IOP Conf. Series: Materials Science and Engineering **433** (2018) 012041 doi:10.1088/1757-899X/433/1/012041

Strengthening Aspects to Improve Serviceability of Open Web Expanded Steel-Concrete Composite Beams in Combined Bending and Torsion

N K Oukaili[1] and S Sh Abdullah[2]

[1]Professor, College of Engineering, University of Baghdad, Iraq
[2]Ph.D, General Directorate of Works and Maintenance, Ministry of Construction and Housing, Iraq

Abstract. The performance of open web expanded steel-concrete composite beams under combined bending and torsion was investigated up to failure. Two strengthening techniques were proposed: the first, by adding steel stiffeners only to web sections, and the second by exposing composite beams to external prestressing after supporting the web sections with steel stiffeners. Six specimens were tested divided across the two main groups. Each group included three specimens, which were designated according to the type of strengthening technique used. Load capacity, load-deformation responses, and strain across section depth were monitored. The results showed that the first strengthening technique reduced the deflection under service loads by 14.13% and 11.55% for castellated and cellular specimens, respectively, while the second technique decreased the comparative values by 147.82% and 30.11%, respectively. In terms of the angle of twist, torsional stiffness increased by 27.58% due to the application of steel stiffeners for castellated specimen, while, in the cellular specimens, there was no apparent contribution from adding these stiffeners in terms of improving torsional performance at the early stages of loading. The second technique did show a greater reduction in the angle of twist, by 93.10% and 39.53% for castellated and cellular specimens, respectively.

Keywords: Castellated, Cellular, Composite, Strengthening, External Prestressing

1. Introduction

Structural engineers are constantly seeking new methods to enhance their practices in the design of steel and composite buildings in order to minimise the overall cost of building construction. One such method is the use of open web expanded steel beams. These types of steel beams can lead to a decrease in storey height, reducing interior volume and minimising the exterior surface of a building, offering cost savings in building constructions due to the presence of web holes in the regular pattern of steel beams with different geometrical properties [1]. In addition, they have been used for many years to pass ductwork or utilities through. Furthermore, in comparison with solid beams, open web expanded steel beams offer increased shear capacities, provide better vertical bending stiffness, and increase the capacities of the structure. They can be achieved by amending an original solid steel beam by cutting the web of a solid beam into a certain pattern and then re-welding the two parts to each other so that the beam sections are modified to intensify their strength. As a result of these cutting and re-welding processes, the overall beam depth increases which in return causes an increase in the capacity of the original section. There are two common types of open web expanded steel beams based on the shapes of their web holes: the first, with hexagonal openings, are also called Castellated beams, while the second, with circular openings, are referred to as Cellular beams. These types of steel beams have been used in various types of constructions for many years [1, 2]; however, the fabrication of castellated and cellular beams was not used economically until the appearance of appropriate automated manufacturing techniques. Improved automation in fabrication using Computer Numerical Control (CNC) processes coupled with the demand by architects led to the search for less costly and more efficient ways to design steel structural members that developed the web expanded steel beams industry in the United States. Many advantages are provided by using open web expanded steel beams, such as improved flexural strength due to increased section depth without increasing the self-weight, increases in depth-to-weight ratios,

and improved stiffness due to increases in the strong axis moment of inertia and section modulus, Moreover, more holes also allow plumbing pipelines and electrical conduits to pass through, ultimately reducing the elevation of floor level [2, 3].
Few studies have been done on the performance of open web expanded steel-concrete composite beams under combined bending and torsion, with or without proposed strengthening systems. In this paper, the web castellation of circular and hexagonal configurations were selected to study the effects of two strengthening systems on the overall behaviour of flexural composite beams with castellation shapes, under combined bending and torsional effects.
The objective of this investigation was to study the effect of steel stiffeners and external prestressing on the serviceability, performance, and improvement of load carrying capacity in composite concrete-open web expanded steel beams.

