation in the upper part of cover plates in NS150-RAM. The ratio of the plastic deformation in the end parts of the member is larger in NS150-RA1. The ratio of the plastic deformation in the upper part of cover plates is larger in NS150-RA2.



(a) original (b) after repair

Figure 9. Analytical simple model

CONCLUSIONS

In the present study, the loading tests of H-shaped steel members before and after repair were carried out. The repair effect of the Box-shaped repair method was investigated experimentally and the main conclusions of this paper are as follows:

1. The stiffness of the repaired test specimens becomes more than the one of the original test specimens, or becomes as same as it.
2. The maximum strength and energy absorption capacity of the repaired test specimens becomes more than these of the original test specimens.
3. In the repaired test specimens, a rate of increase of the maximum strength is small if the plate of flange is broken.
4. The post-repair performance of the test specimens without scallop becomes more than that of the test specimens with scallop.
5. From the comparison of test results and analytical results, it shows good agreements with test results.

REFERENCES

Architectural institute of Japan (2012) "Relilient Society: Commemorating the 3.11 East Japan Earthquake Disaster", *Journal of Architecture and Building Science*, March, vol.127, No.1629

Tanaka A, Izumi M, Narihara H, (1990) "Experimental Study on the Statical Characteristics of Repaired or Reinforced Steel Structures" , *Jounal of Structural Engineering*, Japan, March, No.36B, pp.377-384

Matsumoto T, Mori k, Kato T, Choi C, Ito T, (2013) "An Experimental Study on Repairability and Recovery of Structural Performance for Damaged Steel Members" , *Proceedings of Pacific Structural Steel Conference*, Singapore, October, pp.721-726