STRENGTHENING ANGLE STEEL USING UNBONDED CFRP LAMINATES

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Steel angle are largely used in spatial latticed structures (i.e. transmission towers, communication tower), long-span trusses, and/or lateral force resisting systems. In the structures, it is very susceptible to undergo buckling since it is also intended to support compressive loads. The angle steel needs to be strengthened to provide stronger structures. A technique for strengthening steel has been being developed by numerous researchers using CFRP material which is considered to be very effective compared to those conventional methods of welding/bolting additional steel plates. CFRP is light-weight material, high strength-to-weight ratio, corrosion resistance, and also excellent fatigue resistance. Nowadays, strengthening steel using CFRP is mostly focused by adhesively-bonding technique. This technique is less effective because it requires complicated steel surface treatments before application. In this paper, strengthening angle steel using unbonded CFRP laminates is investigated. The CFRP is expected to contribute in strength through its flexural rigidity. The main advantage of this method is that steel surface treatments such as sand blasting, hand grinding, or grit blasting are no longer needed because CFRP will not be adhesively stuck onto steel surface but it is separated by a peel ply as unbonded material. Thus, installation time can be reduced and lead to save in construction cost.

Key Words : *unbonded CFRP, angle steel, strengthening, compressive load*

1. INTRODUCTION

Nowadays, the use of Carbon Fiber Reinforced Polymer (CFRP) for repairing and strengthening steel structures have been increasingly performed by adhesively-bonding technique (in several literatures it is also termed as “externally-bonded” or just only “bonded”). In this method of strengthening, CFRP laminates are patched onto steel surface using adhesive materials (usually epoxy resin). Steel surface treatments such as sand blasting, grit blasting, or hand grinding, are needed prior to bonding of the CFRP, to roughen the steel surface in order to attain good bond (both chemical and mechanical bonding) between steel and CFRP[1)]. The bonding strength is of critical importance to the performance of the structures.

The effectiveness of this strengthening method in improving the performance of steel structures, especially for axial compression members, has been proven by researchers in many research programs. Imran et al.[2)] investigated the effect of CFRP strengthening layout (transverse layers or longitudinal layers, and the combinations) on the axial compression capacity of SHS steel short columns. Their experimental results revealed that the capacity enhancement was up to about 2.6 times. Abu-sena et al.[3)] studied the behavior of short SHS and RHS columns strengthened with CFRP in three different techniques (full wrapping, strips with single layer, and strips with two layers). They found that the ultimate capacity enhancement were 19.1-34.5% and 18.0-41.3% for SHS and RHS columns, respectively. Haedir and Zhao[4)] strengthened ten short CHS columns using CFRP sheets which were applied in parallel and perpendicular to the column axis. They confirmed the possibility of enhancement of axial compression capacity of the columns. Kumar and Senthil[5)] evaluated the performance of CFRP strengthened CHS steel members under axial static and cyclic loading. The members load carrying capacity increased up to 37.13% for static loading and 42% for cyclic loading. Ghaemdoust et al.[6)] studied the behaviors of SHS short columns having horizontal and vertical deficiencies. The columns strength-lost due to deficiency could be significantly recovered after strengthened with CFRP sheets. Shaat and Fam[7)] experimentally investigated the behavior of slender HSS square steel columns strengthened with high modulus CFRP plates. The increases in axial load capacity were observed ranged from 6 to 71%. Ritchie et al.[8)] tested I-shaped section slender steel columns having slenderness ratio of 197. The CFRP plates used for strengthening the columns were varied in length, modulus, and cross-sectional area. The test results indicated that the gain in axial strength of the columns after strengthening ranged from 11 to 29%. Sayed-ahmed et al.[9)] strengthened HSS columns using high modulus CFRP laminates to investigate the behavior of the columns subjected to eccentric loading (25, 50, and 100 mm). Experimental results showed that the increases in axial load capacity of the columns ranged between 40 and 107% depending on slenderness ratio (ranged between 68 and 131) and the load eccentricity.

