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A REPAIR METHOD FOR LOCAL BUCKLED WIDE FLANGE COLUMNS

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SUMMARY

An experimental study on probable repair techniques for steel frames was carried out. The purpose of this study was to investigate a repair method for wide flange columns subjected to local buckling which are supposed to be caused by earthquakes. Steel portal frames and column members were tested. They were horizontally loaded to severe plastic region under constant vertical load, before and after the repair or reinforcement. The test results and the design procedure were discussed and the structural performance of the post-repaired columns were evaluated.

INTRODUCTION

A number of structures have been damaged due to past major earthquakes. In Japan, there were many damage of steel structures at their bolted connections and their column footings etc.. The main reason of those failure are supposed to be an unsatisfactory workmanship or inadequate design of the broken part. However it is also one of the reason that such structures were designed only taking account of elastic characteristics. Most of the members of these moment-resisting steel frames were consisted of comparatively thin plate with large width-to-thickness ratio. They easily suffer from local buckling almost at the start of yielding of the members. At present, there were very few systematic approach to repair methods of such steel structures or members . From these reasons, an experimental study on the repair of damaged steel frames was executed to develope the repair and reinforcement techniques for damaged steel structures.

As for the experiment of the frame specimens, the authors already reported at PSSC in 1986.[1]) In this report, the experiment of the column specimens are mainly referred.

EXPERIMENTAL PROGRAM

Wide flange column members, which were built up using SM50A (JIS G 3106) steel plates, were tested in this experiment. SS41 (JIS G 3101) mild steel plates were applied to repair and reinforcement. Mechanical properties of the steel used in this experiment are shown in Table 1. The applied repair method and dimensions of the specimens were shown in Fig.1. It was adopted as the repair method of damaged column that steel plates were welded perpendicular to the local buckled flange plates, leaving proper gaps between column end and the edge of welded plates. The thickness of the repair plates was equal to that of flange plates of the specimen to be repaired. The tee joints connecting buckled

Table 1 Mechanical Properties by Tensile Test

Section of Specimen	Grade of Steel		Y.P. (kg/mm²)	T.S. (kg/mm²)	El. (%)
BH-250×250×6×9	Flange	SM 50	39	55	22
	Web	SM 50	40	52	19
BH-250×250×9×12	Flange	SM 50	38	54	25
	Web	SM 50	39	55	22
Steel Plate for Repair	PL-9	SS 41	31	48	25
	PL-12	SS 41	31	47	29

Y.P. : Yield Point, T.S. : Tensile Strength, El. : Elongation

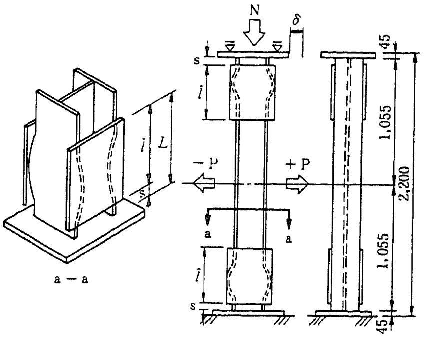

Fig.1 Specimen

buckled flange and patching plates were welded by partial penetration welding after edge preparation of buckled flange plates was done. Though root opening was rather wide (maximum 5 mm), these welding in field was performed satisfactorily. Six column type specimens in total were tested. The test parameters and the dimensions of the each specimen are listed in Table 2. The influence of such parameters as axial load, width-to-thickness ratio of flange plate (b/t), dimensions of s and $\bar{l}$ (see Fig.1) and degree of damage were investigated. An original specimen before repair or reinforcement settled in the loading apparatus is shown in Fig.2. Using hydraulic jacks, five original specimens except for No.6 were horizontally loaded cyclically beforehand. Consequently, there occurred considerable local buckling at the top and the bottom of the column. The wave of the local buckling of the flange was nearly 250 mm in length and 23-45 mm in height, as shown in Photo 1. The degree of damage of No.3 specimen was less than the others. It was also one of variables of this experiment. No.6 specimen was referred to a reinforcement of a non-damaged column. Their lateral drift deformation were reformed to almost zero before repair. After repair or reinforcement, specimens were horizontally loaded again to severe plastic region cyclically, being subjected to a constant vertical load which was 20 % (10% for No.4 specimen) of the axial yield load of the specimens. The loading program is shown in Fig.3.

