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Strengthening Glued Laminated Non-circular Timber Columns with CFRP Jacketing

Omer Asim SISMAN [1], Ali ISIKARA [2], and Alper ILKI [3]

[1] MSc candidate, Structural Engineering Program, Istanbul Technical University (ITU), Istanbul, Turkey

[2] MSc candidate, Energy Institute, ITU, Istanbul, Turkey

[3] Professor, Civil Engineering Faculty, ITU, Istanbul, Turkey

Contact e-mail: ailki@itu.edu.tr

ABSTRACT: Recent developments in polymer and composite industry brought new solutions in construction techniques. In this study, compression tests are executed on glued laminated timber (glulam) columns confined with carbon fibre reinforced polymer (CFRP) sheets to assess potential enhancement in the structural performance of these members due to external confinement. In the experimental program, 8 timber column specimens were tested after jacketing with 1 and 3 plies of CFRP sheets and two columns were tested as reference specimens. Before external confinement with CFRP sheets, the corners of six of the columns were either rounded to 30 or 40 mm. Two columns were externally confined without rounding their corners. The aim of this investigation is to evaluate the failure modes and the stress-strain relationships of the externally confined specimens and to study the effect of the corner radius on the behaviour. At the end of the test, it was seen that external reinforcement using CFRP jackets have resulted in a significant increase in deformability. The improvement was more pronounced for the specimens jacketed with 3 plies of CFRP sheets with the corner radius of 30 mm.

1 INTRODUCTION

Advanced fibre reinforced polymer (FRP) composite usage has progressed rapidly in the area of civil engineering during the past few decades. FRP composites have a high strength-to-weight ratio and corrosion resistance. In addition, they are lightweight, easily applicable, and durable. FRP reinforcement has proven to be an effective solution for improving the ductility, durability and strength of existing and new structural elements (Holloway (2003)). Therefore, many studies have been carried out reinforcing/ strengthening of concrete, masonry and steel members with FRPs (ie. Matthys et al. (2006), Teng et al. (2007), Cosgun et al. (2019)). Based on these studies, several technical documents have been published for the design of FRP reinforcing/ strengthening (ie. Turkish Seismic Design Code (2018), ACI 440 (2002), CEN (2005)). More recently, the use of FRPs has been extended to timber members (ie. Gentry (2011), Jorge et al. (2011), Song et al. (2016)). Based on the studies executed for timber members, a pioneering design guide was also published for timber structures (National Research Council (2007)). The research work on concrete and masonry columns show that one of the most efficient ways of use of FRPs is external confinement of columns (Ilki et al. (2008), Mezrea et al. (2016)). Few studies on confinement have also been carried out on timber specimens. These studies have focused on FRP confinement of cracked timber specimens (Zhang et al. (2011)) and small clear wood specimens with circular cross-sections (Najm et al. (2007)) and glulam specimens with circular cross-sections (Sisman et al. (2018)).

2 MOTIVATION AND OBJECTIVE

The motivation of this study is to present an alternative non-circular composite column by using CFRP reinforced glulam. Despite previous researches on the FRP confinement of circular small clear wood specimens, cracked timber columns and glulam members, in this study rectangular glulam columns with larger cross-sectional areas were tested to reach a better understanding of confinement effectiveness. The objective of this research is to investigate the failure modes, the effect of corner radius and to obtain stress-strain relationships of the non-circular FRP reinforced glulam columns before and after jacketing with different thickness of CFRP sheets.

3 EXPERIMENTAL PROGRAM

3.1 *Specimens and materials*

Glulam columns made of spruce wood were chosen from GL24h class due to the availability and extensive usage in Europe. Two unconfined reference and 8 confined column specimens were used for the experimental program. In total, 10 rectangular glulam columns were with the cross-sectional aspect ratio of 1 were tested under concentric compression. The cross-sectional dimensions were 200 x 200 mm and the height of all specimens was 400 mm. The mechanical characteristics and thickness (t) of the CFRP sheets were taken from the manufacturer that elastic modulus (E), tensile strength (σ_t), and ultimate strain (ε_{ult}) were obtained based on coupon tests. Mean modulus of elasticity parallel to grain ($E_{0,mean}$), characteristic compression strength parallel to grain ($\sigma_{c,0,k}$), moisture content and the average density of GL24h class timber specimens are given in Table 1. The test specimens are denoted according to their cross-sectional shape (S: Square), the number of plies of CFRP jackets and lastly their corner radius. For example; S-1-30a represents a square specimen jacketed with 1 ply of CFRP sheets with a corner radius of 30 mm.