Even though the performance of steel structures can be much improved, strengthening steel using adhesively bonded CFRP is susceptible to its performance degradation because the bonding strength between CFRP and steel, where this method is highly dependent, can be influenced by many factors. This becomes the weakest point of this strengthening method. Long-term environmental exposures lead to the bond strength decrease due to effects of temperature, moisture, and ultraviolet (UV) exposure. The bond strength will also be affected by the quality of steel surface treatment produced by the workers who work on it, as their skills are different. Steel surface treatment is a necessity to obtain a good bond between CFRP and steel, but it is not a simple task. It becomes difficult, especially when the strengthening will be applied to existing structures. Steel surface treatment will take longer and require more effort, which will lead to higher construction costs.

As an alternative to the adhesively bonded CFRP, unbonded CFRP method has been proposed by Authors for strengthening steel[10)]. This strengthening method does not rely on bonding strength between CFRP and steel, but flexural rigidity of CFRP becomes the most important point. In this experiment, unbonded CFRP will be applied and investigated for strengthening angle steel under compression.

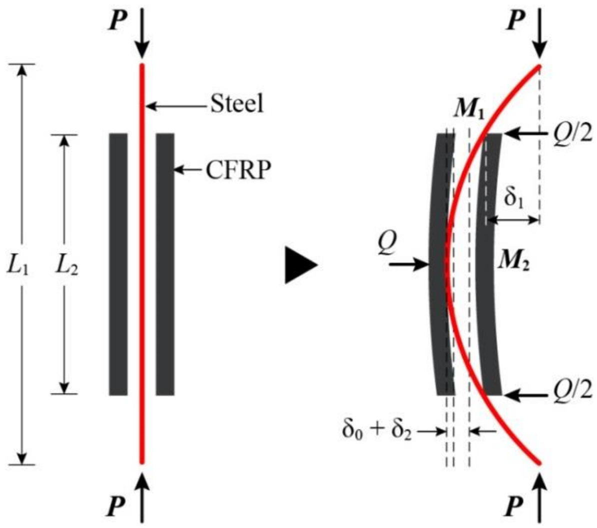


Fig.1 Buckling model for unbonded CFRP strengthening[10)].

2. STRENGTHENING REQUIREMENTS

Following Yoresta et al.[10)], the governing equation for partially strengthened steel member subjected to compressive load P (**Fig.1**), to allow hinge occurs at non-restrained portion of the steel, can be expressed as:

$$P\left(\delta_0 + \delta_2\right) < \frac{1}{4} Q L_2 \tag{1}$$

where δ_0 is a gap between CFRP and steel, δ_2 is deformation of CFRP, and Q is lateral thrust that occurs when CFRP and steel come into contact. The value of Q can be calculated from Equation 2.

$$Q = \frac{\delta_2}{\dfrac{L_2{}^3}{48 E_{CF} I_{CF}} + \dfrac{L_2}{2 G_{CF} A_{CF}}} \tag{2}$$

where E_{CF} and G_{CF} are elastic modulus and shear modulus of CFRP, respectively, and can be determined by Classical Lamination Theory; I_{CF} and A_{CF} are moment inertia and sectional area of CFRP, respectively.

Subtituting Equation 2 into 1 and then simplifiying the Equation, the strengthening requirement can be expressed as in Equation 3.

$$P\left(1 + \frac{\delta_0}{\delta_2}\right) < \left(\frac{L_2{}^2}{12 E_{CF} I_{CF}} + \frac{2}{G_{CF} A_{CF}}\right)^{-1} \tag{3}$$

3. EXPERIMENTAL PROGRAM

This experimental program consisted of compressive testing of totally 8 specimens including 2 bare steel and 6 unbonded CFRP strengthened specimens. The specimens are devided into two different lengths i.e., 1200 mm and 1600 mm. The CFRP is positioned at middle of span. **Fig.2** shows the specimen configuration, while the detail of its CFRP length and layers number can be found in **Table 1**.

