Design Formula for Rehabilitated Angle Steel Member Using Carbon Fiber Reinforced Plastic Plates

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SUMMARY:
Aging and deterioration of existing steel structures necessitates the development of simple and efficient rehabilitation techniques. The authors have developed a tensile force strengthening method using bonded carbon fiber reinforced plastic (CFRP) plate to enhance the lives of existing buildings. This paper reports the results of compressive loading tests on an angle steel brace before and after rehabilitation using bonded CFRP plates.
These results show enhanced compressive force carrying capacity and deformation capacity as follows.

1) Although buckling tests showed enhanced flexural rigidity, there was no increment of axial stiffness.
2) An elastic buckling formula using the experimental flexural rigidity from a three-point bending test, gave a conservative evaluation of load carrying capacity.
3) Taking into count the contribution of CFRP up to the elastic limit strain of the steel member, its load carrying capacity could be evaluated from the formula of the Design Standard for Steel Structures of AIJ.

Keywords: Carbon fiber reinforced plastic plate, Angle steel member, Bonding, Buckling

1. INTRODUCTION

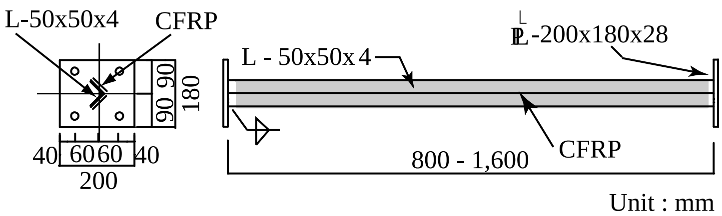
A Steel Tower to transmit the power was designed by a standard based on allowable stress concept.
A steel tower which transmits a necessary outside power supply to cool a nuclear reactor had collapsed due to great Tohoku earthquake in the first Tokyo Electric Fukushima Nuclear Power Plant.
It is very important to keep a function of power supply alive during and after sever earthquake ground motion. Fujii et al.(Fujii, 2004) was pointed out that the higher axial force acts on tall steel tower under severe earthquake such as Hyogoken-Nanbu earthquake than under strong wind of 40 m/s averaged speed. That is because the natural period of tall steel tower accorded in predominant period of base ground and damping ratio of tall steel tower is less than 1.0 %. To keep a function of the tower during and after earthquake, main column member such as steel angle member must be strengthened against the compressive force.
The authors have developed a tensile force strengthening method using bonded carbon fiber reinforced plastic (CFRP) plate to enhance the lives of existing buildings. Aging and deterioration of existing steel structures necessitates the development of simple and efficient rehabilitation techniques. To enhance the strength and plastic deformation capacity of steel structural members, a rehabilitation technique is required for compressive force strengthening as well as for tensile force strengthening.
Ordinary fiber reinforcement is used for tensile force strengthening.
To demonstrate the applicability of compressive force strengthening using bonded CFRP plates for steel structures, monotonically axial load tests were performed on angle steel members with bonded CFRP plates. It was thus verified that the compressive load carrying capacity of members with bonded CFRP plates is 1.9~3.0 times higher than those without plates. Even if the angle member buckles under axial load, there is no concentration of plastic deformation around the kinked portion (Tamai et al, 2005, 2006).
Buckling tests were performed on full-scale angle steel members of a transmission steel tower as an application example (Tamai et al, 2008).

Practical reinforcement design for this tower required a design formula for easily evaluating the effect of bonded CFRP plates.
Hence, concentrically axial loaded tests were performed on rehabilitated angle steel members with various effective lengths. A strut strength curve expressing the relation between slenderness ratio and buckling strength was thus derived. We also proposed a simple design formula for the reinforcement effect of bonded CFRP.

