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Research Article

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Repair Method of Damaged Steel Braced Structure and Restring Force Characteristics after Repair State

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Abstract

A lot of steel structures have experienced severe earthquake disasters in Japan, and its various kinds of failure mode have been reported. Especially on steel braced structure, the failure modes are generally categorized into two modes; buckling and fracture of brace member, and yielding of joints and fasteners. After a lot of earthquake disasters, the technical manual has been published to repair and recover the damaged building structures in Japan [1]. The manual suggests the actual repairing method for damaged steel braced structures; however, it is guessed that a few of these methods have some difficulties related to construction technique and estimation of recovery after repair. In this paper, new repairing method for joints on damaged steel brace structure has been proposed, and its applicability and feasibility are investigated experimentally. Herein, the horizontally loading test on diagonal steel brace are performed with parameters as follows; thickness of gusset plate, layout of bolts, slenderness ratio of brace and the method of joint. At first, the damaged state of gusset plate is reproduced by horizontally loading test. Next, the damaged gusset plate is repaired. Finally, the loading test is done to the repaired specimen again. From the test results, the strength is reinforced after repair, and the rigidity is almost same. The change of failure mode and slenderness ratio is presented, and which is related to eccentric distance and torsional parameters. Furthermore, the evaluation method of the failure mode and buckling strength are proposed, and this estimation method shows good utility.

Keywords: Steel braced structure; Ultimate seismic state; Repair method; Gusset plate; Evaluation method

Introduction

Recently a lot of buildings are damaged variously after huge earthquake disasters, and it is necessary to decide whether they are rebuilt or reuse. The steel frame structures are classified roughly into a rahmen and braced structure, and serious damages are reported to both of them. Receiving that, the word “resilience” is focused on. From the viewpoint of reconstruction and restoration of city function promptly, it is desirable to repair and reuse the public buildings which become the base of recover and reconstruction in the stricken area. Also, these public buildings are mainly braced structure. There are many reports that the various types of failure modes of steel braced structure, such as buckling, fracture of brace member, and yielding of joints and fasteners. In Japan, the corresponding to these failure modes is discussed in the technical guideline). The guideline suggests some actual repair methods, however, it is not necessary the best method considering the state of stricken area. In this study, in case of the gusset plate is damaged, the new method which takes place the conventional method is suggested and the horizontally loading tests are conducted on diagonal steel bracing. And this paper aims to propose an evaluation method of repaired state.

Materials and Methods

Repair methods of damaged steel brace joint

This study focuses on the failure mode of joint which out of plane deformation is occurred during ultimate seismic state. It is premised that the damaged brace and fasteners are replaced and the gusset plate is repaired. When the new brace is attached on the damaged gusset plate, a clearance occurs between gusset plate and brace. And the tapered steel filler is inserted on this clearance. And to restrain the deformation of gusset plate, the side stiffener is attached. The outline of repair method is as follows: First, the tapered steel filler is welded on damaged gusset plate. Next, the side stiffener is welded on the side of gusset plate. The details of proposed repair methods are shown in Figure 1.

Inspection of repair effect by horizontally loading test

The outline of horizontally loading test: In this loading test, the test specimen and test setup are illustrated in Figure 2. The flow of the loading test is as follows: First, the test frame (Figure 2) is horizontally loaded and a brace member and gusset plates are damaged (herein after referred to as “Initial loading”). Second, the gusset plates which damaged by initial loading is repaired. Finally, the loading test is done to the repair specimen again (herein after referred to as “Second loading”).

Experimental parameters: Experimental parameters are as follows: the layout of bolts on joint, the thickness of gusset plate, repair or not repair after initial loading, the slenderness ratio of the brace and the usage of tapered steel filler. The layout of bolts is determined by the length of brace. The thickness of gusset plate is 4.5 mm, 6 mm, 16 mm. The slenderness ratio of the brace is 90, 100,150. And also, the loading program is monotonic and cyclic loading. On the monotonic loading, the brace member or the gusset plate become the ultimate states. During the cyclic loading, maximum story deformation angle is 1/30 radian. Test specimens were instrumented with sensors for measuring below items: horizontal displacement, in and out of plane deformation of brace, out of plane of the gusset plate. Strain of brace is measured at the 200 mm, 400 mm, 600 mm, and 800 mm from the end of brace. Mechanical properties of materials and specimens list are summarized in Tables 1 and 2.