(1) Materials

An equal leg angle steel L65x65x6 is used in this experiment. Its measured wall thickness is 5.5 mm. Yield strength and ultimate stress of the steel are directly obtained from the manufacturer, namely 333 MPa and 448 MPa, respectively.

Bidirectional high strength carbon fiber (BT70-20) is used for CFRP strengthening material. This material has a 0.112 mm thickness with 0 and 90 degrees of fiber directions. Its modulus of elasticity and tensile strength are obtained form the manufacturer, i.e., 230 GPa and 2.9GPa, respectively. The epoxy resin used for CFRP is high strength, ultra-low viscocity, and excellent durability. Its tensile strength is larger than 20 MPa.

(2) Specimen preparation

The unbonded CFRP strengthened specimens are prepared by the process of Vacuum assisted Resin Transfer Molding (VaRTM). The VaRTM technique is chosen because it is able to produce CFRP laminates with a stable mechanical characteristics. The brief summary of specimen preparation is as shown in sequence in **Fig.3(a-c)**. The angle bare steel is firstly wrapped with a layer of peel ply without being preceded by steel surface treatments. The carbon fibers are then wrapped until the determined number of layers are achieved. The carbon fibers are installed so that fiber with angle 0° is in longitudinal direction of steel and the 90° angle is in transverse direction. Following carbon fiber, another peel ply and also resin media are installed sequently. Afterwards, the stage is continued with the installation of PVC hose and the bagging film with firmly gum tape connection before conducting the resin impregnation by way of suction using vacuum pump. Once the vacuuming process is complete, the specimens are then cured for minimum of one week before being tested.

(3) Test setup and instrumentation

All specimens are monotonically tested using a 2000 kN Maekawa compression testing machine (**Fig. 4**). The specimens are tested with pinned-ends condition and allowed to buckle only around their weak axis. The pinned-ends condition are achieved through knife edges at both ends of specimen. Six transducers are mounted around the specimens to measure a reliable out-of-plane displacement. The longitudinal strain is measured by strain gauges attached directly to the steel and CFRP in several locations. Detail of strain gauges and tranducers positions are given in **Fig.5**.

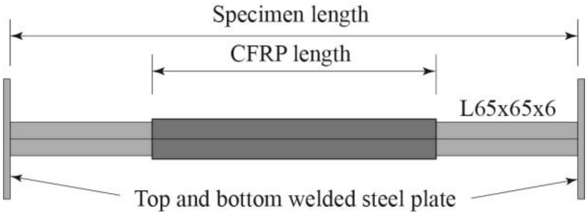
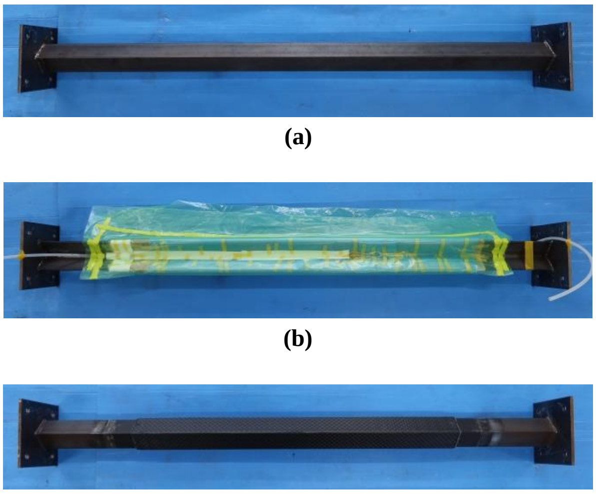


Fig.2 Specimen configuration.



(a)

(b)

(c)

Fig.3 Specimen preparation: (a) angle steel before strengthening, (b) vacuuming preparation, and (c) strengthened specimen after vacuuming process.