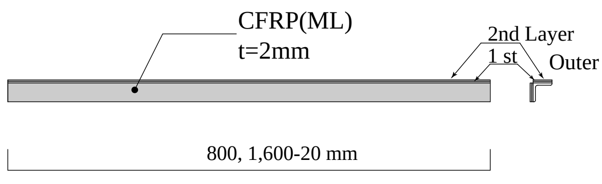
2. DESIGN FORMULA FOR STRENGTHENING BY BONDED CFRP PLATES

2.1. Compression steel angle member bonding CFRP plates

A compression steel angle member with bonded CFRP is shown in Figure 1(a), and the adhesion method is shown in Figure 1(b). The test specimens were angle steel members with carbon fiber plastic plate (CFRP) bonded to their outer surfaces. Two types of CFRP plates were used: TL (high tenacity type carbon fiber, thickness=2mm) and ML (middle modulus type carbon fiber, thickness=2mm). The mechanical properties of these materials are shown in Tables 1(a),(b). The CFRP and adhesive hardened test method was based on the Japan Industrial Standard K7073, K7203. Young's moduli for the CFRP plates were 169kN/mm^2 (TL) and 296kN/mm^2 (ML), which are almost the same as or greater than those of the steel plate. The tensile strengths of the CFRP plates were 3085N/mm^2 (TL) and 2169N/mm^2 (ML), which are 5-7 times of that of steel. The elongation of TL was 1.52% and that of ML was 0.71%. Both the CFRP plates broke suddenly at maximum load. The ML CFRP plate broke into small pieces and the TL CFRP plate exhibited axial tearing. A serrated fracture surface of the fiber was observed in the CFRP plates (TL and ML). Construction by bonding CFRP plates does not need a strong scaffold because CFRP plates are light and easy bond to the members.



(a) Test Specimens



(b) Bonding Method

Figures 1(a),(b). Compression angle steel member bonding CFRP plates

Tables 1(a),(b). Mechanical properties of materials

(a) CFRP and Steel

	Young's Mudulus kN/mm^2	Yield Stress N/mm^2	Tensile Strength N/mm^2	Elongation %
CFRP (TL)	169.1	-	3085.2	1.52
CFRP (ML)	295.7	-	2169.1	0.71
Steel	205.0	318	441	45.7

(b) Adhesive

Young's Mudulus kN/mm^2	Bending Strength N/mm^2	Compressive Strength N/mm^2	Tensile Strength N/mm^2	Tensile and Shear Strength N/mm^2	Impact Strength kJ/m^2
2.28	55.8	59.0	34.8	25.5	4.2
JIS K7208	JIS K7203	JIS K7208	JIS K7113	JIS K6850	JIS K7111

2.2. Design formula for strengthening by bonding CFRP plates

In this section, we propose a strength curve for rehabilitated angle steel members using bonded CFRP plates. The assumptions are:

1) Compression stress is normalized by the area of the steel member.
2) Yield stress for the composite member takes into account the CFRP contribution of axial load resistance up to steel yield.

We imitate the strut curve of the design standard for steel structures, (AIJ, 2005), and adopt the assumptions above. Strut strengths σ_e of the rehabilitated steel angle with bonded CFRP plates are:

For $\lambda^* > \Lambda^*$

$$\sigma_e = \frac{\alpha \cdot \sigma_y^*}{\left(\frac{\lambda^*}{\Lambda^*}\right)^2} \tag{1.a}$$

For $\lambda^* \le \Lambda^*$

$$\sigma_e = \left\langle 1-(1-\alpha)\cdot\left(\frac{\lambda^*}{\Lambda^*}\right)^2\right\rangle \cdot \sigma_y^* \tag{1.b}$$

where,

$$\Lambda^* = \sqrt{\frac{\pi^2 \cdot E_s}{\alpha \cdot \sigma_y^*}} \quad , \quad \lambda^* = \frac{\ell}{i^*} \quad , \quad \sigma_y^* = \frac{\sum_{i=1}^{n} E_{c,i} \cdot \frac{\sigma_{sy}}{E_s} \cdot A_{c,i} + \sigma_{sy} \cdot A_s}{A_s} \tag{2.a-c}$$

α: Experimental constant prescribed in non-elastic region.

$\lambda^*, \Lambda^*, \sigma_y^*, i^*$: Slenderness ratio, elastic limit slenderness ratio, equivalent yield stress, equivalent, radius of gyration of composite member

ℓ: Effective length

E_s, A_s, σ_{sy}: Young's modulus, sectional area, yield stress of steel angle

n: Number of ply of CFRP plate

$(EI)_b$: Flexural rigidity of composite member

The flexural rigidity of a composite member was calculated assuming that the sectional plate normal remains perpendicular to the centroid after deformation.
This assumption is the so called Euler-Bernoulli's hypothesis.

