REFERENCES

1. Alfarabi S., Al-Sulaiman. G. J., Basunbul. I. A., Baluch. M. H., and Ghaleb. B. N. (1994). Strengthening of initially loaded reinforced concrete beams using FRP plates. *ACI Structural Journal*. 91 (2), 160-168.

2. Ali, N., Samad, A., Mohamad, N. and Jayaprakash, J. (2013) Shear Behaviour of Pre-cracked Continuous Beam Repaired using Externally Bonded CFRP Strips. *Procedia Engineering*. 53, 129-144.

3. Ali and Noorwirdawati . (2013). Shear Behavior of Pre-Cracked Continuous Beam Repaired Using Externally Bonded CFRP Strips. *Procedia Engineering 53*, 129-144.

4. Alkhrdaji, T., Nanni, A., Chen, G. and Barker, M. (1999). Upgrading the transportation infrastructure: solid RC decks strengthened with FRP. *Concrete International: Design and Construction*. 21 (10), 37-41.

5. Ariyachandra M R E F , Gamage J.C.P.H, Riadh Al-Mahaidi, Robin Kalfat, (2014) A theoretical approach to predict flexural capacity of anchored CFRP-strengthened concrete beams with transverse end U wraps.

6. Ashour AF, El-Refaie S.A. and Garrity, S.W. . (2004). Flexural strengthening of RC continuous beams using CFRP laminates. *Cement & Concrete Composites*. 26, 765-775.

7. Balamuralikrishnan, R., and C. Antony Jeyasehar. (2009). Flexural Behavior Of RC Beams Strengthened With Carbon Fiber Reinforced Polymer (CFRP) Fabrics. *TOCIEJ 3*.1 . 102-109.

8. Blaschko, M., Niedermeier, R. and Zilch, K. . (1998). Bond failure modes of flexural members strengthened with FRP. *2nd International Conference on Composites in Infrastructure*, Tucson, Arizona.

9. Breveglieri, M., Aprile, A. and Barros, J. . (2015). Embedded Through-Section shear strengthening technique using steel and CFRP bars in RC beams of different percentage of existing stirrups. *Composite Structures*. 126, 101-113.

10. Burgoyne. C. J. (1999). Advanced composites in civil engineering in

Europe. *Journal of The International Association of Bridge and Structural Engineering* [online] 9 (4). Available from : www.iabse.ethz.ch/sei/backissues/abstracts.sei9904/burgoyne.pdf.

11. Deniaud, C., and Chang, J.J.R. (1998). Shear Behavior of Reinforced Concrete T-Beams with Externally Bonded Fiber Reinforced Polymer Sheets. *ACI Structural Journal*. 3, 386-494.

12. Ding, Jun . (2014). The Effect Of CFRP Length On The Failure Mode Of Strengthened Concrete Beams. *Polymers 6.6* . 1705-1726

13. Ehsani, M.R., Saadatmanesh, H., and Al-Saidy, A. (1997). Shear Behavior of URM Retrofitted with FRP Overlays of Composites for Construction . *ASCE*. 1 (1), 17-25.

14. Esfahani, M., Kianoush, M., & Tajari. (2007). A. Flexural behaviour of reinforced concrete beams strengthened by CFRP sheets. *Engineering Structures*. 29, 2428-2444.

15. Ferrier, E., Ennaceur, C., Bigaud, D. and Hamelin, P. (2001). Prestressed externally bonded FRP reinforcement for RC beams. *5th International Conference on FRP Reinforcement concrete Structures (FRPRCS-5),* Cambridge, UK. 1, 271-280.

16. Jones, R., Swamy, R. N., and Charif, A. . (1988). Plate separation and anchorage of reinforced concrete beams strengthened by epoxy –bonded steel plates. *The Structural Engineer*. 66 (5), 85-94.

17. Fathelbab, F.A., M.S. Ramadan, and A. Al-Tantawy. (2011). Finite Element Modeling Of Strengthened Simple Beams Using FRP Techniques: A Parametric Study. *Concrete Research Letters 2*. 2 , 228-240.

18. Gao, B., Kim, J. and Leung, C. . (2006). Strengthening efficiency of taper ended FRP strips bonded to RC beams. *Composite science and technology*. 66, 2257-2264.