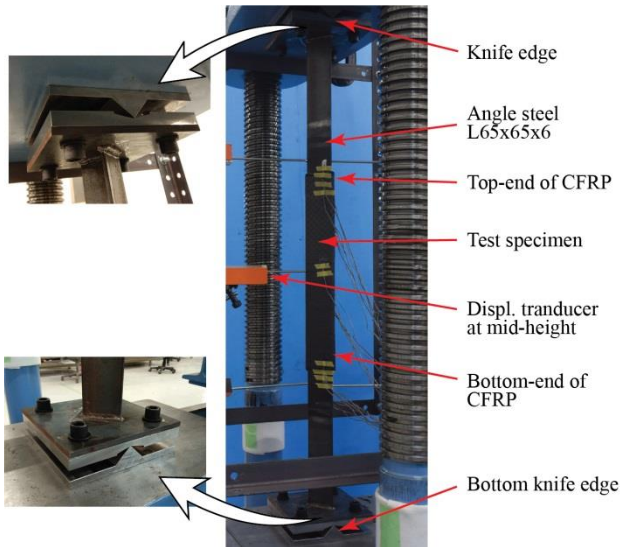
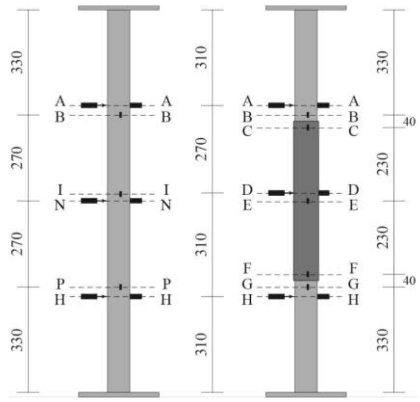
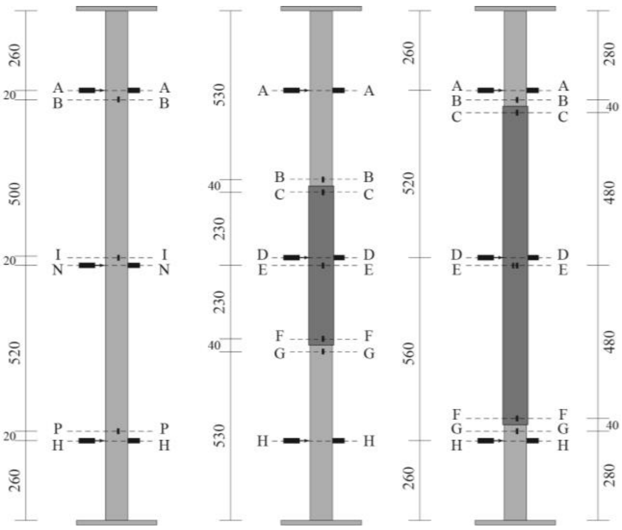


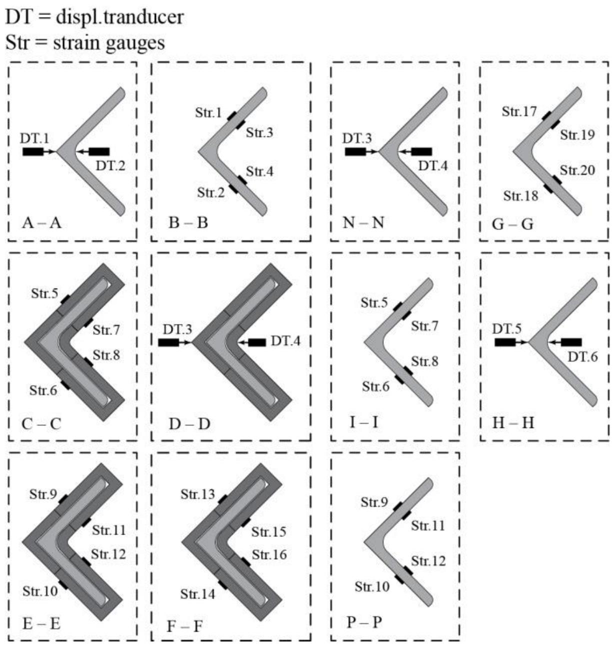
Fig.4 Experimental test setup.