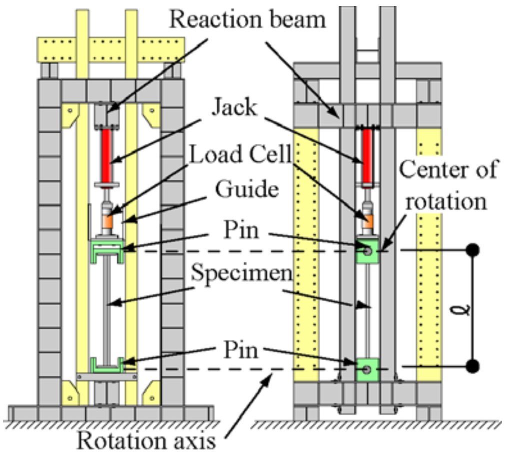
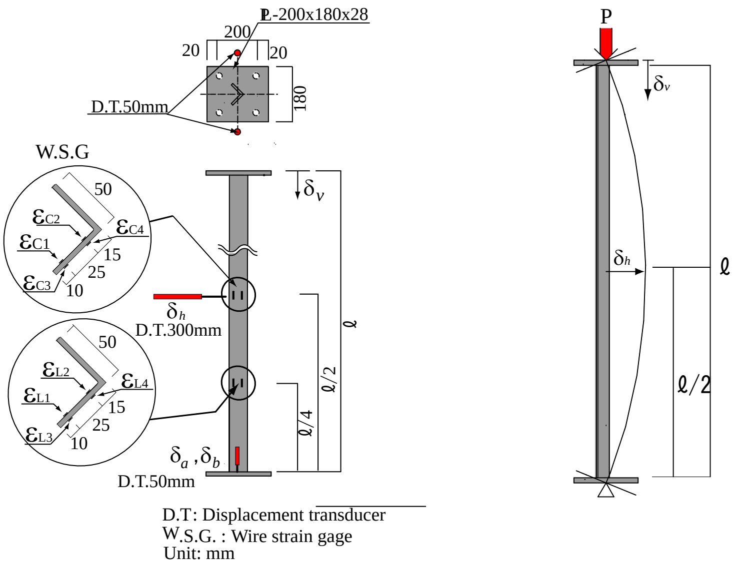


Figure 2. Concentrically axial loading test machine



(a) Location of D.T. and W.S.G. (b) Schematic Illustration of measured values

Figures 3(a),(b). Measurement system

Tables 2(a),(b). List of test specimens

(a) Unstrengthened Specimens

Specimen	ℓ mm	λ* -
L50-08N	800	83
L50-07N	1000	104
L50-06N	1170	122
L50-05N	1300	135
L50-04N	1500	156
L50-03N	1600	166

$i = 9.61mm$, $\Lambda = 103$

σy*=318N/mm2

(b) Strengthened Specimens

Specimen	ℓ	λ*	Thickness of adhesive	
			1st Layer	2nd Layer
	mm	-	mm	mm
L50-08C	800	53	1.22	1.30
L50-07C	1000	66	1.12	1.12
L50-06C	1170	77	1.35	1.06
L50-05C	1300	86	1.27	1.26
L50-04C	1500	99	1.23	1.32
L50-03C	1600	106	1.19	1.28
Average			1.23	

$i^* = 15.1mm$, $\Lambda^* = 78$

σy*=554N/mm2

3. CONCENTRICALLY AXIAL LOADED TEST

3.1. Test specimen and test setup

A test specimen is shown in Figure 1 (a). As shown, it is an L-50x50x4 angle steel member with 2 plies of ML CFRP plate bonded to its outer surface and rectangular steel plates (PL-200x180x28) welded to its ends. The adhesion method is shown in Figure 1(b).

The surface mill scale was removed with a grinding machine, and the surface was then polished with glass paper (#100).

The adhesion agent was epoxy resin hardened at room temperature.

Specimens with lengths of 800, 1000, 1170, 1300, 1500, 1600mm were tested, so as to vary the slenderness ratio. Unstrengthened specimens were also tested as references, making a total of twelve specimens. Tables 2(a),(b) show (a) unstrengthened specimens and (b) strengthened specimens, equivalent slenderness ratio, λ^*, thickness of adhesive layer t_1, t_2. The mechanical properties of the materials, i.e., the angle steel, CFRP, and hardened adhesive, are shown in Tables 1(a) ~(c).

The test apparatus, a concentrically axial loading machine, is shown in Figure 2. The loading program was monotonic until failure was detected.