19. Garden, H.N., and Hollaway, L.C. . (1998). An experimental study of the influence of plate end anchorage of carbon fiber composite plates used to strengthen reinforced concrete beams. *Composite Structures*. 42 (2), 175-88.

20. Houssam A.T. (1997). The Durability characteristics of concrete beams externally bonded with FRP composite sheets. 351-358

21. Hawileh, R., Nawaz, W., Abdalla, J. and Saqan, E. . (2015). Effect of flexural CFRP sheets on shear resistance of reinforced concrete beams. *Composite Structures*. 122, 468-476.

22. Jayaprakash, J., Abdul Aziz Abdul Samad, and Ashrabov Anvar Abbasvoch. (2009). Experimental Investigation On Shear Capacity Of Reinforced Concrete Precracked Push-Off Specimens With Externally Bonded Bi-Directional Carbon Fiber Reinforced Polymer Fabrics. *Modern Applied Science 3*.7.

23. Khalifa, A., Tumialan, G., Nanni, A. and Belarbi, A. (1999). Shear strengthening of continuous RC beams using externally bonded CFRP sheet. *American Concrete Institute, Proc., 4th International Symposium on FRP for Reinforcement of Concrete Structures (FRPRCS4),* Baltimore, MD. 995-1008.

24. Khalifa, A . and Nanni, A. (2002). Rehabilitation of rectangular simply supported RC beams with shear deficiencies using CFRP composites. *Construction and Building Materials*. 16, 135-146.

25. Khan, Asad Ur Rehman, and Shamsoon Fareed. (2014). Behavior of Reinforced Concrete Beams Strengthened By CFRP Wraps With And Without End Anchorages. *Procedia Engineering* . 77, 123-130.

26. Li, L., Guo, Y., Liu, F. and Bungey, J. . (2006). An experimental and numerical study of the effect of thickness and length of CFRP on performance of repaired reinforced concrete beams. *Construction and Building Materials*. 20 (10), 901-909.

27. Meier, U. (1995). Strengthening of Structures using Carbon Fibre/Epoxy Composites. *Construction and Building Materials*. 9, 431-351.

28. Morsy, A., El-Tony, E. and El-Naggar, M. (2015). Flexural repair/strengthening of pre-damaged R.C. beams using embedded CFRP rods. *Alexandria Engineering Journal*. 54 (4), 1175-1179.

29. Nanni, Antonio. (2000). FRP reinforcement for bridge structures. *Proc., Structural Engineering Conference,* The University of Kansas, Lawrence, KS. 5.

30. Nguyen-Minh, L. and Rovňák, M. . (2015). Size effect in uncracked and pre-cracked reinforced concrete beams shear-strengthened with composite jackets. *Composites Part B: Engineering*. 78, 361-376.

31. Norris, T., Saadatmanesh, H. and Ehsani, M. R. (1997). Shear and flexural strengthening of RC beams with carbon fibre sheets. *Journal of structural engineering*. 123 (7), 903-911.

32. Smith, S.T. and Teng, J.G. . (2002). FRP-strengthened RC beams. *Review of debonding strength models. Engineering Structures*. 24 (4), 385-95.

33. Swamy, R. N. and P. Mukhopadhyaya. (1995). Role and effectiveness of nonmetallic plates in strengthening and upgrading concrete structures. *Non-metallic (FRP) Reinforcement for Concrete Structure*. 473-482.

34. Sujeeva Setunge. (2002). Project report on "Review Of Strengthening Techniques Using Externally Bonded Fiber Reinfornced Polymer Composites. Report 2002-005-C-01.

35. Sundarraja, M. and Rajamohan, S. (2009). Strengthening of RC beams in shear using GFRP inclined strips – An experimental study. *Construction and building materials*. 23, 856-864.

36. Taerwe, L., Matthys, S., Pilakoutas, K., and Guadagnini, M. (2001). European activities on the use of FRP reinforcement, fib Task Group 9.3 and the on Fibre Crete network. *5th International Conference on FRP Reinforcement Concrete Structures (FRPRCS-5)*, Cambridge, UK, 1, 3-15.

37. Taljsten, B. (1997). Strengthening of beams by plate bonding. *Journal of Materials in Civil Engineering*. 9 (4), 206-212.