(a)



(b)



(c)

Fig.5 Displacement tranducer and strain gauges position: (a) specimen 1200mm length, (b) specimen 1600mm length, and (c) cross-section on strain gauges and tranducer.

4. RESULT AND DISCUSSIONS

Table 1 shows the tested specimens with their length and number of CFRP layers, maximum load obtained from the test, and the percentage of strength increase. It is clear from the table that unbonded CFRP laminates gives positive strengthening effect. The highest increase of maximum load is attained in specimen 3 which is 34.9% strength gain, while the lowest increase is found in specimen 4 with only 8.5%. Generally comparing, strengthening the 1200 mm length specimens shows a greater effect than that of the 1600 mm specimens.

Table 1 Summary of test results.

Spec. No.	Spec. length	CFRP length	CFRP layer	P_{max} (kN)	Strength gain (%)
Control-1	1200	-	-	122.7	-
1	1200	500	10	135.7	10.6
2	1200	500	18	140.6	14.6
3	1200	500	25	165.6	34.9
Control-2	1600	-	-	77.2	-
4	1600	500	18	83.8	8.5
5	1600	500	25	86.9	12.6
6	1600	500	30	90.2	16.8

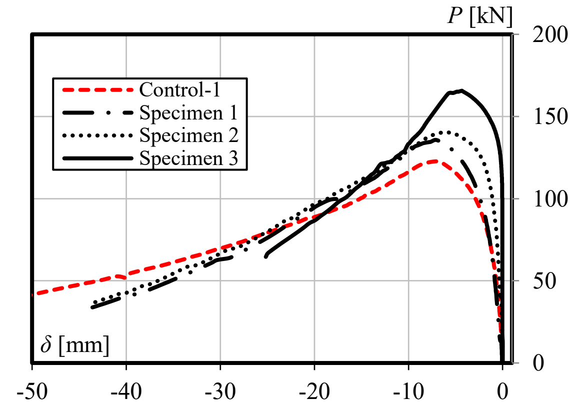


Fig.6 Load-lateral displacement behavior at mid-height of specimen 1200mm length.

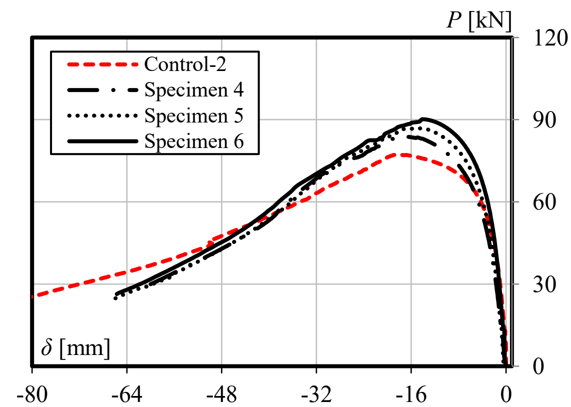


Fig.7 Load-lateral displacement behavior at mid-height of specimen 1600mm length.

