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Experimental investigations on rolled angle sections reinforced with CFRP plates

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Abstract

Telecommunication or power transmission lattice towers may be in need of strengthening due to enhanced operational requirements of 5G systems or extension and upgrading of existing power lines. The members of such towers are mostly angle sections that are conventionally strengthened by a second profile to become a built-up member. As an alternative, hybrid strengthening of tower angle members with carbon fiber reinforced polymers (CFRP) plates may be employed. The present paper provides experimental tests on hybrid angles that include bending tests and compression tests carried out in the frame of the RFCS research project ANGELHY. In 3-point bending tests the specimens were subjected to loading along the principal and the geometric axes. They allow the definition of the bending capacity and the development of appropriate design rules for hybrid cross-sections. The compression tests were performed on specimens of different length and loading eccentricity, with FRPs attached to one or both sides of the legs. Important parameters influencing the buckling capacity were detected.

Keywords

Lattice towers, hybrid angle sections, FRPs, bending tests, compression tests

1 Introduction

Lattice towers are extensively built in Europe and worldwide for telecommunication and power transmission purposes. The members of such towers are frequently composed of equal leg angle sections due to their easier connection that results in a simpler erection, a requirement set by most telecommunication or power providers. The development of 5G telecommunication networks and the extension and upgrading of existing power lines require new tower infrastructure, with preference in the reinforcement of existing lines to erection of new ones [1]. In the conventional strengthening methods, a second angle of equal size is arranged back-to-back or star battened to the existing one to form a closely spaced built-up member. This method is cost demanding and besides results in an increase of the attack area and consequently of the wind loading applied to the structure. As alternative, hybrid strengthening of tower angle members with carbon fiber reinforced polymers (CFRP) plates attached to the angle legs may be employed.

In order to develop design methods for this innovative type of hybrid arrangement, experimental tests have been carried out in the Institute of Steel Structures at the National Technical University of Athens in the frame of the RFCS research project ANGELHY. The experimental investigations include shear tests, 3-point bending tests and compression tests. Shear tests intend to provide information about the bond properties between steel and FRP and are described in [2]. In 3-point bending tests the specimens were strengthened on one or both sides of the legs and subjected to loading along the principal and the geometric axes with one leg either in tension or in compression. This allows the definition of bending and rotation capacities and the development of appropriate design rules for hybrid cross-sections. Compression tests serve to define the buckling capacity of members when subjected to compression and bending. Parameters of these tests are the specimen's length, the loading eccentricity and the strengthening arrangement. The tested cross-sections were rolled angle sections L70.70.7 to allow a direct comparison with previous tests from the same, unreinforced, sections performed at NTUA [3]. The composite material was 50x1,2 mm plates from carbon fiber reinforced polymers (CFRP).

This paper presents the preparation of test specimens, the details of the experimental campaign, measurements prior and during testing and the test results. Involved in the tests were the Institute of Steel Structures NTUA, Greece where the tests were carried out, ArcelorMittal, Belval & Differdange, Luxembourg that delivered the steel profiles and SIKA France that delivered the CFRP plates. Other

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partners of the project were the University of Liege, Belgium, COSMOTE, Greece and CTICM, France.

2 Preparation of the tests – measurements before tests

2.1 Preparation of specimens

Test specimens consisted of L70.70.7 hot-rolled angle profiles, strengthened by CFRP strips of 50x1,2 mm nominal dimensions which were bonded to steel through epoxy adhesive. The production process of the hybrid cross-sections followed the specifications provided by SIKA, producer of the FRP material and adhesive, and is described in the following. Steel sections were sandblasted, as they should be, to achieve an effective connection to FRP plates. Bonding of CFRP plates and steel specimens was realized using adhesive Sikadur 30, which is a two-component resin. The two components are mixed for 5 minutes. After mixing, the adhesive is usable for the next 50 minutes or less, depending on the room temperature. Using special equipment, a small layer of the adhesive is applied uniformly on both surfaces (steel and CFRP) after cleaning them. The CFRP plate is then placed on steel, squeezing all over the length with a special roller and removing any adhesive that overflows. Following this procedure, a uniform layer of 1.5 mm thick adhesive is achieved over the length of the strengthened specimens. In order to reach the maximum adhesive's strength, a curing period of at least 10 days was implemented for all specimens, under constant conditions. Particular concern was given to the non-detachment of the CFRP plates at their ends. For this reason, CFRP strips 30 mm width, were wrapped at the ends to confine the bonded plates, Fig. 1. Two different types of strengthening were used in tests, one where CFRP plates are applied only externally, the other on both sides of each leg. All plates (50mm width) were placed near the tips of the angle.