2. Experimental program

Six composite steel-concrete specimens were fabricated and tested to failure as simply supported beams over an effective span of 2,900 mm. A hot rolled steel I-beam section (IPE 200) was used where the total height after castellation was 360 mm, of which 60 mm was concrete deck slab and 300 mm was open web steel I-beam section. Figure 1 shows the castellation process.

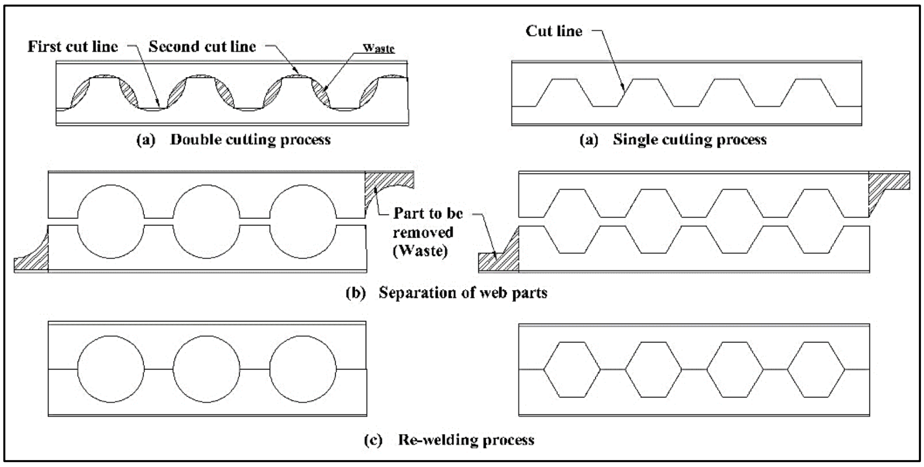


Figure 1. Manufacture of celular and castellated beams [3].

A good connection between the two components of a composite system is essential. Accordingly, a fabricated steel channel section of 40 x 30 x 3 mm with 50 mm total length was used in form of shear connectors distributed at the top flange of the steel I-beam, perpendicularly, 150 mm c/c apart. The width of the concrete deck slab was 500 mm, reinforced in both directions with deformed steel bars of 6 mm diameter spaced at 150 mm c/c. For the specimens subjected to external prestressing, two low-relaxation seven-wire steel strands of grade 270 were used. The jacking prestressing force (P_j) consisted of 40% of the ultimate strength of the strand (f_{pu}). Two deviators were placed at the third points of the span, which consisted of 25 mm diameter cylindrical rods welded to the soffit of the steel I-beam. Figures 2 and 3 show details of the experimental specimens. The mechanical properties of the steel I-beam, steel stiffeners, steel plates for shear connectors, prestressing strands, and welded wire fabric are mentioned in Table 1. The concrete mix was prepared using Type I cement, with crushed stone of 10 mm maximum aggregate size and fine river sand. By weight, the cement: sand: aggregate proportions were 1:1.5:3, with a water-cement ratio of 45%. The concrete compressive strength was determined by testing three standard 150 x 150 x 150 mm concrete cubes taken from each specimen, where the target value was 32 MPa [3]. Six specimens were tested in which the first castellated (CBR-FT) or cellular (CEB-FT) specimens were considered as reference specimens, the second specimens (CBS-FT) and (CEBS-FT) were characterised by strengthening with intermediate steel stiffeners on both sides of the web-posts, and the third specimens (CBP-FT) and (CEBP-FT) were subjected to external prestressing in addition to the use of vertical steel stiffeners. It should be mentioned that external prestressing was applied to the steel section before pouring the concrete of the deck slab. All specimens were subjected to a monotonically increased loading up to failure using a load control test. All measurements, such as midspan deflections, angle of twist, and strain across the section depth, were recorded twice, both immediately after the application of the load and 10 minutes later [4].