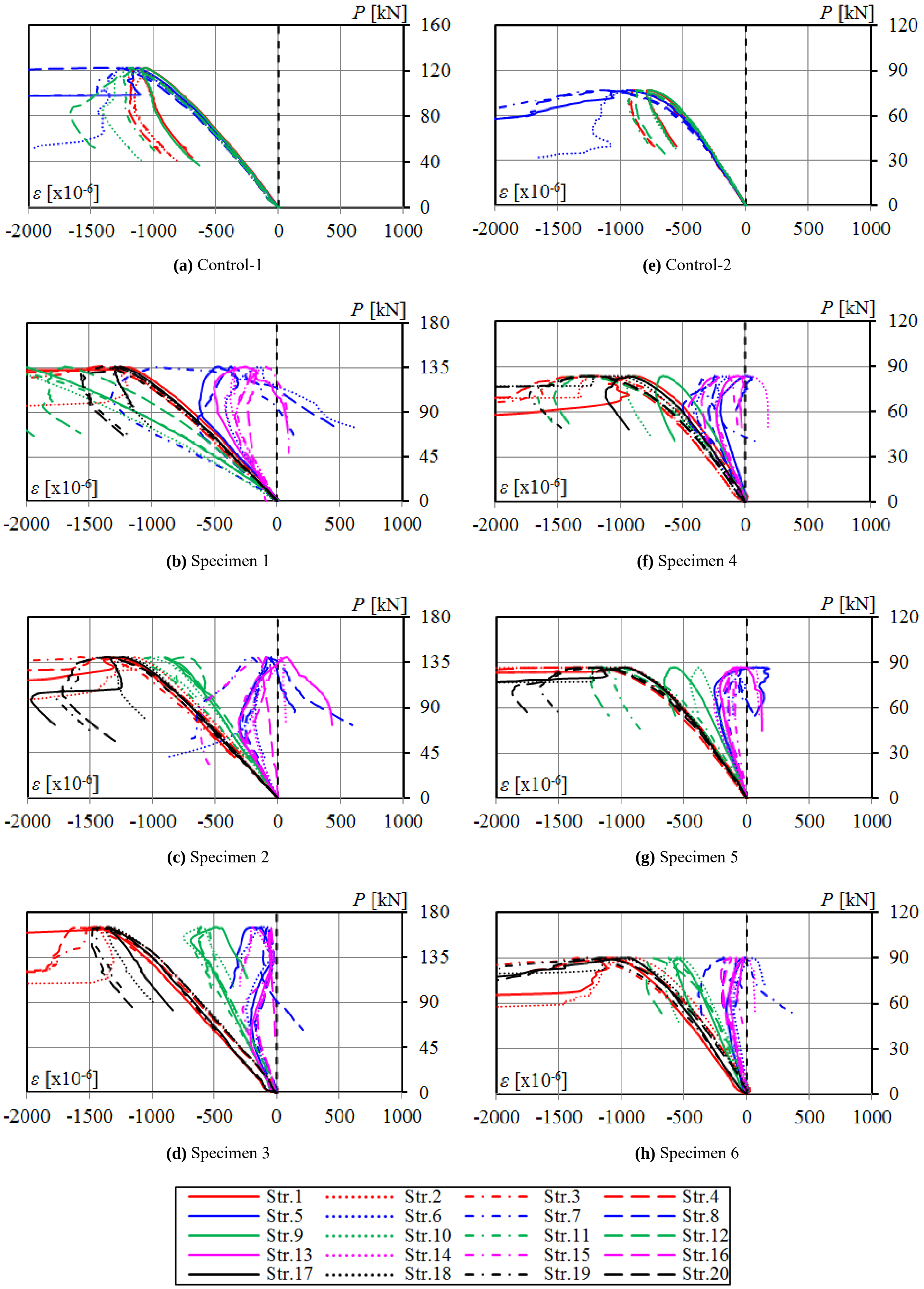


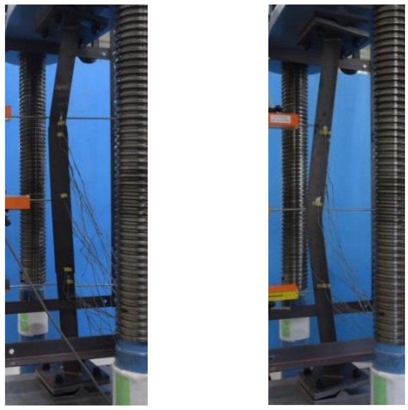
Fig.8 Load-longitudinal strain responses of tested specimens.