3.2. Measurement method

The axial load, *P*, was measured from a load cell in the upper joint. Central deflection in the weak-axis direction, δ_h , and shrinkages of end tabs , δ_a, δ_b were measured by 300mm and 50mm stroke displacement transducers. Axial direction strains at the central section ($\varepsilon_{c1}, \varepsilon_{c2}, \varepsilon_{c3}, \varepsilon_{c4}$) were measured by wire strain gages attached as shown in Figure 3(a). The shrinkage of specimen, δ_v , was calculated from shrinkages of the end tabs, δ_a, δ_b , as:

$$\delta_v = \frac{\delta_a + \delta_b}{2} \tag{3}$$

The measured variables are illustrated in Figure 3(b).

4. TEST RESULTS AND DISCUSSIONS

4.1. Test results

The results are shown in Figures 4~6, Tables 3, 4, and Photograph 1. Figure 4 shows the relations between slenderness ratio, λ^*, and flexural rigidity from maximum buckling loads normalized by flexural rigidity of steel member, $\left((EI)_a / E_s I_s\right)$.

Figure 5 compares the compression strength, σ_e , obtained from present formulae Eqns.(1.a), (1,b) with experimental results. Symbols ○, □ show the experimental results. The rigid line and dashed line denote the design formula curves. Tables 3(a),(b) shows effective length, ℓ, maximum load, P_{max} , equivalent slenderness ratio, λ^*, compression strength from experimental result, σ_e , ratio of σ_e to equivalent yield stress, (σ_e/σ_y^*), flexural rigidity from experimental compression strength, $(EI)_a$, ratio of $(EI)_a$ to calculated flexural rigidity, $\left((EI)_a/(EI)_b\right)$, Euler's buckling strength, σ_e^*, and ratio of σ_e to σ_e^* .

Equivalent flexural rigidity for (a) unstrengthened specimens and (b) strengthened specimens are derived from:

$$(EI)_a = \frac{P_{max} \cdot \ell^2}{\pi^2} \tag{4}$$

From the experimental results for specimens with various slenderness ratios, λ^*, the equivalent flexural rigidity $(EI)_a$ for longer specimens (larger slenderness ratios) is constant as calculated $(EI)_b$. For the shorter specimens, the equivalent flexural rigidity $(EI)_a$ becomes smaller, and we can identify the slenderness ratio limit for the non-elastic region from the $(EI)_a$ vs. λ^* relation.

Figures 6(a),(b),(c) show (a) the axial load normalized by full plastic axial force of steel angle $\left(P/P_{sy}\right)$ vs. axial shrinkage normalized by elastic limit shrinkage of steel angle $\left(\delta_v/\delta_{sy}\right)$ relations, (b) the $\left(P/P_{sy}\right)$ vs. central deflection toward weak-axis direction normalized by effective length, $\left(\delta_h/\ell\right)$, relation and (c) the $\left(P/P_{sy}\right)$ vs. axial strain of central section, ($\varepsilon_{c1}, \varepsilon_{c2}, \varepsilon_{c3}, \varepsilon_{c4}$) relations.

Photograph 1 shows the specimens after tests (a) long type (L50-07C) specimens, (b) short type (L50-08C) specimens. In Figure 6(a), the assumed initial stiffness and one without CFRP are drawn for reference. Table 4 compares the maximum axial loads before and after strengthening.

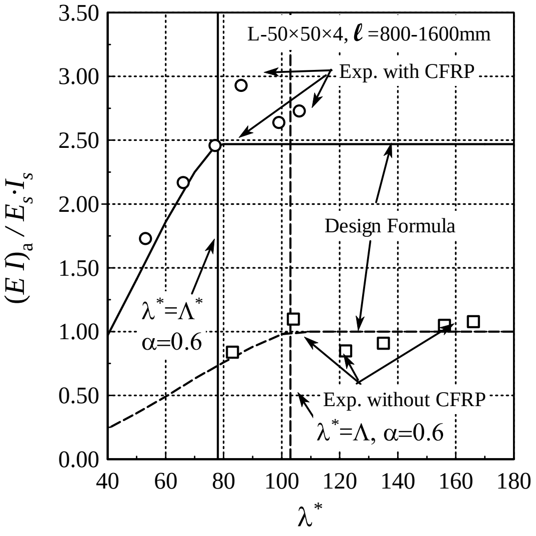


Figure 4. Relations between slenderness ratio and flexural rigidity from axial strength