Test results

Initial loading test results

During loading test, three kinds of failure mode were observed, and it is summarized in Figure 3. Also, on the occasion of the buckling

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occurred, two kinds of bending mode were observed as showed in Figure 4.

L150 series: During the monotonic loading, it was observed that the brace remained within elastic when the buckling was occurred. The gusset plate and the brace members deformed to out of plane in one unit until the buckling is occurred. After buckling was occurred, the plastic hinge was formed at the middle of the brace and the connection between brace and gusset plate (herein after referred to as "failure mode C"). And also, the out of plane of the brace was remarkable. In case of large slenderness ratio, the bending moment to the gusset plate does not become so large. Therefore, out of plane of gusset plate wasn't so large. Furthermore, the connection between brace and gusset plate was twisted. During the cyclic loading, the connection was twisted and the plastic hinge was formed at the middle of brace and connection.

L100-6 series: From the results of strain during monotonic and cyclic loading, the occurrence of intermediate of elastic and plastic buckling was considered. A plastic hinge was generated on middle of the brace (herein after referred to as "failure mode A") on the all specimens. The out of plane deformation is observed on gusset plate.

L100-16 series: The occurrence of intermediate of elastic and plastic buckling was considered. The plastic hinge was generated on middle and both end of brace, because the gusset plate didn't deform. (herein after referred to as "failure mode B").

L90 series: In case of small slenderness ratio, axial load was larger than any other series and bending moment to gusset plate exerted enough. Therefore, the out of plane of gusset plate was the largest. Also the failure mode A was observed on all specimens.

The damage situation and the repair method

Exclude the L100-16 series; all gusset plates have plastic deformation. The result of residual deformation was summarized in Table 3. In case of the L150 series, the tapered steel filler wasn't

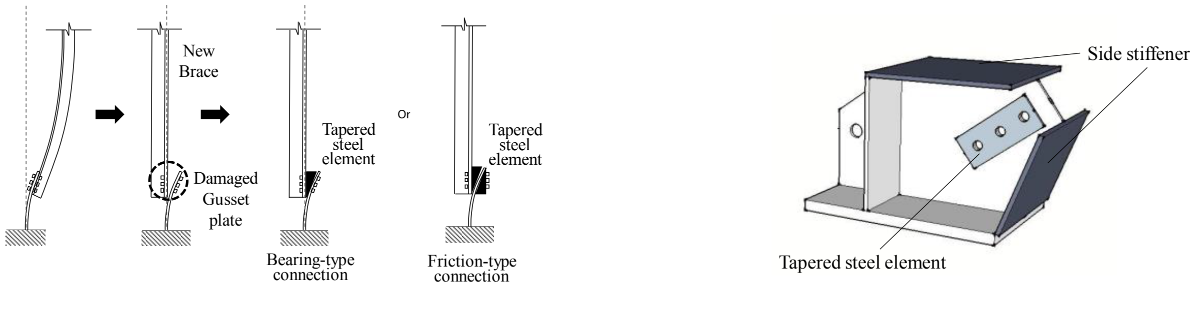

Figure 1: Repair method.

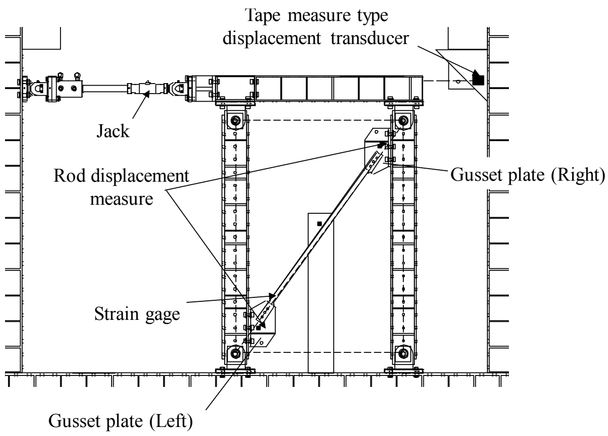

Figure 2: Test set up.