Table 2 List of Specimens

No.	section	b/t	δ max (mm)	N/Ny	s (mm)	$\bar{l}$ (mm)	remarks
No. 1	BH-250×250×6×9	14	60	0.2	50	450	prototype
No. 2	BH-250×250×9×12	10	60	0.2	50	450	b/t
No. 3	BH-250×250×6×9	14	40	0.2	50	450	damage
No. 4	BH-250×250×6×9	14	60	0.1	50	450	N/Ny
No. 5	BH-250×250×6×9	14	60	0.2	75	450	s
No. 6	BH-250×250×6×9	14	0	0.2	50	650	non-damage

b/t : width to thickness ratio of the flange plate
δmax : maximum lateral displacement at former loading
N/Ny : ratio of axial compressive load to yield load
s : distance between the edge of the repair plate and the end plate
$\bar{l}$: length of the repair plate

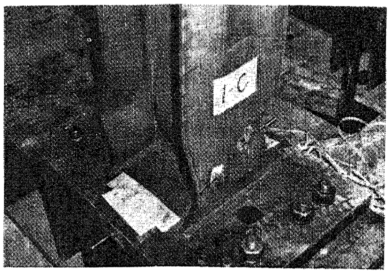

Photo 1 Local Buckling of Column End

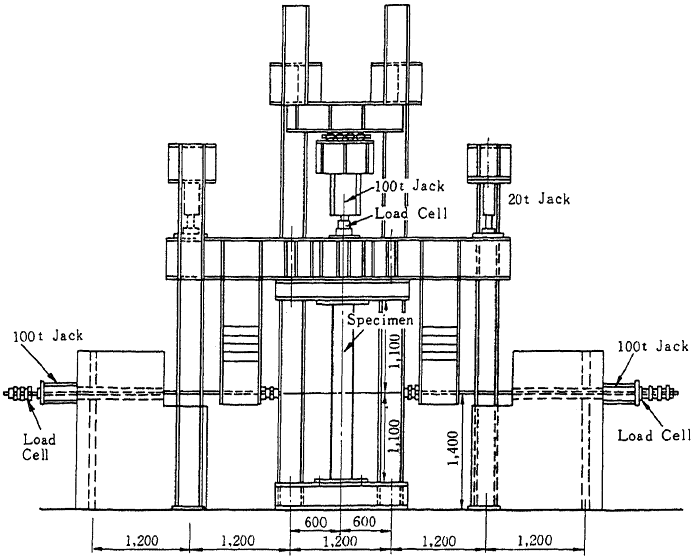

Fig.2 Loading apparatus

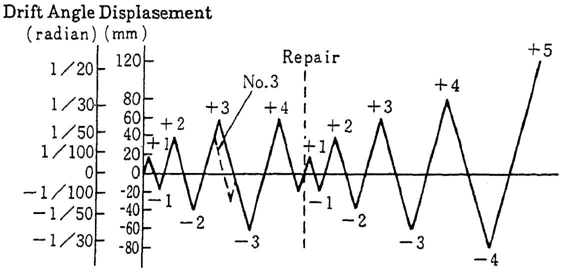

Fig.3 Loading Program

EXPERIMENTAL RESULTS

The load versus displacement relations of the repaired or reinforced specimens are shown in Fig.4, where the dotted lines indicate those of the original specimens and the broken lines express the calculated values of elastic stiffness and full-plastic load of the original specimens, taking into account p-δ effect. The test results and the calculated values are listed in Table 3, where the elastic stiffness K_e gives the secant modulus at the horizontal load of 5.0 tonf (49 kN), and the yield load P_y, which is so called the general yield strength, gives the load at the point where the tangent modulus is 1/3 K_e in each initial load-displacement curve.

As shown in Fig.4, the load-displacement relationships of the original specimens were accurately predicted by simple plastic analysis taking into P-δ effect. The original specimens were subjected to local buckling of all flange plates and web plates at the column ends. The initial local buckling of the original frames occurred at the time when the column end moment reached almost the yielding moment, because of large width-to-thickness ratio of the plates. The restoring force clearly decreased after maximum strength. The specimens lost their restoring force about 40 % of maximum strength at the stage of horizontal displacement of 60 mm in the case of No.1 and No.5 specimens. Subsequently, these damaged specimens were repaired according to the way as mentioned before (see Fig.1, Table 2).