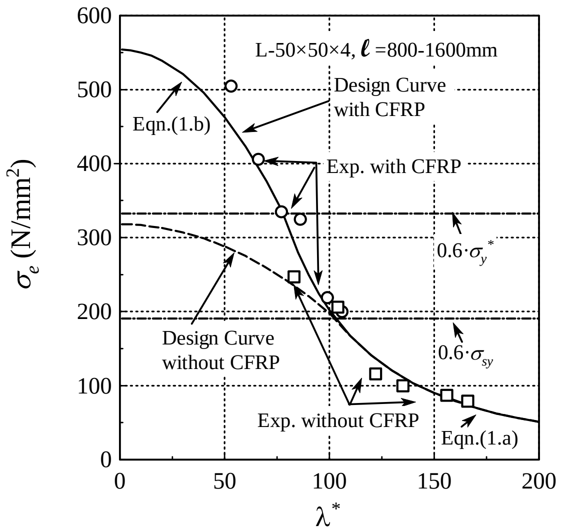
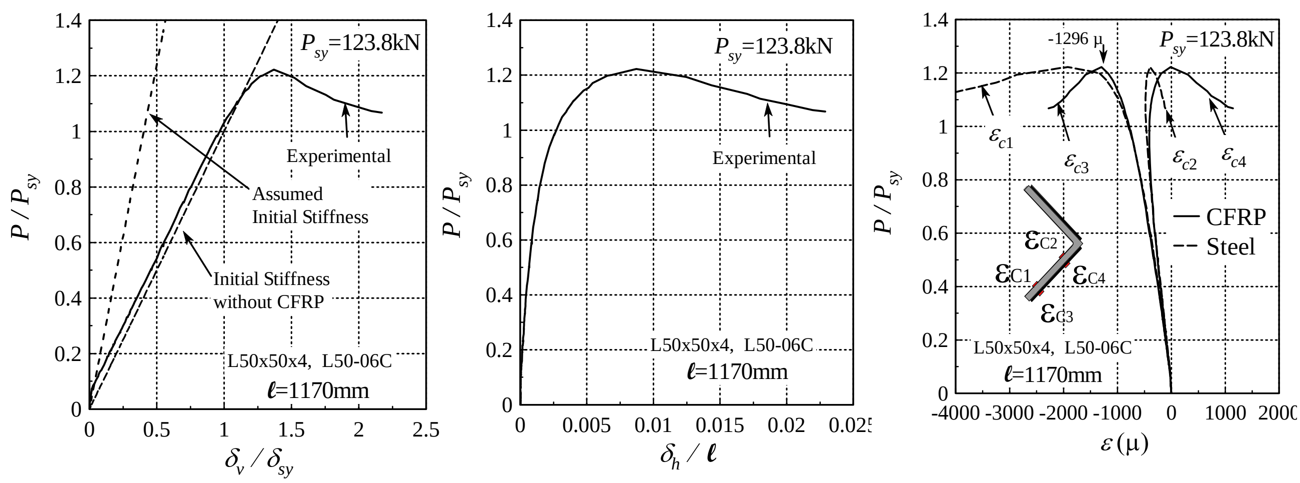


Figure 5. Comparison of compressive strength with formula and experiment



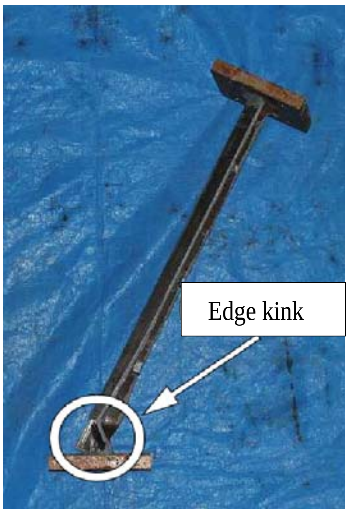
(a) P/P_{sy} vs. δ_v/δ_{sy} relration

(b) P/P_{sy} vs. δ_h/ℓ relration

(c) P/P_{sy} vs. ε_c relration

Figures 6(a),(b),(c). Test results for L50-06C specimen

(a) Relatively longer specimen (L50-07C)



(b) Relatively shorter specimen (L50-08C)