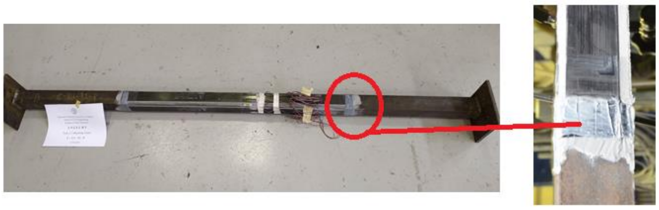


Figure 1 Hybrid specimen with confined CFRP ends

2.2 Actual dimensions and initial geometrical imperfections

The actual specimen dimensions have been measured on both steel and hybrid cross-section. The actual width of the steel section is almost identical to the nominal value, 70.27 mm, while the mean thickness is a little higher, 7.13 mm. Both values are within the tolerance ranges of EN 10056-2: 1993 [4]. Due to the manual application, the adhesive's thickness varies but is close to the anticipated 1.5 mm.

Local and global initial geometrical imperfections were measured for all compression specimens, using a special device shown in Fig. 2, The system includes four displacement transducers (DTs), two at each leg, run along the specimen taking measurements at close distances. For each specimen three cycles of measurements were made for both legs simultaneously, which means that for each leg six measurements have been recorded over the column length. Due to the specimen's end plates, it wasn't possible to take measurements quite close to the end-plates. As a result, all measurements start and finish approximately 125 mm before the end-plates.

The recordings were post-processed and the resulting imperfections were determined in respect to the corner and the tips of the angle. Based on them, global bow imperfections were converted to principal axes u, v of the cross-section. In addition, local leg's imperfections were calculated separately, Fig. 3.

Figure 2 Device for the imperfection measurements

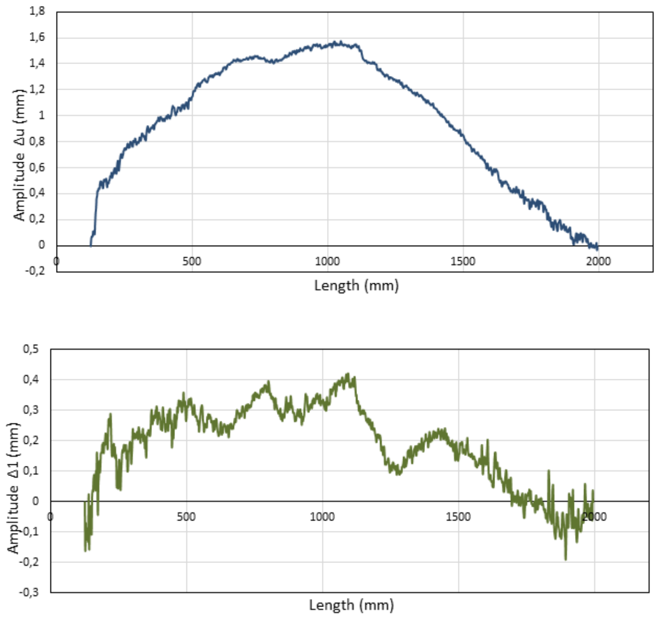


Figure 3 Global and local geometrical imperfections

The results of the evaluation are summarized in Table 1, which presents the maximum absolute imperfections of the specimens compared with the tolerance limits of European specifications EN 10056-2 [4] or hot-rolled angle cross-sections. EN 10056-2 makes a distinction between out-of-squareness (local imperfection) and out-of-straightness (global imperfection) deviations. Table 1 shows that on average, the maximum obtained global imperfection didn't exceed 2.09 mm, while the maximum local imperfection didn't exceed 0.58 mm. As noticed, all specimens have much smaller imperfections, especially global ones, than the limits provided by [4].

Table 1 Maximum values of initial imperfections of the specimens compared with the tolerance limits of 10056-2 [4]

Type of specimens		Straightness		
		Imperfection strong axis in mm	Imperfection weak axis in mm	Tolerance to [4] in mm
Short **L_{cr} = 1.74 m**	Max	0.79	0.40	6.28
	Mean	0.56	0.28	
Long **Lcr = 2.29 m**	Max	2.09	0.88	8.48
	Mean	1.01	0.48	
		Squareness		
		Imperfection in mm		Tolerance to [4] in mm
Short **L_{cr} = 1.74 m**	Max	0.41		1
	Mean	0.27		
Long **Lcr = 2.29 m**	Max	0.58		1
	Mean	0.36		

2.3 Material properties

The angle profiles were ordered from Steel S235J2 to EN10025-2 [5]. However, analysis did not rely on nominal material properties. Brinell hardness test was used to estimate steel's ultimate tensile strength. For each specimen, three measurements were made on each leg. Based on the average of 20 test values (HBW), the ultimate material strength was estimated as fu = 434 MPa. In addition, tensile tests were performed on steel coupons in an INSTRON 300LX universal testing machine. The position of the test samples from the angle profile was in accordance with EN10025-1 [6], whereas the tests were carried out in accordance with EN ISO 6892-1 [7]. Average values of the yield and ultimate stress from the three tests were equal to 306 and correspondingly 436 MPa.