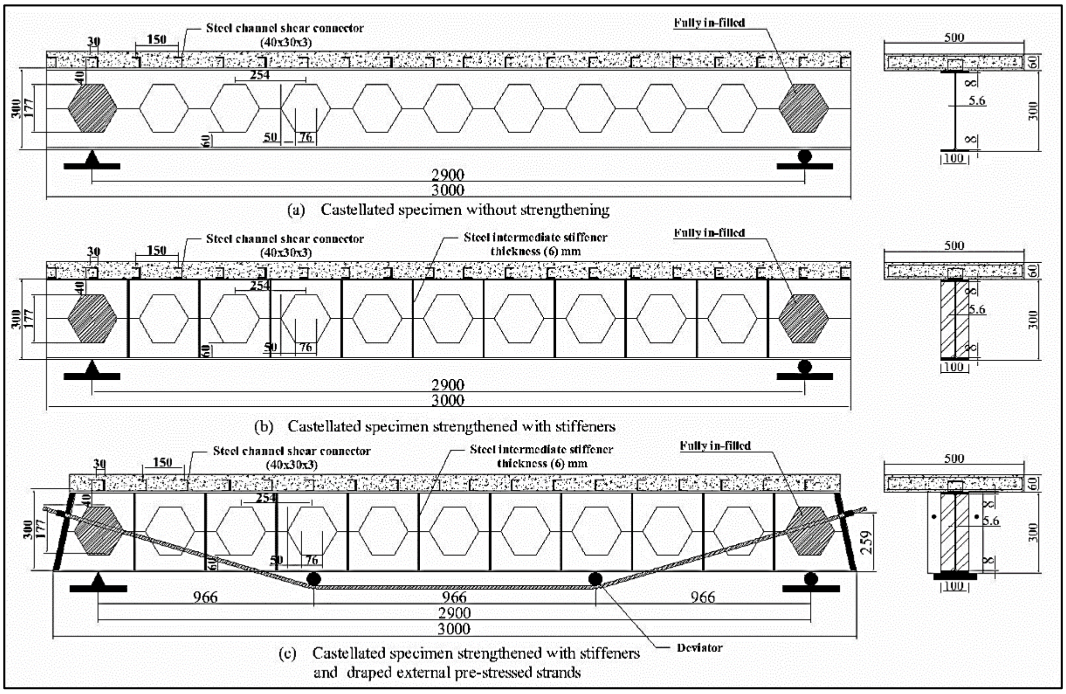


Figure 2. Details of experimental castellated specimens [3, 4].