38. Täljsten, B. . (2003). Strengthening concrete beams for shear with CFRP sheets. *Construction and Building Materials*. 17 (1), 15-26.

39. Thomas, J., Kline, T., Emmons, P. and Kliger, H. (1996). Externally bonded carbon fiber for strengthening concrete. *Material for the new millennium: Proc. of the 4th Materials Engineering Conference*, Washington, D.C. 2, 924-930.

40. Tumialan, J. G. . (1998). Concrete cover delamination in reinforced concrete beam

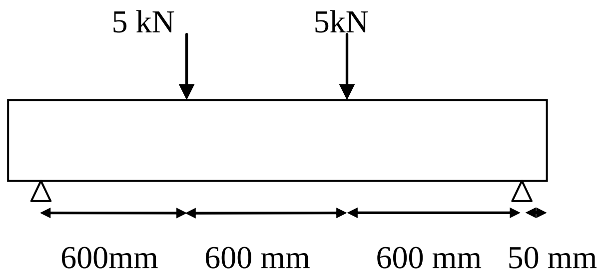
strengthened with CFRP sheet. *MS thesis*, Department of Civil Engineering, University of Missouri-Rolla.

41. Yoshizawa, H., Myojo, T., Okoshi, M., Mizukoshi, M. and Kliger, H. S. (1996). Effect of sheet bonding condition on concrete members having externally bonded carbon fiber sheet. Washington, D.C. 2, 1608-1616.

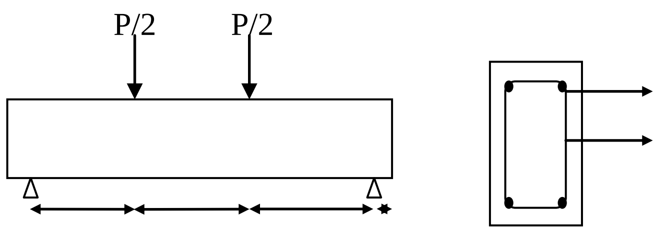
APPENDIX

APPENDIX - 1

Design calculation for the flexural failure.

Reference	Calculations	Output
BS 8110: Part 1 1985 3.4.4.4	Uniformly distributed self weight = 1*.125*.2*2400 kg = 0.589 kN/m  M= bending moment due to self weight + bending moment due to point loads $= (0.589*1.8^2)/8 + 10*(1.8/6)$ = 3.24 kNm Assume main reinforcement bar diameter= 8 mm Assume shear link bar diameter= 6 mm Effective depth = d = 200-25-6-4 = 165 mm $K=M/bd^2f_{cu}$ $=3.24*10^6/125*165^2*30$ =0.0317	Effective depth= 165 mm

	K'=0.156, K<0.156; compression reinforcement not required z=d(0.5+√(0.25-0.0317/0.9)) =165(0.5+√(0.25-0.0317/0.9)) = 159 mm < 0.95 d Since f_{cu} = 30 N/mm^2 and f_y = 250 N/mm^2 As=M/(0.87 f_yz) =3.24*10^6/(0.87*250*159) =94 mm^2 Main Reinforcement = 2R8 [2 mild steel bars] As =2*π*r^2 mm^2 =100.5 mm^2	Main R/F = 2R8

Reference	Calculations	Output
BS 8110: Part- 1, 1985, Cl : 3.4.5.2	Take failure load under shear = 60 kN $V = 60/2$ $= 30$ kN	Failure load under shear = 60 kN
	Diameter of shear links = 6 mm Effective depth = 165 mm $v = V/b_vd$ $= 30*10^3/125*165$ $= \underline{1.4\ N/mm^2}$ <lesser of ($0.8\sqrt{f_{cu}}$, or 5 N/mm^2)	
Table 3.9	$v_c = 0.79(100\ As/(b_vd))^{1/3}(400/d)^{1/4}/\Upsilon_m$ $= 0.79(100*100.5/(125*165))^{1/3}(400/165)^{1/4}/1.25$ $= \underline{0.62\ N/mm^2}$	
Table 3.8	$v_c+0.4 = 1.02\ N/mm^2 < v$ $A_{sv} >= b_vs_v(v- v_c)/0.87f_{yv}$ $A_{sv} = 2*\pi*3^2\ mm^2$ $= \underline{57\ mm^2}$ $s_v <= 127$ mm	
Cl : 3.4.5.5	Minimum spacing of links = 0.75d = 124 mm Spacing of links = 100 mm  	Spacing of links = 100 mm