The mechanical properties of the two-component adhesive resin Sikadur-30 as provided by the producer were 32 MPa tensile strength and 20 MPa shear strength. CFRP plates were of type SIKA CARBODUR S512. Actual properties were extracted from the certificate of the batch number of the delivered product provided by the producer and are summarized in Table 2.

Table 2 Nominal and actual properties of the CFRP plates

	Dimensions	Tensile strength	Tensile Strain	Tensile modulus
Nominal	50x1.2	>2800 MPa	>1.7 %	>160 GPa
Actual	50.33x1.2	3187 MPa	1.84 %	174 GPa

3 Bending tests

Five (5) three-point bending tests were performed to determine the cross-section properties and the bending resistance. Table 3 shows the test matrix. B stands for bending specimen. Loading was applied along the weak principal axis with tips in compression (specimens -V, -V2) or the geometric axis with one flange in tension (specimen -L) or in compression (specimen -LI). CFRP plates were applied externally (specimens -T1) or on both sides of the angle legs (specimens -T2), Fig. 4.

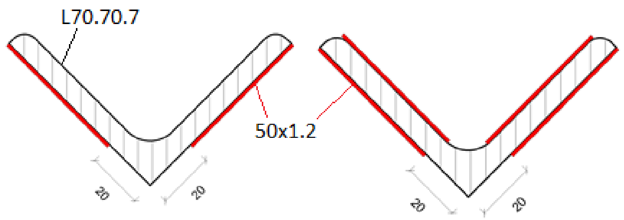


Figure 4 Types of strengthening with CFRP plates applied externally or on both sides of the legs

The load was applied in the middle section with a 300 kN hydraulic actuator by means of imposed displacement with a constant velocity. Simple pinned supports were realized by attaching a rounded bar beneath the end-plates. Load application was in the webs through special steel components in order not to damage the FRP-plates. For geometric axis loading, twist of the specimen was restrained by provision of appropriate lateral supports. Fig. 5 gives a general view of the test configuration for geometric axis bending. Following measurements were taken during the tests:

- Load and displacement of hydraulic actuator
- Mid-span displacements on each side of the angle section to determine the deflection and the twist at mid-span.
- Longitudinal displacement of end-plates at two levels to determine the end rotation and confirmation by inclinometers.
- Strains at steel profile and FRP-plates at several points at mid-span.

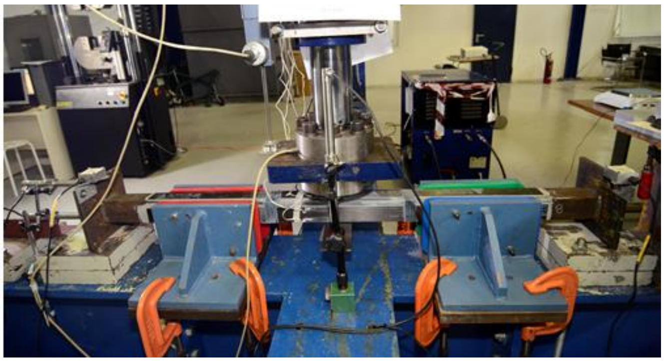
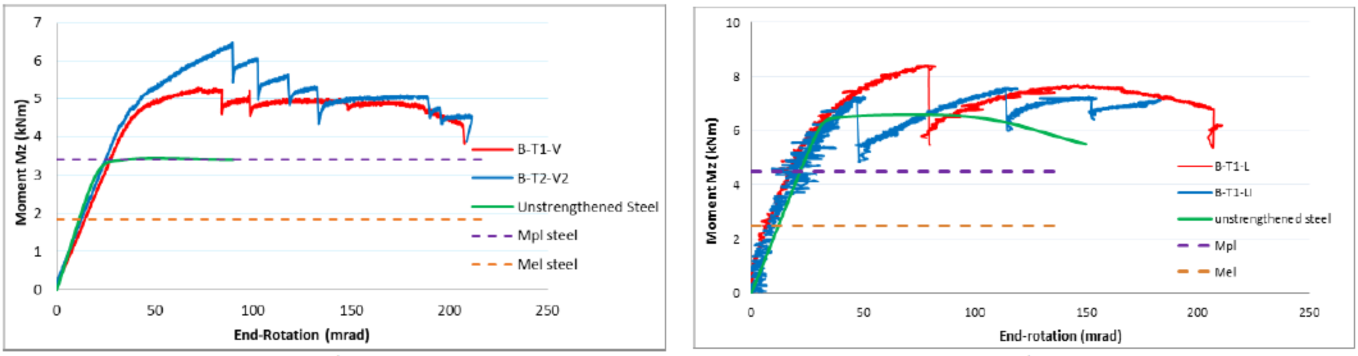