	Rot	Young's modulus (GPa)	Yield strain (μ)	Yield strength (N/mm²)	Tensile strength (N/mm²)
Gusset plate	a	205	1657	274	437
	b	218	1882	357	444
	c	203	1531	311	459
	d	201	1860	351	433
	e	207	2260	416	538
Brace	a	209	1558	337	472
	b	212	1598	338	454
	c	188	1422	299	398
	d	206	1510	285	396

Table 1: Mechanical properties of steel materials.

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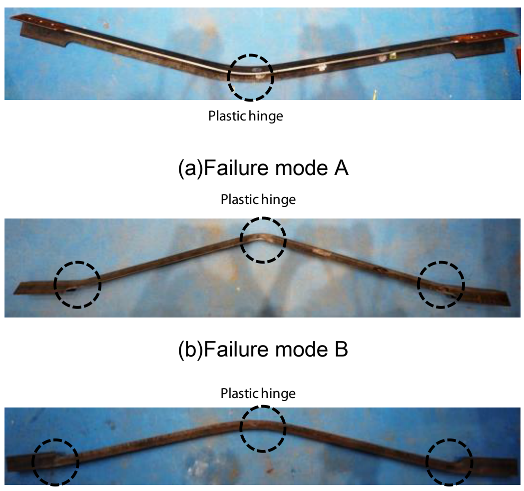
<table>
<tr><th rowspan="2">Specimen name</th><th rowspan="2">Slenderness ratio</th><th rowspan="2">Thickness (mm)</th><th rowspan="2">Bolt layout (mm)</th><th rowspan="2">Friction</th><th rowspan="2">Repair</th><th rowspan="2">Loading pattern</th><th colspan="2">Lot</th></tr>
<tr><th>Gusset plate</th><th>Brace</th></tr>
<tr><td>L90-4.5-0-F-R-M1</td><td rowspan="4">90</td><td rowspan="16">4.5</td><td rowspan="24">0</td><td rowspan="16">Friction</td><td rowspan="8">Repair</td><td rowspan="2">Monotonic</td><td rowspan="16">a</td><td rowspan="4">a</td></tr>
<tr><td>L90-4.5-0-F-R-M2</td></tr>
<tr><td>L90-4.5-0-F-R-C1</td><td rowspan="2">Cyclic</td></tr>
<tr><td>L90-4.5-0-F-R-C2</td></tr>
<tr><td>L150-4.5-0-F-R-M1</td><td rowspan="4">150</td><td rowspan="2">Monotonic</td><td rowspan="4">b</td></tr>
<tr><td>L150-4.5-0-F-R-M2</td></tr>
<tr><td>L150-4.5-0-F-R-C1</td><td rowspan="2">Cyclic</td></tr>
<tr><td>L150-4.5-0-F-R-C2</td></tr>
<tr><td>L90-4.5-0-F-N-M1</td><td rowspan="4">90</td><td rowspan="12">Non-repair</td><td rowspan="2">Monotonic</td><td rowspan="4">a</td></tr>
<tr><td>L90-4.5-0-F-N-M2</td></tr>
<tr><td>L90-4.5-0-F-N-C1</td><td rowspan="2">Cyclic</td></tr>
<tr><td>L90-4.5-0-F-N-C2</td></tr>
<tr><td>L150-4.5-0-F-N-M1</td><td rowspan="4">150</td><td rowspan="2">Monotonic</td><td rowspan="4">b</td></tr>
<tr><td>L150-4.5-0-F-N-M2</td></tr>
<tr><td>L150-4.5-0-F-N-C1</td><td rowspan="2">Cyclic</td></tr>
<tr><td>L150-4.5-0-F-N-C2</td></tr>
<tr><td>L100-6-0-NF-N-M1</td><td rowspan="18">100</td><td rowspan="12">6</td><td rowspan="8">Non- friction</td><td rowspan="2">Monotonic</td><td rowspan="4">d</td><td rowspan="4">d</td></tr>
<tr><td>L100-6-0-NF-N-M2</td></tr>
<tr><td>L100-6-0-NF-N-C1</td><td rowspan="2">Cyclic</td></tr>
<tr><td>L100-6-0-NF-N-C2</td></tr>
<tr><td>L100-6-0-NF-R-M1</td><td rowspan="8">Repair</td><td rowspan="2">Monotonic</td><td rowspan="8">b</td><td rowspan="8">c</td></tr>
<tr><td>L100-6-0-NF-R-M2</td></tr>
<tr><td>L100-6-0-NF-R-C1</td><td rowspan="2">Cyclic</td></tr>
<tr><td>L100-6-0-NF-R-C2</td></tr>
<tr><td>L100-6-40-F-R-M1</td><td rowspan="4">40</td><td>Friction</td><td rowspan="2">Monotonic</td></tr>
<tr><td>L100-6-40-NF-R-M2</td><td rowspan="3">Non- friction</td></tr>
<tr><td>L100-6-40-NF-R-C1</td><td rowspan="2">Cyclic</td></tr>
<tr><td>L100-6-40-NF-R-C2</td></tr>
<tr><td>L100-16-0-F-N-M1</td><td rowspan="6">16</td><td rowspan="4">0</td><td rowspan="6">Friction</td><td rowspan="2">Non- repair</td><td>Monotonic</td><td rowspan="6">e</td><td rowspan="2">d</td></tr>
<tr><td>L100-16-0-F-N-C1</td><td>Cyclic</td></tr>
<tr><td>L100-16-0-F-R-M1</td><td rowspan="4">Repair</td><td>Monotonic</td><td rowspan="4">c</td></tr>
<tr><td>L100-16-0-F-R-C1</td><td>Cyclic</td></tr>
<tr><td>L100-16-40-F-R-M1</td><td rowspan="2">40</td><td>Monotonic</td></tr>
<tr><td>L100-16-40-F-R-C1</td><td>Cyclic</td></tr>
</table>