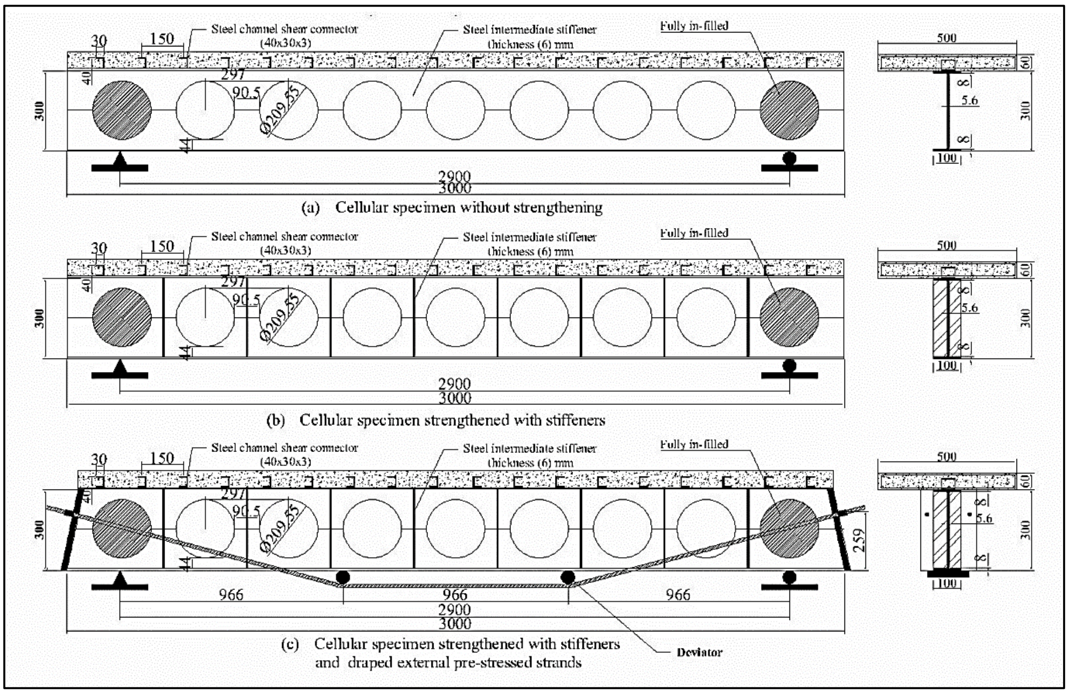


Figure 3. Details of experimental cellular specimens [3, 4].

IOP Conf. Series: Materials Science and Engineering **433** (2018) 012041 doi:10.1088/1757-899X/433/1/012041

Table 1. Mechanical properties of steel components.

	Thickness (mm)	Yield Stress (MPa)	Ultimate Stress (MPa)
Plate for web	5.6	397.87	520.52
Plate on top and bottom flanges	8.0	378.95	519.80
Plate for stiffeners	6.0	394.71	520.52
Plate for shear connectors	3.0	246.14	332.79
Welded wire fabric	Ø 6	456.62	615.60
Prestressing steel strand	Ø 12.7	1675.0	1862.0

3. Experimental results

Different failure modes for open-web expanded steel beams can be identified. These may be due to flexural mechanism; lateral torsional buckling; Vierendeel or shear mechanisms; web-post buckling due to shear force; distortional buckling; web-post buckling due to compression force; ultimate deflection; or rupture of welded joints [5,6]. In the current study, failure due to lateral torsional buckling did not occur due to the fully lateral bracing achieved by the concrete deck slab. The monitored failure mode for all specimens considered in this study was due to combined flexure and shear mechanism. Plate 1 and Table 2 show the failure modes of all tested specimens.

Plate 1. Modes of failure for experimental specimens [3].

Table 2. Load carrying capacity and modes of failure for experimental specimens [3].

	Type of castellation	$P_{u,}$ (kN)	$(P_u/P_{u,\ ref})$, (%)	Mode of failure
CBR-FT	Hexagonal	55.00	100	Combined flexural and shear mechanisms
CBS-FT		64.00	116.36	
CBP-FT		130.0	236.36	
CEBR-FT	Cellular	90.00	100	Combined flexural and shear mechanisms
CEBS-FT		120.0	133.33	
CEBP-FT		195.0	216.67	

For castellated and cellular specimens strengthened by adding intermediate steel stiffeners to the web-posts, the ultimate load capacity was improved by 16.36% and 33.33%, respectively. In the same manner, using the second strengthening technique led to enhancing the load carrying capacity by 136.36% and 116.67 % for both castellated and cellular specimens, respectively. Figure 4 shows the effect of strengthening techniques on the load carrying capacity of the tested specimens. The first technique decreased the midspan deflection under ultimate service loads by 14.13% and 11.55% for castellated and cellular specimens, respectively (Figure 5), while using prestressing as a second strengthening system reduced the mentioned values under ultimate service loads by 147.82% and 30.11%, respectively (Figure 5). In terms of the angle of twist, torsional stiffness increased due to the application of web steel stiffeners for specimen (CBS-FT) under combined flexure and torsion by 27.58%. Meanwhile, in specimen (CEBS-FT), there was no contribution seen from adding these stiffeners in terms of improving torsional performance at the early stages of loading. For load levels which exceeded the ultimate service load for the reference specimen (CEBR-FT), the strengthening system showed significant improvement in the torsional performance of (CEBS-FT). On the other hand, specimens subjected to external prestressing along with intermediate steel stiffeners showed greater reductions in the angles of twist, by 93.10% and 39.53% for (CBP-FT) and (CEBP-FT), respectively. Figure 6 shows the torque- angle of twist response diagram for all tested specimens.