Figure 5 Test configuration for geometric axis bending, leg in compression

Table 3 Text matrix for bending tests

Specimen	Steel profile	Length	Axis of bending	Loading direction	Type of strengthening
B-T1-V	L70.70.7	1.5 m	Weak principal axis	Tip in compression	External
B-T2-V					External + Internal
B-T2-V2					External + Internal
B-T1-L			Geometric axis	Leg in tension	External
B-T1-LI				Leg in compression	External



a) b)

Figure 6 Mid-span moment – end rotation curves. a) Weak and b) geometrical axis loading

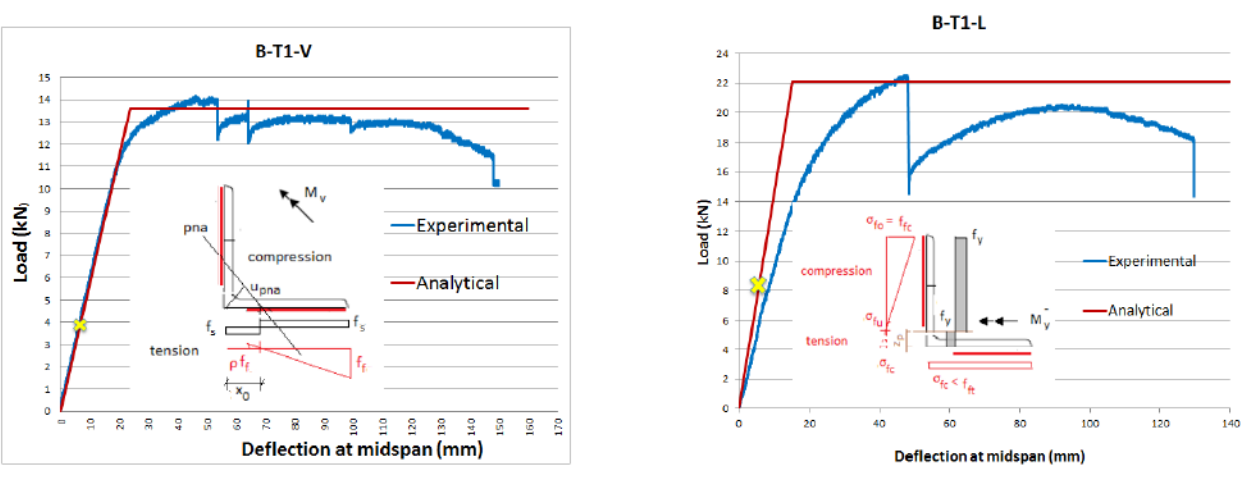
Figure 6 shows test results in form of moment-end-rotation curves for weak and geometrical axis loading. The graphs show also test results on unreinforced angle profiles from previous tests done at NTUA [3], as well as the elastic and plastic moments of the pure steel angle section calculated on the basis of the actual material properties.

Following observations can be made:

- Consecutive drops in the experimental curves indicate either debonding of the FRP-plates from steel or fracture of FRP fibers. The former occurs in the compression zone, the latter in the tension zone, Fig. 7.
- There was no slip between steel and FRP material. This was confirmed also by previously executed shear tests.
- The strengthening measures do not affect the stiffness of the member due to the very small thickness of the strengthening FRP plates.
- The strengthening measures have a beneficial effect to both bending capacity and rotation capacity of the angles.
- For geometric axis bending the increase in bending resistance in comparison to the unstrengthened angle profile is moderate. It amounts to 10% or 25% depending on whether the leg is in compression or tension.
- For weak axis bending the corresponding increase in resistance is substantial. It amounts to 60% or 90% for strengthening the legs externally or externally and internally respectively. This is very important for compression members that usually buckle around the weak axis. It may be seen that the bending capacity of the hybrid sections around the weak axis is raised substantially, approaching the corresponding capacity around the geometric axis. This alleviates a drawback of the angle profiles which is the very low weak axis bending resistance.