Photographs 1(a),(b). Failure pattern after tests

Tables 3(a),(b). Test results

(a) Unstrengthened Specimens

Name	ℓ mm	Pmax kN	λ* -	Exp. σe N/mm2	Exp. σe/σy* -	(EI)a kN m2	(EI)a/(EI)b -	Cal. σe N/mm2	Exp./Cal. -
L50-08N	800	96.0	83	247	0.78	6.2	0.84	235	1.05
L50-07N	1000	80.1	104	206	0.65	8.1	1.10	187	1.10
L50-06N	1170	45.3	122	116	0.37	6.3	0.85	137	0.85
L50-05N	1300	39.0	135	100	0.32	6.7	0.91	111	0.91
L50-04N	1500	33.9	156	87	0.27	7.7	1.05	83	1.05
L50-03N	1600	30.6	166	79	0.25	7.9	1.08	73	1.08

σy*=318N/mm2 (EI)b=7.37kN m2

(b) Strengthened Specimens

Name	ℓ mm	Pmax kN	λ* -	Exp. σe N/mm2	Exp. σe/σy* -	(EI)a kN m2	(EI)a/(EI)b -	Cal. σe N/mm2	Exp./Cal. -
L50-08C	800	196.5	53	505	0.91	12.7	0.70	452	1.12
L50-07C	1000	158.1	66	406	0.73	16.0	0.88	394	1.03
L50-06C	1170	130.5	77	335	0.61	18.1	0.99	335	1.00
L50-05C	1300	126.3	86	325	0.59	21.6	1.19	273	1.19
L50-04C	1500	85.2	99	219	0.40	19.4	1.07	205	1.07
L50-03C	1600	77.7	106	200	0.36	20.2	1.11	180	1.11

σy*=554N/mm2 (EI)b=18.2kN m2

Table 4. Effect of strengthening by bonding CFRP plates

ℓ mm	Name	Pmax kN	Name	Pmax kN	Effect of Strengthening -
800	L50-08C	196.5	L50-08N	96.0	2.05
1000	L50-07C	158.1	L50-07N	80.1	1.97
1170	L50-06C	130.5	L50-06N	45.3	2.88
1300	L50-05C	126.3	L50-05N	39.0	3.24
1500	L50-04C	85.2	L50-04N	33.9	2.51
1600	L50-03C	77.7	L50-03N	30.6	2.54

4.2. Discussion

From the test results, we can determine the following:

・**Axial rigidity**

From Figure 4 and Figure 6(a), we can see that the flexural rigidity is increased by the bonded CFRP plates, and hence the buckling strength is increased. However, the axial rigidity is almost the same before and after bonding CFRP plates except in the initial small loading range. This is because the large deflection at the central section reduces the axial stiffness, and the edge of the CFRP does not transfer axial load. Hence, the axial force resistance of the CFRP plates requires large shear deformation of the adhesive layer.

・**Applicability of strut strength design curve under elastic region**

From Table 3(b) and Figure 4, we can see that for equivalent slenderness ratios larger than 78, the flexural rigidity obtained from the experiment is larger than obtained from the formula. Hence, Euler's theory can be adopted in the elastic range for a composite member.

From Figure 5 and Figures 6(a),(b),(c), we can see that for equivalent slenderness ratios smaller than 78, the strengthened specimen (for instance L50-06C specimen) has 1.2 times higher maximum strength than the fully plastic axial force of the steel angle. The strain of the CFRP (ML) plate when buckling occurred reached the plastic strain of steel (=1200μ). Hence, the equivalent yield stress obtained from the formula takes into account the CFRP plate’s axial resistance when its strain reaches steel-yield strain.

The presented design formulae of Eqns. (1.a) and (1.b) accurately predict strut strength of rehabilitated steel angle with bonded CFRP plates.

・**Failure pattern**

From Photographs 1(a),(b), we can see that, except for the short specimens (for instance, L50-08C specimen), all specimens buckled at their centers in the weak-axis direction. In L50-08C specimen, local buckling was observed at the end of the steel angle. For short members, adhesion is required over their full lengths.

5. CONCLUSION

This paper has reported the results of compressive loading tests on an angle steel member before and after rehabilitation using bonded CFRP plates.

The results showed enhanced compressive force carrying capacity and deformation capacity as follows.

1) Although buckling tests showed enhanced flexural rigidity, there was no increment of axial stiffness.
2) An elastic buckling formula using the experimental flexural rigidity from a calculation, gave a conservative evaluation of load carrying capacity.
3) Taking into account the contribution of CFRP up to the elastic limit strain of the steel member, its load carrying capacity could be obtained from the formula of Design Standard for Steel Structures of AIJ.
4) The CFRP must be bonded over the full length of the angle member.

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