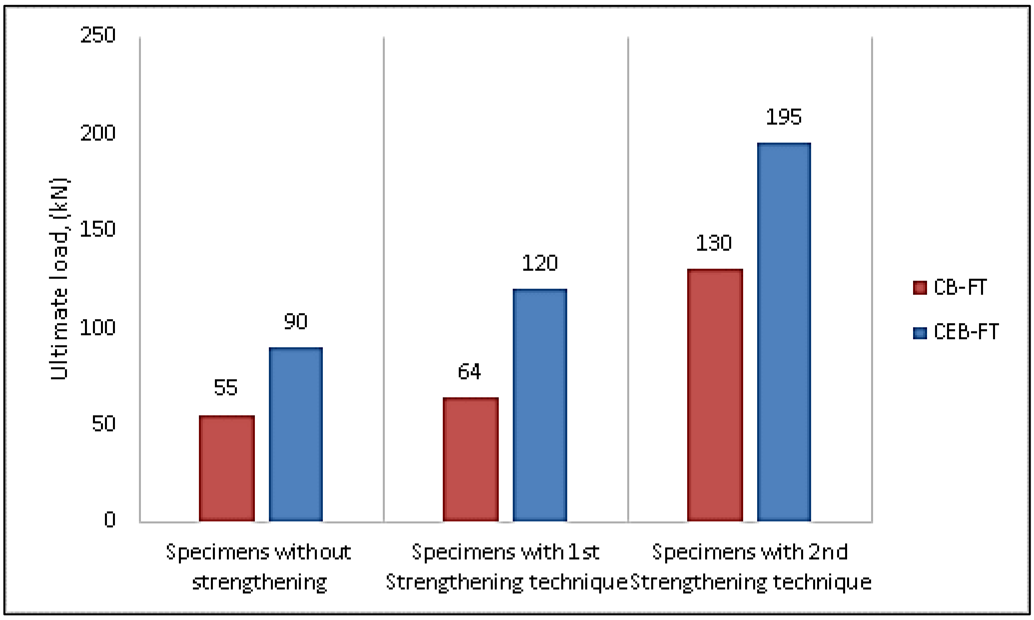


Figure 4. Comparison of load carrying capacity of experimental specimens.

The strain across the midspan section depth was measured at each loading stage using steel and concrete electrical strain gauges. These electrical strain gauges were installed at different levels of the specimen section. Figures 7 to 12 show variations of strain across the section depth in concrete and steel beams according to the applied load level. For the cellular reference specimen (CEBR-FT), strain in concrete fibres varied across the thickness of the deck slab, and increased as the increase of the applied load level approached +162 x 10^{-6} at the extreme top fibres and +124 x 10^{-6} at the extreme bottom fibres as the load attained its ultimate level. Meanwhile, the tensile strain values in extreme fibres of the bottom steel flange reached +1,366 x 10^{-6} at ultimate load.