Table 2: Specimens list.



(a)Failure mode A

(b)Failure mode B

(c)Failure mode C

Figure 3: Failure modes on ultimate state.

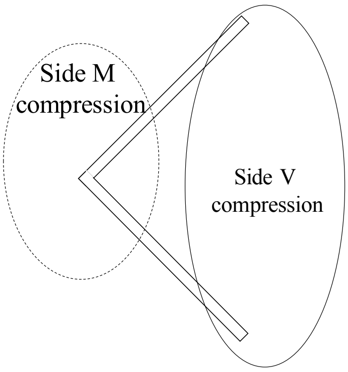


Figure 4: Compression side.

Specimen	side	Residual deformation
L90-4.5-0-F-R-M	L	13.9
	R	13.2
L90-4.5-0-F-R-C	L	11.2
	R	17.8
L150-4.5-0-F-R-M	L	5.1
	R	8.8
L150-4.5-0-F-R-C	L	5
	R	1.9
L100-6-0-F-R-M	L	3.1
	R	4.2
L100-6-0-F-R-C	L	8.1
	R	3.7
L100-6-40-F-R-M	L	38
	R	37.8
L100-6-40-F-R-C	L	11.2
	R	20.5

Table 3: Residual deformation (mm).

Name of specimen	Axial rigidity (kN/mm^2)	Ratio of rigidity	Buckling load (kN)	Ratio of buckling load	Buckling length (mm)	Failure mode*	Compression side
L90-4.5-0-F-R-M1	10.5	1.0	57.0	1.5	1360	B→TB	M
L90-4.5-0-F-R-M2	10.7		85.1		800	TB	V
L90-4.5-0-F-R-C1	13.2	0.7	56.4	1.0	1440	B→TB	M
L90-4.5-0-F-R-C2	9.3		56.5		880	TB	V
L150-4.5-0-F-R-M1	8.4	1.0	20.3	1.1	1760	B→TB	M
L150-4.5-0-F-R-M2	8.4		21.7		800	B	V
L150-4.5-0-F-R-C1	8.4	1.0	23.2	1.0	1200	B→TB	M
L150-4.5-0-F-R-C2	8.1		23.2		800	B	V
L90-4.5-0-F-N-M1	12.0	0.8	57	1.2	1520	B	M
L90-4.5-0-F-N-M2	10.0		70.7		1200	B	M
L90-4.5-0-F-N-C1	12.4	0.8	57.9	1.2	1600	B	M
L90-4.5-0-F-N-C2	9.7		67.1		1200	B	M
L150-4.5-0-F-N-M1	7.0	0.9	19.1	0.9	960	B→TB	M
L150-4.5-0-F-N-M2	6.1		17.1		800	TB	V
L150-4.5-0-F-N-C1	6.6	0.8	18.6	1.0	1440	B→TB	M
L150-4.5-0-F-N-C2	5.4		18.3		800	TB	V
L100-6-0-NF-N-M1	15.2	0.9	38.1	1.2	1150	B	M
L100-6-0-NF-N-M2	13.2		47.5		-	B	M
L100-6-0-NF-N-C1	11.1	0.9	35.9	1.4		B	M
L100-6-0-NF-N-C2	10.5		49.7			B→TB	M
L100-6-0-NF-R-M1	15.4	0.6	37.8	1.1	1340	B	M
L100-6-0-NF-R-M2	9.1		41.4		950	B→TB	V

L100-6-0-NF-R-C1	12	1.0	39.8	1.2		B	M
L100-6-0-NF-R-C2	11.5		48.5			B	V
L100-6-40-F-R-M1	12.3	1.1	42.1	1.0	1320	B	M
L100-6-40-NF-R-M2	13.3		40.7		1050	B	V
L100-6-40-NF-R-C1	15.5	0.6	37.9	1.5		B	M
L100-6-40-NF-R-C2	9.4		55.2			B→TB	V
L100-16-0-F-N-M1	15.5		63.4		880	B→TB	M
L100-16-0-F-N-C1	18.1		61.2			B→TB	M