Figure 7 Types of failure for CFRP. Debonding from steel for compression and fracture of fibers for tension

On the basis of the experimental results, analytical methods were employed to determine the stiffness and bending resistance of hybrid member. The stiffness is calculated considering no slip between surfaces, the bending resistance considering at failure the steel section to be fully plastic while the FRP material fully elastic. Fig. 8 gives a comparison between analytical and experimental load-deflection curves for specimens bent around the weak and the geometric axis. Hybrid sections strengthened only externally or on both sides of the legs are considered. A good agreement between experimental and analytical results may be observed, indicating that the assumed stress distributions at the ultimate state for both materials are correct, i.e. that at failure steel is in the plastic state while the FRP strips behave elastic.



a) b)

Figure 8 Analytical vs experimental load-deflection curves a) for weak and b) for geometrical axis bending with assumed stress distributions.

4 Compression tests

4.1 Test specimens

Sixteen (16) compression tests were performed to determine the buckling capacity of hybrid angle members. The steel section was in all tests L70.70.7. The parameters examined were: the buckling length – 1.75 or 2.30 m, the type of strengthening – external or external + internal, Fig. 4, the point of load application, and the length of FRP strengthening - over the entire specimen's length or ½ length. The point of load application varied in order to examine the buckling resistance to compression and bending. The chosen points of load application were five, Fig. 9. Point 2 coincides with the cross-section's centroid, to correspond to concentric compression. Point 1 that coincides with the angle heel and its symmetrical, 3, lead to weak axis bending, producing tension and respectively compression to the tips. Point 4 coincides with the recommended position of the bolt holes in the leg, producing mainly strong axis bending. Finally point 5 that coincides with the angle's tip is producing biaxial bending.

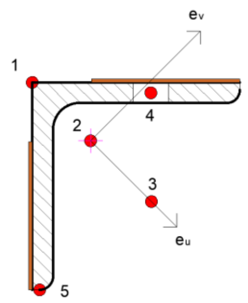


Figure 9 Point of load application

The test matrix is presented in Table 4. The specimens' designation is as following: C for compression tests, S for short L for long specimens, T1 for external T2 for external + internal strengthening, F for full P for partial strengthening. The table shows also the nominal and the actual eccentricities.

4.2 Test set-up and measurements

The general lay-out of the test arrangement is shown in Fig. 10. Pin-end boundary conditions were implemented at both ends through steel plates with specially designed spherical steel components. The buckling length presented in Table 4 is the distance between the two spherical steel components. It is a little larger than the clear length of the angle section which is measured between their end plates. The load was applied in the top, with a 300 kN hydraulic actuator by means of imposed displacements. Holes in the welded end plates of the specimens combined with slotted holes of load actuator plates allowed the specimen to be connected to the actuator in various positions and implement the anticipated eccentricity.

Following measurements were taken during the tests:

- Load and displacement of hydraulic actuator
- Mid-span displacements at 3 points in two different directions via wire transducers to measure deflections in two principal directions and twist
- Strains at steel profile and FRP-plates at several points at mid-span.
- End rotations at both specimen's ends by two inclinometers.