Figs. 6 and 7 present the relationships between the applied axial load and the resulting mid-height lateral displacement of the tested specimens. It can be seen from the figures that maximum load increases with the increase of number of CFRP layers used. For specimens with 1200 mm length, the maximum loads occur before lateral deflection reaches 10 mm. But, it occurs at deflection greater than 10 mm for specimen with 1600 mm length.

The load versus longitudinal strain responses in all specimen including control angle bare steel is shown in **Fig. 8**. It can be seen from the figures (b, c, d, f, g, and h) that strains on CFRP (Str.5-Str.16) are under compression at the early stage of loading. However, up to certain point of loading (on each specimen) before ultimate load, strains near the edges of CFRP (Str.5-8 and Str.13-16) tend to revert to zero, while strains at the mid-height (Str.9-12) tend to continue developing higher compressive strains.

Fig. 9 presents typical failure modes of unbonded CFRP strengthened specimens and control bare steel angle. The control specimens experience failure due to the classical global buckling of pinned-ends column (**Fig.9b**). Compared with control specimens, all the strengthened angle steel undergoes a change in curvature on steel near the top edge of CFRP. This can be understood as a result of changes in stiffness between the strengthened and unstrengthened part of steel. However, in both control and CFRP strengthened specimens, twist of the cross-section is also clearly observed.

The recommended allowable compressive stresses for the strengthened steel are determined by equivalent slenderness ratio (λ_{eq}) method[10]. The procedure is as illustrated in **Fig.10**. The angle steel has a certain value of Euler stress (point A in **Fig.10**). After strengthening, the Euler stress will increase (to point B). This value will correspond to the elastic critical buckling stress (F_e) expressed in Equation (4) (Point C). The increased Euler stress will be the lower and upper values which are respectively based on assumption of fully unbonded and fully composite behavior between angle steel and CFRP (**Fig.11**). By this, the equivalent slenderness ratio can be obtained from Equation (4). The allowable stress (F_{cr}) is then calculated according to provisions used. In this study, the provision of the Architectural Institute of Japan (AIJ 2005) is used; so, Equation (5) or Equation (6) and Equation (7) will be involved. Properties of the angle steel utilized in this study, namely: F_y is yield stress (333 MPa), E is assumed elastic modulus (205 GPa), L_{cr} is buckling length (1236 mm and 1636 mm), r is minimum radius of gyration (12.8 mm), and $k = 1$ (pin-ends member).



(a) **(b)**

Fig.9 Failure modes: (a) strengthened specimen, (b) bare steel.

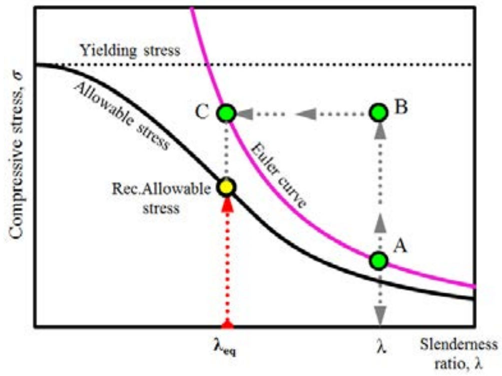


Fig.10 Equivalent slenderness ratio for allowable compressive stress determination.