L100-16-0-F-R-M1	14.6		61		800	B	V
L100-16-0-F-R-C1	14.5		57.9		-	B	V
L100-16-40-F-R-M1	14.6		49.7			B	V
L100-16-40-F-R-C1	12.8		47.2			B	V
*B = Bending, TB = Torsional bending							

Table 4: Comparison of test results.

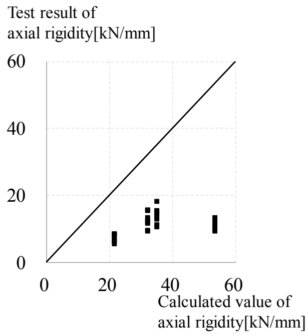


Figure 5: Comparison of axial.

attached. According to the "Guidebook on Design and Fabrication of High Strength Bolted Connections [2]. When the clearance is less than 1 mm, filler isn't necessary. The reason is that the gusset plate wasn't repaired by tapered steel filler. The details of repair materials are bellow. As mentioned in chapter 2, the tapered steel filler is welded on damaged gusset plate. Note that the repair method of connection is one of the experimental parameters, the specimen by using friction joint is soaked rust by medicine. And also, when the brace is fastened with the gusset plate by the bolts normally, and then the same shape of tapered steel filler is adopted on both side of brace test specimen. The usage of tapered steel filler is shown in Figure 1.

Second loading test results

L150-N series: On the damaged state, a clearance between gusset plate and brace were existing. And this clearance was disappeared little after the bolts were fastened. From the test results, the elastic buckling was occurred on all specimens, and side V is presented as the state of compression. Since the initial deformation exist on the brace, not enough bending moment exerted to the gusset plate.

L100-N series: In a similar manner of L150 series, there was a clearance between the gusset plate and the brace. From the test results, with comparison to the initial loading, the maximum load (buckling load) becomes larger. Differ from the L150 series; bending moment exerted enough to return the gusset plate. Therefore, during second loading, the maximum load became larger compared with initial loading.