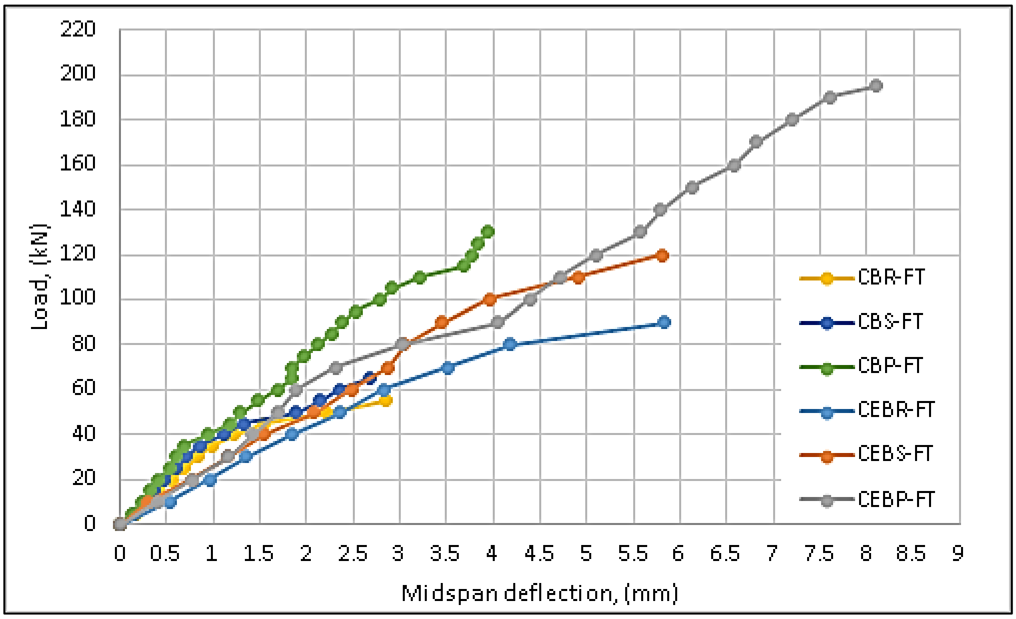


Figure 5. Load -midspan section deflection response for all specimens.

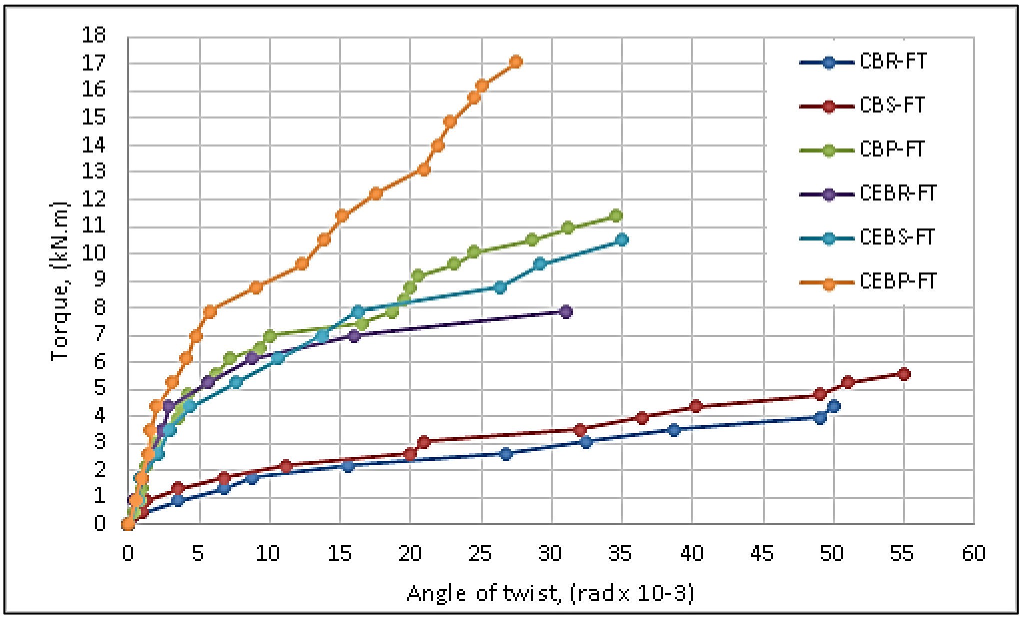
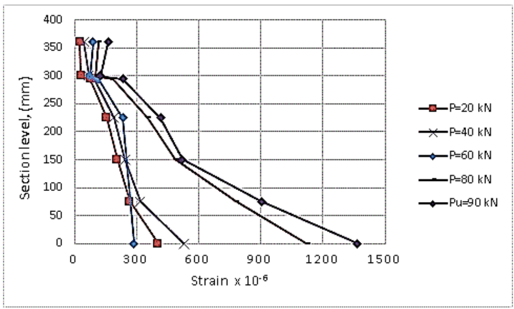


Figure 6. Torque –angle of twist response for all specimens.