APPENDIX - 2

Expected Theoretical Calculations

Reference	Calculations	Output
	<u>Beam Parameters</u> Span of the beam = 1900 mm Overall depth = 200 mm Breadth = 125 mm Grade of concrete = 30 N/mm^2 Top Reinforcement = 8mm ø mild steel Bottom Reinforcement= 8mm ø mild steel Stirrups = 6mm ø mild steel Grade of mild steel = 250 N/mm^2 Cover = 25 mm Effective depth = 200 – 25 – 6 – 4 = 165 mm	
BS 8110: Part 1: 1985	<u>Flexural Capacity</u> Flexural capacity was calculated as follows As = Tension Reinforcement f_y = Yield stress of Reinforcement x = Depth to the neutral axis b = Breadth of the beam f_{cu} = Compressive strength of concrete = The average 28 days concrete compressive strength from Appendix- 2 = 35.3 N/mm^2	

Compressive force in concrete = $0.9 \times 0.67 \times X \, x b \times fcu$

Tensile force in steel = $0.87 A_s f_y$

Considering beam to be singly reinforcement,

Tensile force of the beam = Compressive strength of the beam

$$0.87 A_s \times f_y = 0.9 \times 0.67 \times x \, \mathbf{x} b \times fcu$$

$$0.87 \times \pi \times 4^2 \times 2 \times 250 = 0.9 \times 0.67 \times 125 \times 35.3 \times x$$

$$x = 8.21 \text{ mm}$$

Lever arm (Z) = $d - (0.45x)$

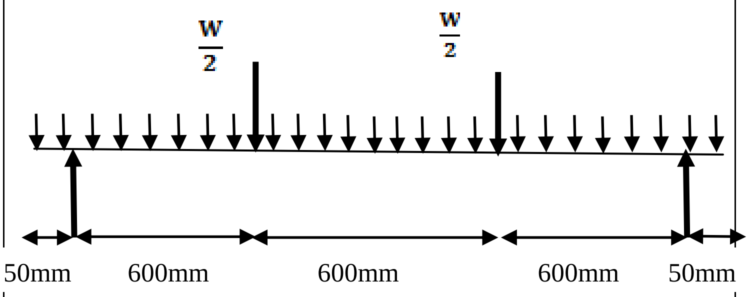
= $165 - (0.45 \times 8.21)$

= 161.3 mm

Flexural capacity = $F_t \times Z$

= $\pi \times 4^2 \times 2 \times 250 \times 161.3$

= <u>4.04 kNm</u>



<u>Expected flexural capacity of beam</u>

1. Bending moment due to W/2 point loads

Maximum moment will be occurred between point loads,

Moment, M $= \frac{W}{2}(x - 0.05) - \frac{W}{2}(x - 0.65)$

BS8110: Part 1: 1985 Table 3.9	2. Bending moment due to beam self-weight [0.050 m < x < 1.850 m] Moment, M = $\frac{wl}{2}(x-0.05)$ - $\frac{wx^2}{2}$ For maximum moment, $\frac{dM}{dx}=0$ Therefore x = l/2 = 0.95 m By principal of super position, Moment for total load = $\frac{wl}{2}(x-0.05)$ - $\frac{wx^2}{2}$ + $\frac{W}{2}(x-0.05)$ - $\frac{W}{2}(x-0.65)$ Therefore maximum moment M_{max} = 0.3W + 0.40375w According to the previous calculation, Flexural capacity of the beam = 4.02 kNm At failure, 0.3W + 0.40375w = 4.04 0.3W + 0.40375 × 0.125 × 0.2 × 2.4 × 9.81 =4.04 W = <u>12.7 kN</u> Hence expected failure load under flexure =12.7 kN <u>Expected shear capacity of beam</u> $v_c = 0.79 \times \left(\frac{100As}{bv \times d}\right)^{1/3} \times \left(\frac{400}{d}\right)^{1/4} \times \left(\frac{fcu}{25}\right)^{1/3} \times \frac{1}{rm}$ v_c = Design shear stress of concrete As = Req. Tension Reinforcement f_{cu} = Compressive strength of concrete b_v = breadth of section γ_m = safety factor for materials (taken as 1.15)	