Table 1. Materials

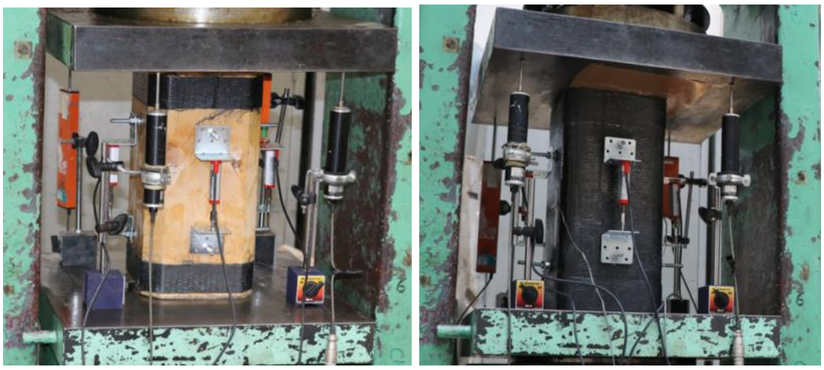
CFRP	E (GPa)	σ_t (MPa)	ε_{ult}	t (mm)
	92,39	1400	1,5%	0,533
GL24h	$E_{0,mean}$ (GPa)	$\sigma_{c,0,k}$ (MPa)	Moisture Content	Average Density (g/cm^3)
	11,6	24	12%	0,446

3.2 *Preparation of specimens*

Before the application of FRP confinement, corners of a group of specimens were rounded to 30 and 40 mm radius by using cutting and sanding machines. Six specimens were externally wrapped with 1 ply of CFRP sheets and 2 specimens were externally wrapped with 3 plies of CFRP sheets in the transverse direction. After all column surfaces were cleaned, one layer of epoxy putty and epoxy-polyamine primer were formed respectively to prevent voids at the interface and to provide good bonding during the jacketing process. After mixing epoxy system components, the epoxy adhesive was used for bonding CFRP sheets around the specimens through wet layup procedure. An overlap of 150 mm was formed at the end of the wrap to avoid premature debonding. In order to avoid failures at the top and bottom of the columns, an additional layer of 50 mm wide CFRP sheet was used at these regions. Tests were executed three weeks after wrapping of FRP sheets.

3.3 Test setup

Uniaxial compression loading was applied for all specimens using an Amsler testing machine. In the test setup, displacement transducers with two different gauge lengths were used to measure average axial strains. Four transducers with the gauge length equal to half of the height were placed on specimens at mid-height. Four transducers with the gauge length equal to specimen height were also used between loading plates. They were installed with 90-degree intervals. The stress-strain curves of the specimens are plotted by making use of average measurements of four displacement transducers placed on mid-height of the specimens until the peak load. After the peak load, the other four displacement transducers measuring the displacement change between loading plates were used due to damages of the specimens at around the mid-height. The tests were continued until the axial strain at which the axial stress was reduced to 85% of the ultimate strength was reached on the descending branch. The test setup of the reference and confined specimens is shown in Figure 1a and 1b, respectively.



a b

Figure 1. The test setup of a) a reference specimen and b) a confined specimen

4 RESULTS AND DISCUSSIONS

Compression test results for timber columns with or without CFRP jackets are presented in Table 2. Considering the definition of Frese et al. (2012), linear parts of the stress-strain curves are used to calculate elastic moduli of the specimens. Since FRP confinement contributes to the compressive behaviour of the specimens after the formation of relatively high transverse strains, no consistent change was observed in the modulus of elasticity as a function of external confinement. As it can be seen in Table 2, the average strength gains in the specimens jacketed with 1 ply of FRP sheet were more than %10 with respect to reference specimens. However, the average strength of the specimens jacketed with 3 plies of FRP sheets was lower with respect to the other confined specimens due to the lower strength of specimen S-3-30b. This once more indicates the potential high scattering in timber members and shows the necessity of testing a relatively higher number of specimens as it has been also stated before (Sisman et al, 2018). The ratio of the axial strains corresponding to 85% of the ultimate load on the descending and ascending branches was used to obtain the deformability (μ) of each specimen. The external confinement was remarkably effective on the deformability of timber members for all cases, except the specimens without corner rounding. As seen in Table 2, the average deformability of S-3-30 series was 2,4 times that of the reference specimens.