IOP Conf. Series: Materials Science and Engineering **433** (2018) 012041 doi:10.1088/1757-899X/433/1/012041

The results of the castellated reference specimen (CBR-FT) show that the strain in concrete fibres followed the same manner of change across the thickness of the deck slab with excessive increase of the applied load. Accordingly, at ultimate load, the concrete strain attained +89 x 10^{-6} and +102 x 10^{-6} at the extreme top and bottom fibres, respectively. The tensile strain at the extreme fibres of the bottom flange approached +845 x 10^{-6}. As a result of using strengthening techniques exposed to combined flexure and torsion, the ultimate load capacity was increased. Accordingly, at failure, the strains were increased in comparison with the strains on the reference specimens [5]. It should be mentioned that no compression strains were monitored or recorded during the testing of specimens under combined flexure and torsion.



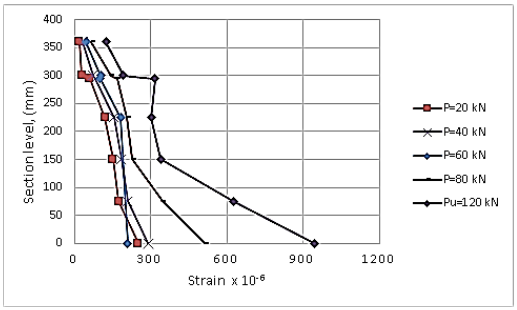
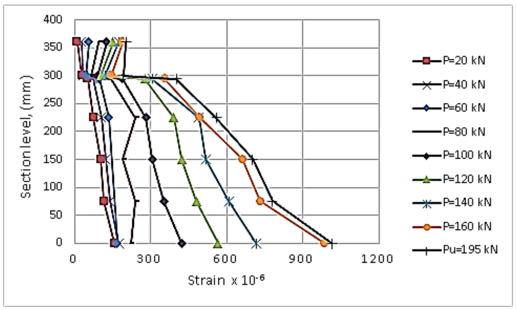


Figure 7. Strain across section depth of CEBR-FT. **Figure 8.** Strain across section depth of CEBS-FT.



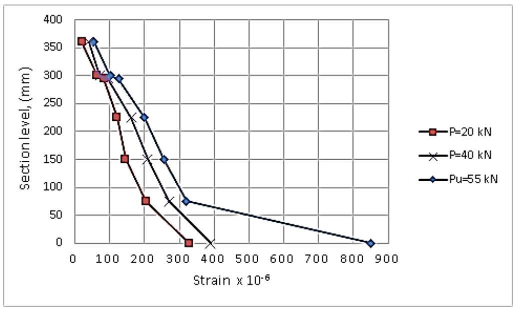
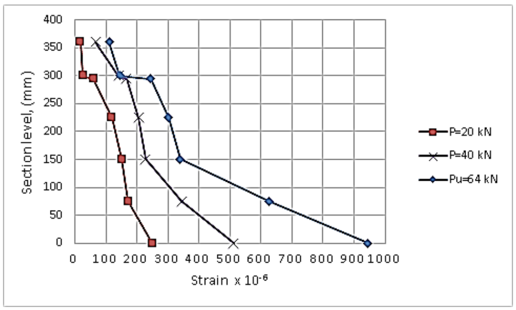


Figure 9. Strain across section depth of CEBP-FT **Figure 10.** Strain across section depth of CBR-FT



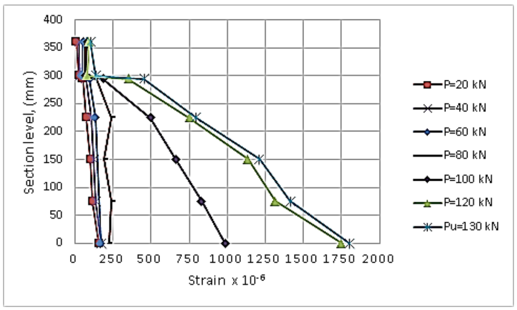


Figure 11. Strain across section depth of CBS-FT **Figure. 12**. Strain across section depth of CBP-FT

The strain increment in the prestressing strands due to the applied loads in the castellated specimen (CBP-FT) and cellular specimen (CEBP-FT) are demonstrated in Figure 13, where these values attained failure at +655 x 10^{-6} and +1,100 x 10^{-6}, respectively.