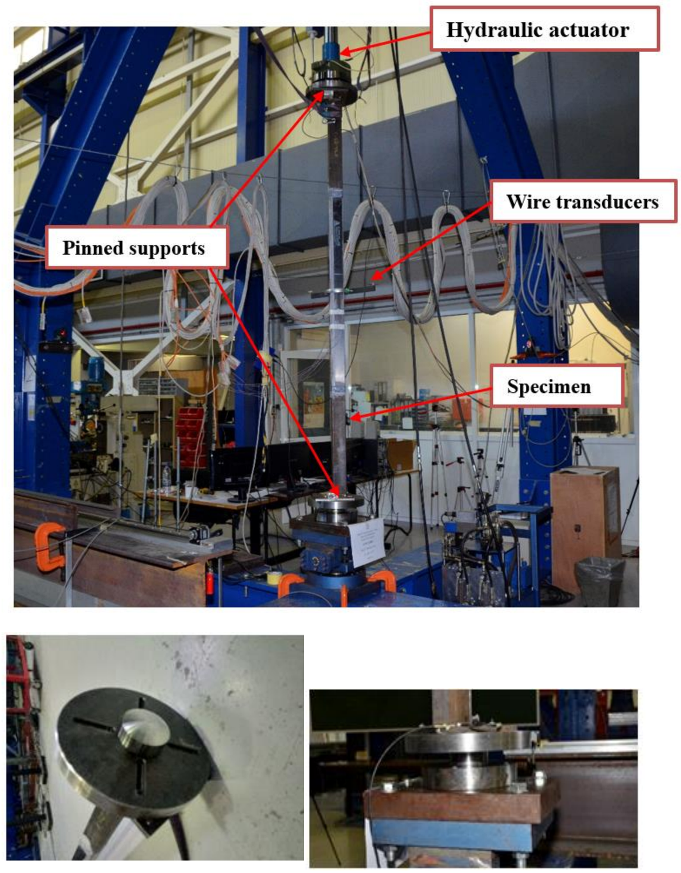


Figure 10 General lay-out and pin-support end plates for compression tests

Table 4 Text matrix for compression tests

Specimen	Steel cross-section	Buckling length	Loading point	Nominal eccentricity	Actual eccentricity	Type of strengthening	Length of strengthening
C-S1-T1	L70.70.7	1,75 m	Point 1	e_u = -30 mm	e_u = -30 mm	External	Partial
C-S2-T1			Point 2	0	0	External	Partial
C-S3-T1			Point	e_u = +30 mm	e_u = +30 mm	External	Partial
C-S4-T2			Point 3	e_u = +30 mm	e_u = +30 mm	External + Internal	Partial
C-S5-T1			Point 4	e_v = +28 mm	e_v = +29 mm	External	Partial
C-S6-T2			Point 4	e_v = +28 mm	e_v = +29 mm	External + Internal	Partial
C-S7-T1			Point 5	e_u =+20 e_v = -49 mm	e_u =+20 e_v = -49 mm	External	Partial
C-S8-T2			Point 5	e_u =+20 e_v = -49 mm	e_u =+20 e_v = -49 mm	External + Internal	Partial

Table 4 Text matrix for compression tests (cont.)

C-L1-T1-P			Point 1	e_u = -30 mm	e_u = -31 mm	External	Partial
C-L2-T1-P			Point 2	0	e_u = -4 mm	External	Partial
C-L3-T1-P			Point 3	e_u = +30 mm	e_u = +30 mm	External	Partial
C-L4-T2-P	L70.70.7	2,30 m	Point 3	e_u = +30 mm	e_u = +30 mm	External + Internal	Partial
C-L5-T1-F			Point 4	e_v = +28 mm	e_v = +29 mm	External	Full
C-L6-T2-P			Point 4	e_v = +28 mm	e_v = +27 mm	External + Internal	Partial
C-L7-T1-P			Point 4	e_v = +28 mm	e_v = +23 mm	External	Partial
C-L8-T2-F			Point 4	e_v = +28 mm	e_v = +27 mm	External + Internal	Full

4.3 Test results

Test results for the short specimens are presented in Fig. 11. They indicate a pronounced effect of loading eccentricity. Three groups of response may be distinguished: Concentric compression leads to the highest load capacity and stiffness. This is followed by eccentric loading with strong axis bending, in which the effect of strengthening on one or both sides of the legs is not evident. In the 3rd group belong the specimens that are subjected to weak axis or biaxial bending that have a similar response concerning load capacity and stiffness. Here again the effect of FRP application on one or both leg sides is not visible. Comparing the tests with weak axis and biaxial bending it may be seen that the higher eccentricity of the former is compensated by the double eccentricity of the latter. Concerning post-buckling behavior, it may be seen that the 3rd group of tests had a large ductility allowing a possible redistribution of forces, while for concentric compression the resistance was high by dropped sharply followed by a loud bang immediately after the attainment of the maximum load. For strong axis bending the ductility was less compared to weak axis bending but reached also high values allowing force redistribution.

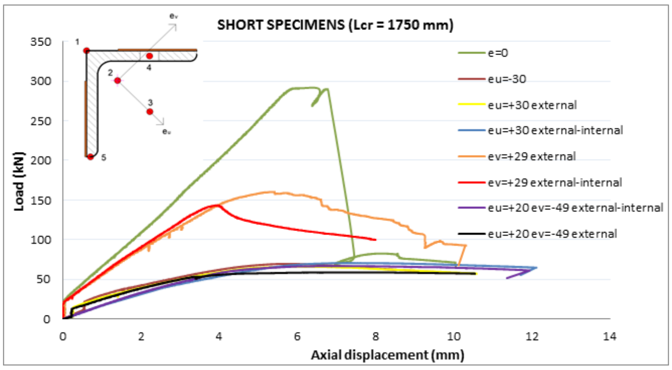


Figure 11 Load-displacement curves for the short specimens

The load-deflection curves, Fig. 12, indicate that specimens displaced mainly in direction of the loading eccentricity, i.e. specimens S1 to S4 in direction of the strong axis u, S5 and S6 direction of the weak axis v and specimens S7, S8 in both axes but mainly in direction of the u axis. It should be noticed that in all tests but two failure occurred in the strengthened region at mid-span. However, maximum deflections in specimens S5 and S6 that were strengthened partially and were subjected to strong axis bending were observed in the upper part, outside the strengthened region. This indicated that the steel section outside the strengthening zone yielded, leading to a lower buckling load.