Table 2. Test results

Specimens	Plies of CFRP	Corner Radius	E		$\sigma_{\max}$		μ	
			(GPa)	Average	(MPa)	Average		Average
S-0-0a	Ref.	0	11,68	13,51	35,44	35	2,88	4,07
S-0-0b	Ref.	0	15,34		34,66		5,26	
S-1-0a	1	0	12,76	12,8	39,97	39,18	4,05	3,64
S-1-0b	1	0	12,84		38,39		3,23	
S-1-30a	1	30	13,92	13,32	38,79	39,37	5,61	5,51
S-1-30b	1	30	12,72		39,94		5,41	
S-1-40a	1	40	15,53	14,17	39,65	38,79	6,37	6,1
S-1-40b	1	40	12,81		37,94		5,83	
S-3-30a	3	30	14,41	13,06	38,57	36,21	10,7	9,8
S-3-30b	3	30	11,71		33,85		8,9	

4.1 Observed failure modes

For the reference specimens, localized compressive failures were observed at around mid-height of the specimens (Figure 2a). Timber columns started to crush with a continuous sound of compression while reaching the peak load. After that, wood fibres were locally buckled on the surfaces of specimens. As the applied load was reducing to 85% of the ultimate load, bulging occurred circumferentially. At last, longitudinal splits were seen in some part of the wood between parallel timber grains. The reference specimens failed under compression in a common way of stocky timber columns. In the case of confined specimens with 1 ply of CFRP sheet, the observed failure was due to tension rupture of the CFRP sheets which was propagated vertically at timber columns' corners (Figure 2b). These jackets limited crack propagation within the timber. The jackets ruptured relatively large axial deformations when the resisted axial load has dropped to approximately 85% of the peak load. The contribution of local defects to failure which is often seen in timber members, was reduced to some extent by the external confinement. An explosive sound was heard when the jacket ruptured in S-1-30 and S-1-40 series. Then, wood fibres were suddenly crushed and buckled at the location where the jacket has ruptured. After tension ruptures continued brittlely in the fibres of CFRP sheets, the failure mode turned into localized compression failure of wood.

a b

Figure 2. a) Reference specimens and b) S-1-30 and S-1-40 specimens after tests

In S-1-0 series, the specimens confined with 1 ply of CFRP sheets and without corner radius, jackets were suddenly ruptured right after the peak load. The fracture of these jackets was initiated at a sharp edge and continued through the midsections of the columns in a brittle manner (Figure 3a). Therefore, the effect of confinement was reduced and gradual strength loss was seen similar to the reference columns. In both series, it was observed that localized timber compression failure was responsible for the post-peak behaviour.

On the other hand, in S-3-30 series, the specimens confined with 3 layers of CFRP sheets that have 30 mm corner radius, tension rupture failure did not occur in the jackets (as it can be seen in Figure 3b), even though relatively large axial deformations were reached. In these columns, the perpendicular-to-grain enlargement and crackings in timber were successfully restrained due to external confinement. Therefore, the strength was almost constant after the peak load and the deformability enhanced significantly due to the positive effect of confinement.


a b

Figure 3. a) S-1-0 series and b) S-3-30 series after tests

4.2 *Stress-strain relationships*

4.2.1 Effect of thickness of CFRP jacket

The stress-strain relationships of reference and externally FRP confined specimens are shown in Figure 4. All of the reference specimens exhibited a softening behaviour due to local compression failure at the peak load. After that, a significant gradual strength loss was noted while the axial strains were increasing. For the externally jacketed specimens, S-1-30 and S-3-30 series, the adverse effects of local defects were lowered by the jackets. Hence, the post-peak behaviour of glulam columns was enhanced, particularly in terms of deformability (Figure 4). In contrast to reference specimens, for example, the average deformability was increased 1,35 and 2,4 times respectively in S-1-30 series and S-3-30 series. Except for the S-3-30b specimen, the strengths of all jacketed specimens were approximately 1,1 times that of reference specimens. The difference in the strength of S-3-30b specimen which has a lower density (0,424 g/cm^3) compared to the average density (0,446 g/cm^3) of all specimens, could relate to the scattering in timber compressive strength parallel to grain.