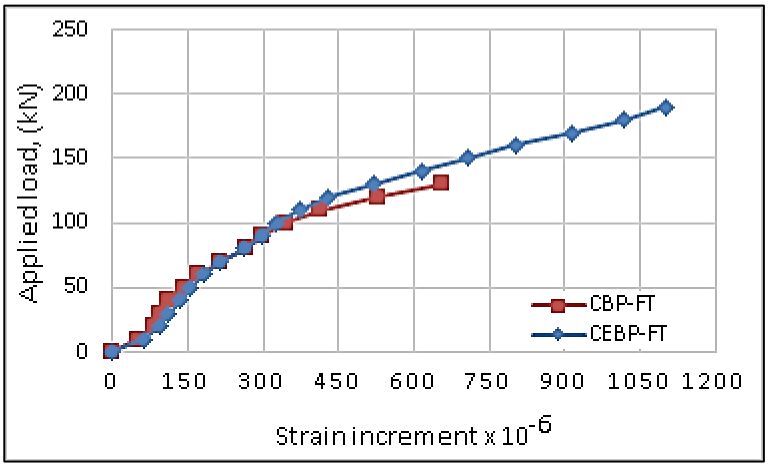


Figure 13. Strand load-strain increment diagram.

4. Conclusion

According to the studied configurations of strengthening composite open web expanded steel beams, (castellated and cellular), which were subjected to combined bending and torsion, the following conclusions can be drawn:

1. Using the first strengthening system with steel stiffeners at each web post led to increases in load carrying capacity by 16.36% and 33.33% for castellated and cellular specimens, respectively.
2. Applying external prestressing in addition to web stiffeners improved the load carrying capacity by 136.36% and 116.7% for castellated and cellular specimens, respectively.
3. Adding intermediate steel stiffeners decreased the ultimate service midspan section deflection by 14.13% and 11.55% for castellated and cellular specimens, respectively. Subjecting the composite beam to external prestressing in addition to web stiffeners reduced the mentioned values by 147.82% and 30.11%, respectively.
4. In term of the angle of twist, torsional stiffness increased due to the application of web steel stiffeners for specimen (CBS-FT) under combined flexure and torsion by 27.58%. Meanwhile, in specimen (CEBS-FT) there was no contribution from adding these stiffeners in terms of improving torsional performance at the early stages of loading. However, specimens subjected to external prestressing along with intermediate steel stiffeners showed more reduction in the angles of twist, by 93.10% and 39.53% for (CBP-FT) and (CEBP-FT), respectively.

5. References

[1] Erdal F 2011 *Ultimate load capacity of optimally designed cellular beams* (Middle East Technical University)

[2] American Institute of Steel Construction (AISC) 2016 Castellated and Cellular Beams Design *Steel Design Guide* p 31

[3] Abdulla Seezar Sh 2018 *Behavior of Composite Concrete – Open Web Expanded Steel Beams under Combined Flexure and Torsion* (Baghdad University)

[4] Oukaili N and Abdullah S 2017 *Experimental Behavioral Inspection Of Composite Concrete-Open Web Expanded Steel Beams Exposed To Static Loading*

[5] Kerdal D and Nethercot D A 1984 Failure modes for castellated beams *J. Constr. Steel Res.* **4** 295–315

[6] Afefy H M E-D, Atta A M and Taher S E-D F 2012 Behavior of strengthened composite castellated beams pre-stressed with external bars: Experimental study *Arab. J. Sci. Eng.* **37** 1521–34