$$F_e = \frac{\pi^2 E}{(kL/r)^2} \tag{4}$$

$$F_{cr} = \frac{1.5F_y\left(1-0.4(kL/r\Lambda)^2\right)}{1.5+0.667(kL/r\Lambda)^2} \quad \text{for} \quad \frac{kL}{r} \le \sqrt{\frac{\pi^2 E}{0.6F_y}} \tag{5}$$

$$F_{cr} = \frac{0.4155F_y}{(kL/r\Lambda)^2} \quad \text{for} \quad \frac{kL}{r} > \sqrt{\frac{\pi^2 E}{0.6F_y}} \tag{6}$$

$$\Lambda = \sqrt{\frac{\pi^2 E}{0.6F_y}} \tag{7}$$

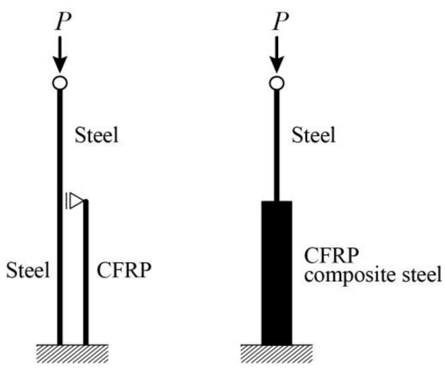


Fig.11 Structural model: (a) lower limit, (b) upper limit.

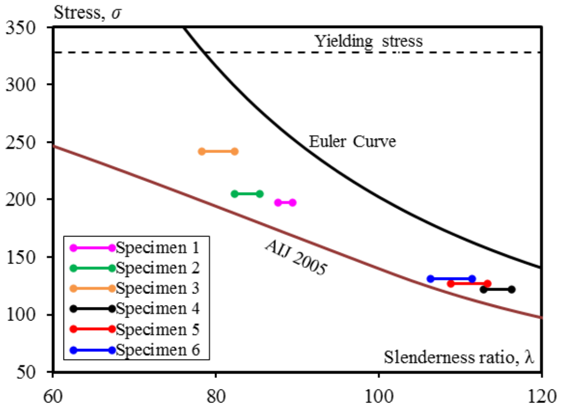


Fig.12 Compressive stresses of the unbonded CFRP strengthened angle steel plotted based on the equivalent slenderness ratio.

Table 2 Strength recommendation for strengthened angle steel.

Spec No.	σ_{exp}	F_e (low-up)	λ_{eq} (low-up)	F_{cr} (low-up)	σ_{exp} / F_{cr} (low-up)
1	198.2	253.0-263.8	89.42-87.58	168.6-173.6	0.85-0.88
2	205.3	277.8-298.9	85.35-82.28	179.7-188.1	0.88-0.92
3	241.8	298.8-330.7	82.29-78.22	188.0-199.1	0.78-0.82
4	122.4	149.8-159.1	116.2-112.8	103.7-110.2	0.85-0.90
5	126.9	157.8-170.9	113.3-108.8	109.2-118.4	0.86-0.93
6	131.7	163.1-179.0	111.4-106.3	112.9-124.0	0.86-0.94

Note: unit in N, mm.

Maximum stress (σ_{exp}) of all unbonded strengthened angle steel obtained from the experimental study are summarized in **Table 2** and plotted together with allowable stress curve and Euler curve, as shown in **Fig. 12**. The stresses are plotted within the range of lower and upper limit of its recommended allowable compressive stress. It is clear from the figure and the table that the maximum stress lies between allowable stress curve and Euler buckling curve. This is the indication that the method of equivalent slenderness ratio can be applied for design of axial compression angle steel strengthened with unbonded CFRP laminates.

5. CONCLUSIONS

This paper investigates the use of unbonded CFRP laminates for strengthening angle steel under compressive load. Based on the experiment conducted, several findings can be summarized as follows:

1. Unbonded CFRP strengthening method is effective for improving compressive strength of the angle steel.
2. The maximum compressive load increase as increasing number of CFRP layers used.
3. The unbonded CFRP provides a higher effect in strengthening angle steel having length of 1200 mm compare to those specimens having length of 1600 mm.
4. The unbonded strengthened angle steels experience a change in curvature near the edge of CFRP.
5. Method of equivalent slenderness ratio can used for determining recommended allowable compressive stress of angle steel strengthened with unbonded CFRP laminates.

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