L90-N series: The clearance between gusset plate and the brace was the largest of all series. In a similar manner of the L100 series, the maximum load was larger than initial loading. However, the bolts slipped frequently.

L150-R series: Differ from the non-repair specimens, the clearance became less than 1 mm by welding the tapered steel filler on the gusset plate. And also, the side V is presented as the state of compression.

L100-R series: Since the bolts weren't vertically fastened on the gusset plate, they were stiffened as vertically as possible. And also all specimens slipped frequently. So the critical damage was confirmed around the bolt hole of tapered steel element and the gusset plate.

L90-R series: The tapered steel filler was welded on gusset plate. Since the residual deformation was large, measurement error and processing precision was not precisely. Therefore, clearance existed between brace and tapered steel filler. This clearance was disappeared little after the bolts stiffened. And also, initial deformation occurred on brace.

A verification of repair

To make a comparison between initial loading and second loading is shown in Table 4. Expect for L150-4.5- 0-F-N-M, ratio of buckling load is 1.0 or more. From that, the effectiveness of this repair method is confirmed.

Study on the strength and ductility

Initial stiffness: Figure 5 compares the rigidity obtained from test and theoretical result. On all specimens, test result underestimates the rigidity. This is assumed that the frictional force function not sufficiently because of slip.

Buckling length: The buckling length of repaired specimens become shorter than before repair. Judging from that, the bearing situation is enhanced and come close to the fix support.

Deformed state: About the L100-16 and repaired specimens, deformation of brace advances in plane, whereas other specimens (before repaired specimens) advance out of plane. By this, in case of the bearing situation come close to fix, direction of deformation proceeds to in plane. In addition, as showed in Table 4, repaired specimens (in brief, in the case of bearing situation of joint is enhanced) tend to be compressed "side V".

Curvature distribution: As a representative example of specimens, the curvature description of L100-6-0-F-R-M is described in Figure 6. Focusing on 600 mm in Figure 5a, as the ductility factor rises, the curvature rises too. However, focusing on 600 mm in Figure 5b, there is no difference in curvature. By this, side stiffener restrains the deformation not only gusset plate but brace.

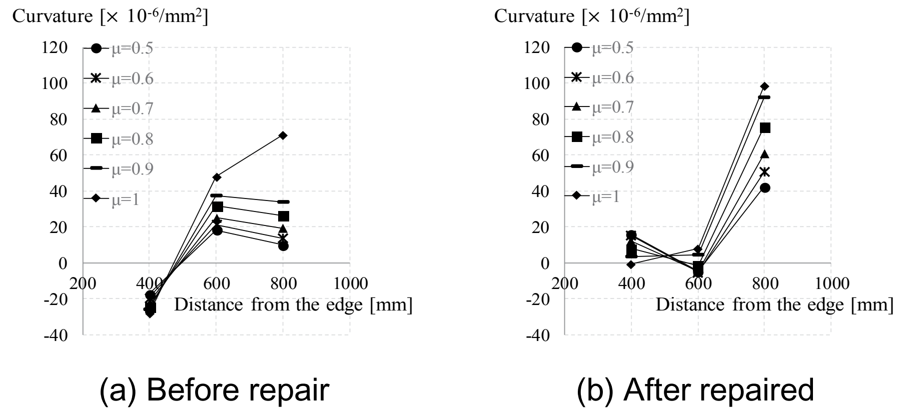


Figure 6: Comparison of curvature distribution.