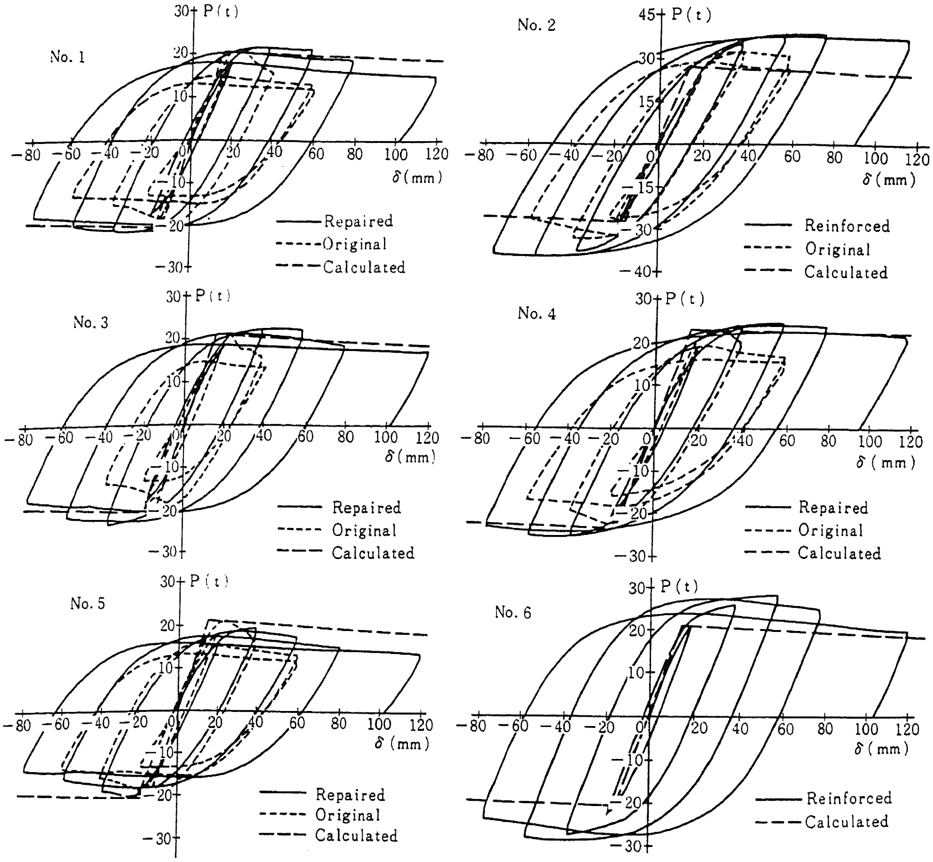

Fig. 4 Load versus Displacement Relations

Table 3 Test Results

Characteristics / No. of Specimen		Elastic Stiffness			Yield Load	Disp. at Py	Maximum Load			Disp. at. Pu	Ductility Factor	Height of Local Buckling (cm)
		Ke (t/cm)	cKe (t/cm)	Ke/cKe	Py (t)	δy (cm)	Pu (t)	cPu (t)	Pu/cPu	δu(cm)	δu/δy	
No. 1	Original	12.5	14.1	0.89	19.8	1.99	20.6	21.1	0.98	2.18	1.10	4.5
	Repaired	12.0	14.1	0.85	19.1	2.06	21.8	21.1	1.03	3.78	1.83	–
	Rep./Ori.	0.96	–	–	0.96	1.04	1.06	–	–	1.73	1.66	–
No. 2	Original	15.5	18.9	0.82	27.0	2.05	32.8	27.4	1.20	3.83	1.87	2.3
	Repaired	16.9	18.9	0.89	30.0	2.56	38.7	27.4	1.41	6.63	2.59	–
	Rep./Ori.	1.09	–	–	1.11	1.25	1.18	–	–	1.73	1.38	–
No. 3	Original	12.0	14.1	0.85	20.0	2.06	20.7	21.1	0.98	2.41	1.17	2.5
	Repaired	12.4	14.1	0.88	20.0	2.09	22.6	21.1	1.07	4.39	2.10	–
	Rep./Ori.	1.03	–	–	1.00	1.01	1.09	–	–	1.82	1.80	–
No. 4	Original	11.3	14.2	0.80	21.6	2.39	22.6	23.1	0.98	2.70	1.13	2.8
	Repaired	11.8	14.2	0.83	20.0	2.59	24.3	23.1	1.05	5.78	2.23	–
	Rep./Ori.	1.04	–	–	0.93	1.08	1.08	–	–	2.14	1.97	–
No. 5	Original	12.2	14.1	0.87	20.0	1.98	21.0	21.1	1.00	2.39	1.21	4.3
	Repaired	10.7	14.1	0.76	17.0	2.24	19.6	21.1	0.93	3.99	1.78	–
	Rep./Ori.	0.88	–	–	0.85	1.13	0.93	–	–	1.67	1.48	–
No. 6	Reinforced	14.9	14.1	1.06	21.8	1.86	28.3	21.1	1.34	5.72	3.08	–

• Prefix c means calculaated values.

The load-displacement relationships of the repaired specimens were excellent in comparison with those of the original specimens. The repaired specimens recovered their stiffness and strength to the same degree as those before being damaged. Besides, the repaired specimens showed satisfactory ductility and less reduction of restoring force in plastic range, as shown in Fig. 4. The relation between the decreasing ratio of restoring force at the original loading (P_{f1}/P_{u1}) and the recovery ratio of those at the loading after repair (P_{u2}/P_{f1}) is shown in Fig.5. From Fig.5, the more specimen suffers from damage, the more it recovers the strength after repair. The failure mode of these repaired specimens is classified broadly into two cases in respect of the location of newly occurred local buckling after repair. The schematic illustration of a typical failure at the repaired column end is shown in Fig.6. In case that the outer end of repaired part of the column is exceedingly strong (case I), new local buckling occurs at the outside of the bounds of repaired parts. In the other case of being moderately repaired(case II), cracks at the gaps between column ends and the edge of welded plates progress gradually, and small waves of new local buckling overlap with previous ones at the repaired parts of column flanges as shown in Fig.6. The welded repair plates prevent further development of local buckling and contribute to keep excellent restoring force characteristics.