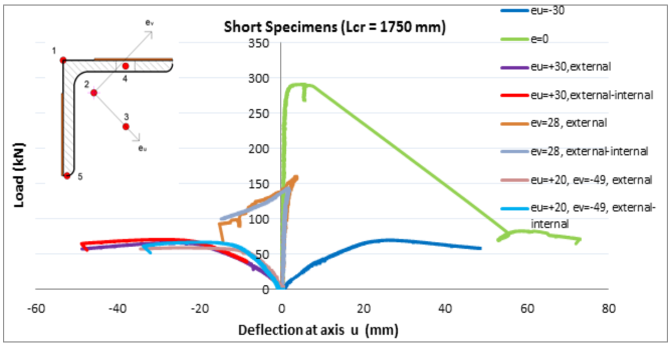


Figure 12 Load-deflection curves for short specimens

Test results for the long specimens are presented in Fig. 13. They can also be grouped in three categories. In the 1st group belong the specimens subjected to compression and weak axis bending. They show low capacity, low stiffness and high ductility. The important factor was the eccentricity, while there was no influence of its direction, whether it leads the tip to compression or tension, or of whether the legs were strengthened on one or both sides. The 2nd group is composed of the specimens in which the load application point was nominally the position of the bolt hole. These specimens are subjected mainly to compression and strong axis bending. The important factor for resistance was the magnitude of actual eccentricity that deviated from the nominal one. The eccentricity played also some role, although less pronounced to the stiffness of the specimens. The strengthening length, partial or full had an influence although less pronounced on the capacity or stiffness. The highest stiffness had the specimen of the 3rd group that was nominally subjected to concentric compression. However, the specimen was actually subjected to compression and some weak axis bending due to an unintended small eccentricity that reduced its capacity to the one of the specimens of the 2nd group. As in the corresponding short test, the load fell sharply after the attainment of the failure load.

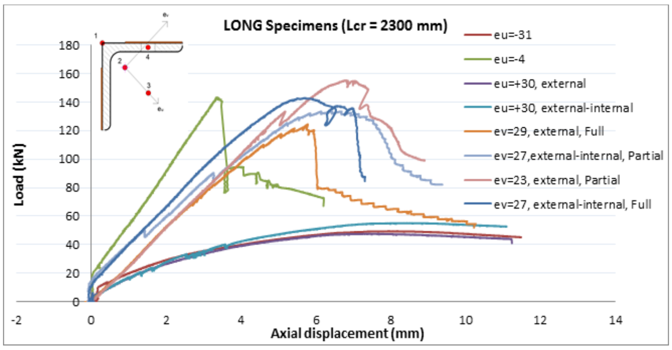


Figure 13 Load-displacement curves for the long specimens

As in the short specimens, displacements of the long specimens up to the failure load were in direction of the loading eccentricity. Displacements in the other direction, accompanied with twist were recorded in the unloading branch after the attainment of the failure load.

In the long tests, maximum deflections, and failure, occurred in the strengthened zone at mid-span. The strengthening length, partial or full, didn't appear to have a substantial effect to the failure load. The same was observed in respect to the type of strengthening, on one or both sides. For specimens L6 and L8 that were identical in respect to geometric and loading conditions, the failure load of the latter that was strengthened on both sides was around 5% higher compared with the failure load of the former that was strengthened on one side. The main advantage of strengthening on both sides is the self-centering ability that was observed in the relevant specimens, L2, L4, L8. Indeed, strain measurements indicated that the CFRP material remained elastic throughout the loading process, while steel material yielded, Fig. 14. Accordingly, the CFRP plates returned at unloading to their initial position driving the steel material to do so. This resulted in the specimen to return after unloading to its initial position with little permanent deflections. It should also be noted that detachment or failure of the CFRP plates was not observed at any compression test.