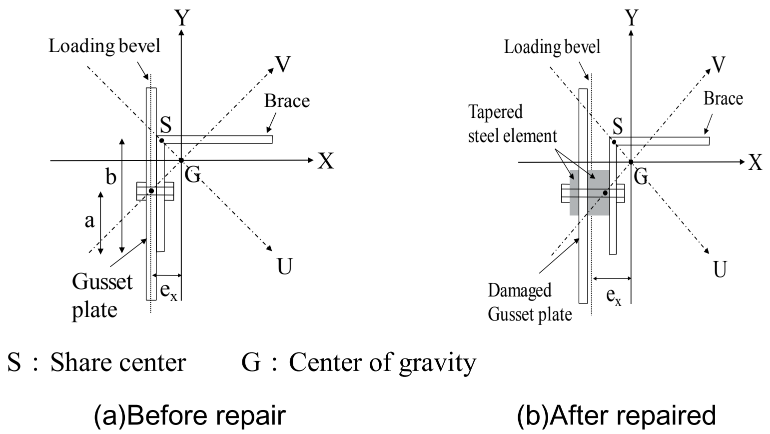


Figure 7: Section of joint.

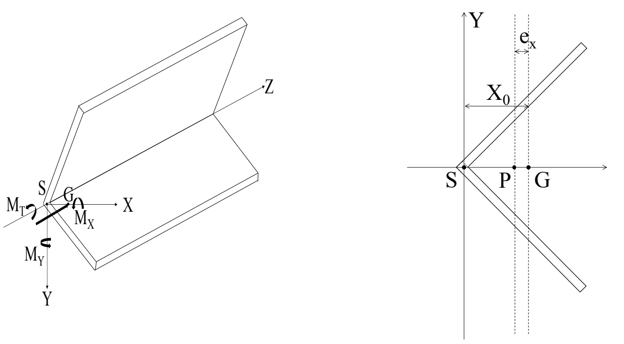


Figure 8: Definition of the variable.

Proposal of evaluation method of buckling load

General description of evaluation method

By a foregoing chapter, in case of the bearing situation is enhanced, torsional buckling is likely to occur. And also, the buckling load reverted to original state by repairing. Therefore, the repairing method in this study is effective for damaged bracing structure. In this chapter, the evaluation method of buckling load for original state and repaired state is discussed.

Variable of evaluation method

Bearing situation: Considering the circumstances of connection, bearing situation is calculated. Furthermore, by attaching side stiffener, the rigidity of gusset plate is ten times as large as original state. So in this method, the rigidity of repaired gusset plate calculated the same way.

Eccentric distance: A cross section of the repaired gusset plate is shown in Figure 7. The eccentric distance of original state is calculated by equation (1), and after repaired is calculated by equation (2). Note that, the tsp1 and the tsp2 is thickness of tapered steel element.

$$e_x = \left(g + \frac{t_g}{\sqrt{2}} - \frac{(b-a) - \frac{t_g}{2}}{\sqrt{2}} - t_b \right)$$

$$e_x = \left(g + \frac{t_g + t_{sp1} + t_{sp2}}{\sqrt{2}} \right) - \frac{(b-a) + \frac{t_g + t_{sp1} + t_{sp2}}{2} - t_b}{\sqrt{2}}$$

Evaluation method

The buckling state is classified into the bending buckling or the lateral torsional buckling by using equation of equilibrium as bending situation and eccentric distance are variables, and buckling load is evaluated. Considering the test situation, boundary conditions are as follows: Mx = Mt = 0, My = pex, P = P, y0 = 0. Equation (3) shows the buckling load in elastic region. The variables of equation (3) are shown in Figure 8. By these equations, the buckling load is called by eccentric distance and bearing situation.