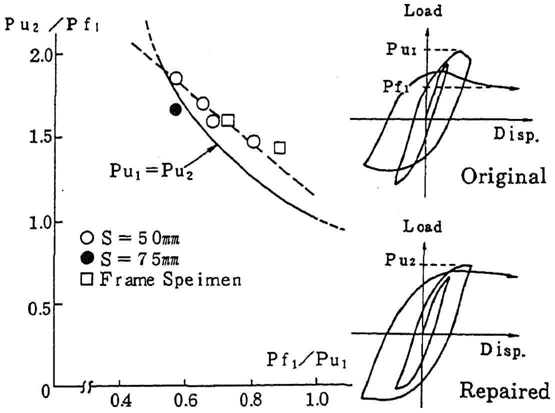

Fig.5 Decreasing Ratio versus Recovery Ratio

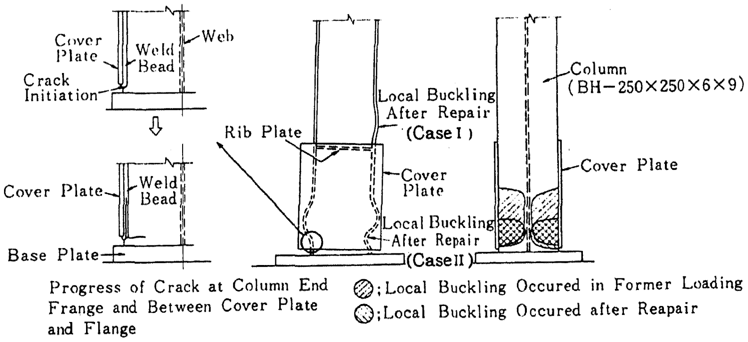

Fig.6 Schematic Illustration of Failure at the End of a Specimen

REPAIRING DESIGN

At the members with large b/t ratio, plastic rotation is mainly caused by bending deformation concentrated in buckled flanges, and the other part scarcely experiences plastic strain. After being repaired, however, the plastic deformation depends on the deformation at the opening gaps of repaired part. Therefore, if repaired adequately, these members, even after damaged severely, will have a sufficient plastic deformability as exhibited in this experiment. To ensure the efficiency of repairing, each dimension L, s shown in Fig.1 and thickness of the repair plate should be designed appropriately.

In order that failure does not occur in unreinforced part, the repair length should be designed as larger than the length L given by equation (1). The length L consists of the essential length l and the spare length x by which shearing force is transmitted at the boundary of reinforcement.

$$L = l + x = (1.0 - M_p/M_u) h + x \quad \text{..............................} (1)$$

where M_p : full plastic moment of original section of the column,
M_u : maximum moment of outer end of repaired part,
h : length between inflection point and outer end of the column

The M_u of the damaged member after repair is considered to depend on the degree of damage and the length of the opening gap at the end of repaired part. But the precise quantitative evaluation of M_u is very difficult at present stage because information about M_u is very little. Thus, tolerating any damage at unrepaired part, if repair length L be given as 1.5 times of local buckling length or twice of the height of the member as designed in this experiment, rather good results will be obtained.

In the case applicable to this repairing manner, flange plate of the member is comparatively thin so that there might be no economic problems, and adequate recovery will be given after repair, even if let thickness of repair plate be equal to that of flange plate of the member.

The opening gap s shown in Fig.1 must be designed, considering the balance between contradictory two requirement. The longer s given, the easier buckles the compressive flange at the opening. On the other hand, the shorter s causes considerable stress concentration and rapid progression of a crack at the opening. The authors propose that the dimension s could be designed as 1/5 times of the width of the column to be repaired, as applied in this experiment which resulted a excellent performance. In addition to it, buckled part of the flange plate should be covered with added plate certainly.

CONCLUSIONS

An experiment was carried out to propose a practical repair technique for damaged steel columns and satisfactory results were obtained. Based on the test results, a design details for repairs of local buckled wide flange columns were proposed, and it was shown that the structural performance of the post-repaired columns were well improved.

REFERENCES

1. Tanaka,A.,Izumi,M. and Narihara,H.,"Experimental Study on the Repair of Steel Structures Severely Damaged due to Earthquake", Proceedings of the Pacific Structural Steel Conference, 4-8 August, 1986, Auckland, New Zealand, Volume 2, pp257-267, (1986)