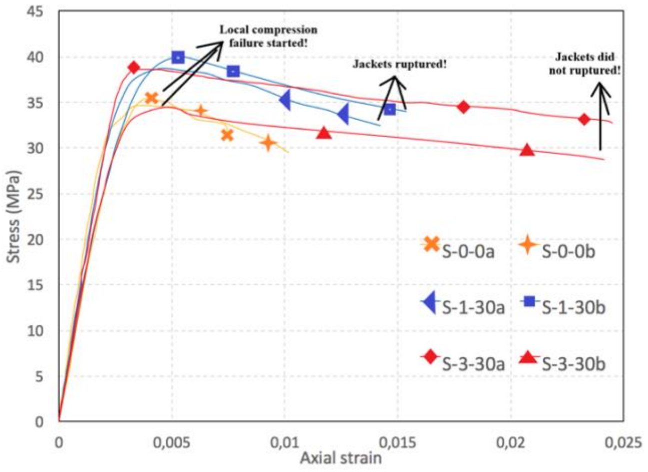


Figure 4. Stress-strain relationships for S-0-0, S-1-30 and S-3-30 series

4.2.2 Effect of corner radius

The stress-strain relationship of timber column specimens with different corner radii are shown in Figure 5. In S-1-0 series, the lack of corner radius apparently caused irregularities in stress distribution, which lead to reduced efficiency of external confinement. Although improvements in strength were observed similar to the jacketed specimens with rounding, the average deformability of jacketed specimens without rounding were very close to that of reference specimens, because the observed failure mode of S-1-0 series was the fracture of CFRP sheets at around the peak load on the descending branch and it was followed with local compression failure of timber, which is almost same behaviour with the reference columns (Figure 5). On the other hand, in S-1-30 and S-1-40 series, jacketed specimens with the corner radii of 30 and 40 mm, the compressive strength could be sustained on the descending branch with a small degradation until considerable axial strains were reached. For instance, the average deformability was respectively 1,35 and 1,5 times that of reference specimens in S-1-30 series and S-1-40 series. This also shows the superior behaviour of S-1-40 series to S-1-30 series due to the positive effect of corner rounding.

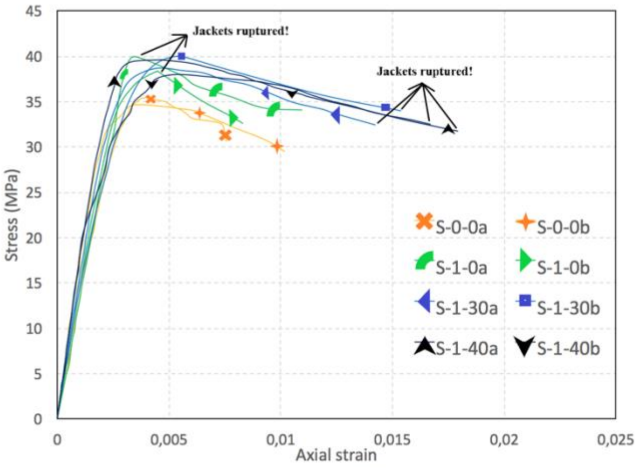


Figure 5. Comparison of specimens with different corner radii of 0, 30 and 40 mm

5 CONCLUSIONS

The compression test results confirm good deformability of composite columns consisting of glulam and CFRP. The CRFP sheets restrained cracking and enlargement of local defects effectively in the inelastic range for externally jacketed timber specimens with corner radii of 30 and 40 mm. However, for the specimens jacketed with a similar thickness of CFRP sheets with sharp corners (without rounding), the positive effect of confinement on deformability was not pronounced due to the stress concentrations at the corners of sections which lead to the sudden tension rupture of CFRP sheets right after the peak load. This demonstrates the vital importance of corner radius on rectangular wood sections for the confinement effectiveness.

In the study of Sisman et al. (2018), the adverse effect of large knots especially at the outer surface of circular specimens induced premature tension rupture failure of CFRP jackets at around peak load. Therefore, the confinement in these specimens was inefficient. Compared to this study, the phenomenon was not pronounced and it was attributed to clear wood surfaces (with no knots) on the rounded corners of the confined non-circular specimens where jackets potentially suppressed damage initiations.

The improvements on deformability were more than two times for the non-circular specimens jacketed with 3 plies of CFRP sheets with respect to the reference specimens. For the circular timber column specimens with 1 ply of CFRP sheet, the improvements on deformability were around four times that of reference specimens according to the study Sisman et al. (2018). Therefore, it can be said that the cross-sectional shape also plays an important role in the behaviour of jacketed columns. Although there was some gain in strength in the rectangular confined specimens due to the external jacketing, more research should be performed for obtaining lower scattering in the compressive strength of wood (parallel to grain) which could lead to better safety factors for design.

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