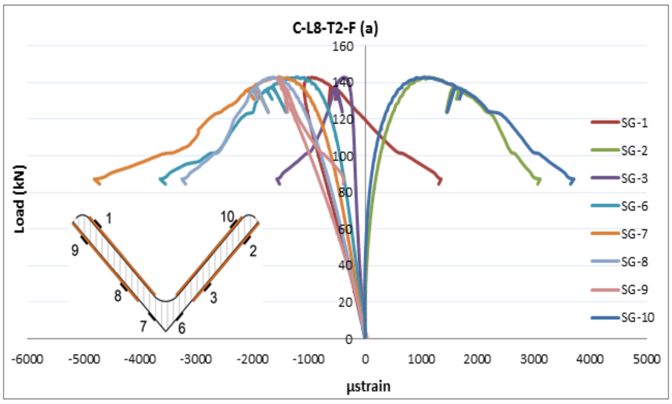


Figure 14 Strain measurements at mid-span of a double-side strengthened long specimen

The design checks for compression and bending of the hybrid sections were defined by following equations expressing verifications in respect to strong and weak axis buckling.

$$\left(\frac{N_{Ed}}{N_{bu,Rd}} + k_{uu}\frac{M_{u,Ed}}{M_{u,Rd}}\right)^{\xi} + k_{uv}\frac{M_{v,Ed}}{M_{v,Rd}} \leq 1 \quad (1)$$

$$\left(\frac{N_{Ed}}{N_{bv,Rd}} + k_{vu}\frac{M_{u,Ed}}{M_{u,Rd}}\right)^{\xi} + k_{vv}\frac{M_{v,Ed}}{M_{v,Rd}} \leq 1 \quad (2)$$

In the above formulae, index Ed expresses the acting forces, index Rd the corresponding resistances, u and v denote the strong and weak principal axes, k_{ij} are buckling parameters and the exponent $\xi = 2$.

Figures 15 and 16 show the ratio between predicted and experimental failure loads for the short and long specimens respectively as a function of the loading point. It may be seen that the analytic formulae are on the safe side. They give very good results when the angles are subjected to weak axis bending, while they are conservative when the angles are subjected to strong axis bending.

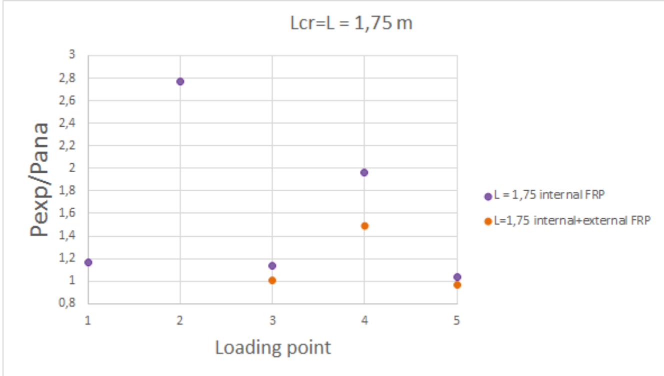


Figure 15 Ratio between experimental and analytical failure load for short specimens

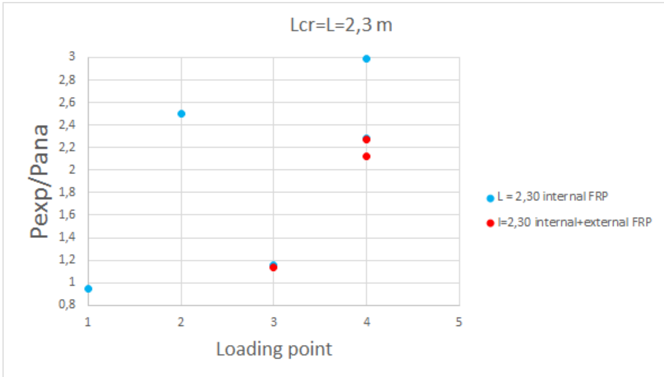


Figure 16 Ratio between experimental and analytical failure load for long specimens

5 Conclusions

This paper presents an experimental campaign that includes five (5) three-point bending tests and sixteen (16) compression tests on hybrid angle members strengthened with CFRP plates [8]. The test results were compared with previous similar tests on angle members without strengthening. Following conclusions may be drawn:

- Application of CFRP plates is a very efficient method for steel angle profiles with possibility of a high increase in bending moment and rotation capacity.
- Most beneficial is the fact that the bending capacity is more effectively increased in the weak axis compared to the geometric axis.
- Most effective is strengthening the legs on the external side. Strengthening on both sides does not increase substantially the buckling resistance but has a beneficial self-centering effect to compression members.
- The hybrid strengthening measures are more effective for slender compression members compared to stocky ones. The former may also be strengthened partially, over a reduced length.
- Good application of the CFRP plates and adequate anchorage length are very important to ensure good connection between steel and CFRP and prevent detachment.

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