	$A_s = \pi \times 16 \times 2$ $= 100.53\ mm^2$ $b_v = 125\ mm$ $v_c = 0.659\ N/mm^2$ Shear taken by stirrups (v_{fv}) $= \frac{Asv \times fy}{bv \times sv}$ s_v = space between shear link reinforcement A_{sv} = Total cross section of links at neutral axis $A_s = \pi \times 9 \times 2$ $= 56.5\ mm^2$ $S_v = 120mm$ $v_{fv} = 0.942\ N/mm^2$ Expected total shear capacity = 0.659 + 0.942 $= 1.601\ N/mm^2$ Maximum shear force is at the support, Shear force due to applied load $= \frac{W}{2}$ Shear force due to self-weight $= \frac{wl}{2} - 0.05 \times w$ Therefore, $S_{max} = \frac{W}{2} + 0.125 \times 0.2 \times 2.4 \times 9.81 \times (1.9/2 - 0.05)$ $= \frac{W}{2} + 0.52974$ S_{max} = Design shear stress of the concrete beam $= 1.601 \times 125 \times 200 \times 10^{-3}$ = 40.05 kN $\frac{W}{2} + 0.52974 = 40.05$ W = <u>79kN</u> Hence expected failure load under shear =79 kN	

APPENDIX – 3

Concrete compressive strength test results

	Date of cast	**Date of test**	**Compressive strength (N/mm^2)**
C1	28/11/2015	28 days after cast	35.48
C2		28 days after cast	37.54
C3		28 days after cast	34.35
C4		28 days after cast	34.3
C5	30/11/2015	28 days after cast	36.67
C6		28 days after cast	34.45
C7	1/12/2015	28 days after cast	37.82
C8		28 days after cast	29.48
C9	3/12/2015	28 days after cast	36.04
C10		28 days after cast	36.76
		Average compressive strength	**35.29**
		Standard deviation	**2.414**

APPENDIX - 4

Comparison between experimental moment and theoretical moment

Non Cracked Beam

	Experimental Moments		Theoritical Moments					
Beam Notation	Ultimate Failure Load(kN)	Max Moment (0.3W+.40375w) /(kNm)	Flexural component from steel /Mns (kNm)	CFRP component for bending /Mnf (kNm)	U wrap component for bending / FL(d-k/2) / (kNm)	Theoritical Values / (kNm)	% increment of Moment capacity w.r.t Experimenta moments	Average Increment %
F1	17.00	5.34	2.736	4.753	0.000	7.489	40.30	30%
F2	20.00	6.24	2.736	4.753	0.000	7.489	20.06	
IN1	35.00	10.74	2.736	4.753	11.400	18.889	75.91	76
IN2	27.00	8.34	2.736	4.753	0.000	7.489	-10.18	-10
M1	27.00	8.34	2.736	4.753	11.400	18.889	126.55	123%
M2	28.00	8.64	2.736	4.753	11.400	18.889	118.68	

Cracked Beam

	Experimental Moments		Theoretical Moments					
Beam Notation	Ultimate Failure Load(kN)	Max Moment (0.3W+.40375w) /(kNm)	Flexural component from steel /Mns (kNm)	CFRP component for bending /Mnf (kNm)	U wrap component for bending / FL(d-k/2) / (kNm)	Theoritical Values / (kNm)	% increment of Moment capacity w.r.t Experimenta moments	Average Increment %
CF1	22.75	7.063	3.141	4.753	0.000	7.894	11.77	2%
CF2	28.00	8.638	3.141	4.753	0.000	7.894	-8.61	
CFE1	21.50	6.688	3.141	4.753	7.630	15.524	132.13	106%
CFE2	28.00	8.638	3.141	4.753	7.630	15.524	79.72	
CFI1	28.00	8.638	3.141	4.753	7.630	15.524	79.72	165%
CFI2	14.00	4.438	3.141	4.753	7.630	15.524	249.82	

W-Failure load under flexture/(kN)
w-Beam self weight/(kN/m)