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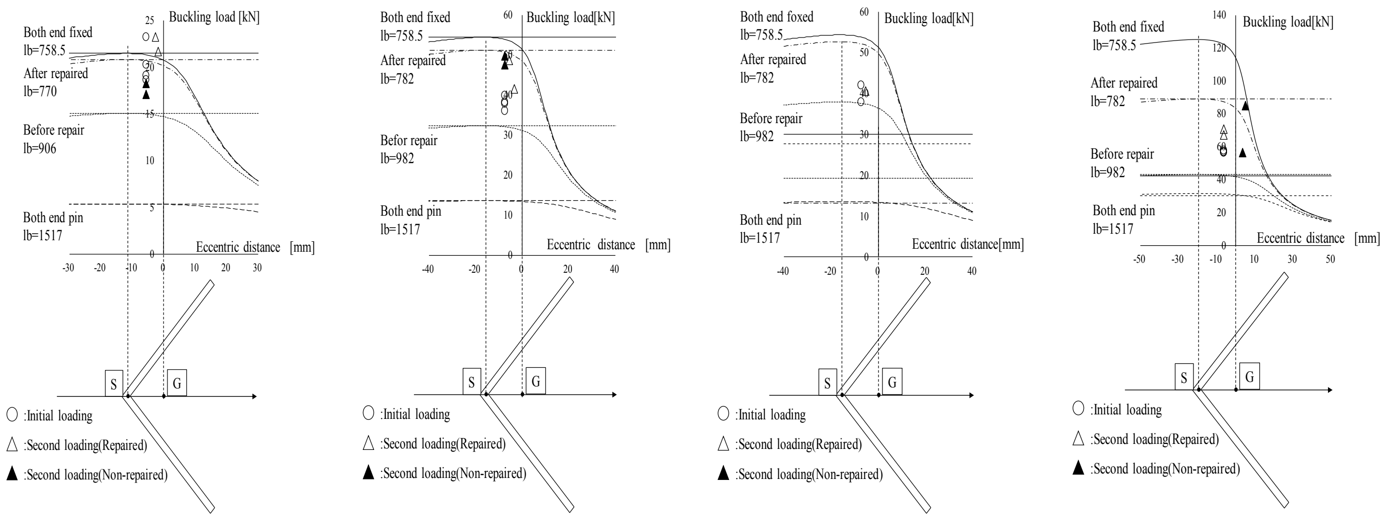

(a)L150series (b)L100-6-0series (c)L100-6-40series (d)L90series

Figure 9: Comparison of test results and evaluation method.

$$P = \frac{(P_w + \alpha P_{EX}) - \sqrt{(P_w - \alpha P_{EX})^2 + 4P_w P_{EX}(x_0/\rho_0)^2}}{2\{\alpha - (X_0/\rho_0)^2\}}$$

$$\rho_0^2 = \int (x^2 + y^2)\,dA/A \qquad (3)$$

$$\alpha = 1 - \frac{e_x\left\{\int x(x^2+y^2)\,dA/A\right\}}{\rho_0^2 I_y}$$

Inspection of evaluation method

L150 series: Relation of eccentric distance and buckling load is shown in Figure 9a. Straight line indicates a bending buckling load; curve indicates a lateral torsional buckling load. In all specimens, the test results exceed the evaluation value. Especially, initial loading test results greatly exceed the evaluation value; it's assumed that the buckling is occurred around the strong axis.

L100-6 series: Relation of eccentric distance and buckling load is shown in Figures 9b and 9c. On the loading test, some specimen became the plastic buckling. Therefore, the plastic buckling load was also described in Figures 9b and 9c. Some repaired specimen, the buckling load is less than the evaluating value. In this case, axial rigidity became around 60%. Therefore, compression stress is not transmitted enough to the brace. Except this specimen, the test results exceed the evaluation value.

L90 series: Relation of eccentric distance and buckling load is shown in Figure 9d. The plastic buckling load is also described in Figure 9d. Except some repaired specimen, test results exceed the evaluating value. In repaired specimens which are falling below the evaluating value, they became a plastic lateral torsional buckling. So this evaluation method is not enough to such situation. However, considering the Young's modules decline to around 65%, this evaluation method can apply to this series.

Conclusion

This paper focused on repair methods for damaged steel brace members. The main conclusions are shown below:

1. To investigate the mechanical property, loading tests was performed. From the test results, it is confirmed the buckling load and rigidity were almost recovered to original state.

2. By using the equation of equilibrium, the evaluation method was proposed and comparison with test results. About specimens which became elastic buckling, evaluating value underestimate the buckling load. However, for other specimens, this method gives good result.

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References

1. The Japan Building Disaster Prevention Association (2001) Technical Manual.
2. Architectural Institute of Japan (2011) Guidebook on Design and fabrication of high strength bolted connection.

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