STRENGTHENING OF RC BEAMS RETROFITTED WITH EXTERNAL TRUSS – AN EXPERIMENTAL STUDY

R. Hemaanitha[*] and S. Kothandaraman
Department of Civil Engineering, Pondicherry Engineering College, Puducherry – 605 014, India

ABSTRACT

The study explores the experimental results of strengthening RC beams attached with external truss. The truss was designed and fabricated with $42 \times 42 \times 6$ mm angle sections for tie members and 2 pieces of 180×3.4mm flats for strut. Two different struts with a height of 300mm and 400mm were used. The result indicates that the load carrying capacity of the retrofitted beams could be increased 2.5 times and 2.7 times respectively compared to the basic beam; the maximum crack width at the ultimate stage was in the range of 2 to 2.5 mm when compared to the basic beam (4 to 5 mm). However, the method adopted in the study has got many advantages such as enhancing the load carrying capacity, controlling the crack width, economical and easy to install.

Keywords: Retrofitting; external truss; flexural strengthening; deflection; crack width.

1. INTRODUCTION

Ever since the engineers and scientists started experimenting on the strengthening of reinforced concrete (RC) structures during 1960s, many techniques have emerged over these years like external bonding of steel plates, glass fibre reinforced plastic (GFRP), external prestressing, fibre reinforced polymer (FRP) sheets, carbon fibre wrapping, external bar reinforcement, improved external rebar technique, and so on [1]. RC structures get damaged due to various reasons like earthquake, flood, poor design, improper construction insufficient curing, etc. In case of damages due any of these reasons, repairing or strengthening the damaged structures by adopting suitable methods is preferable in view of the cost, easy installation, saving of time, money and energy rather than rebuilding which will be quite expensive and unaffordable. Keeping in view the above scenario, the authors of this paper have proposed an improved technique to strengthen the RC beam by attaching an external truss.

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[*]E-mail address of the corresponding author: hemaanithar@yahoo.in (R. Hemaanitha)

2. BACKGROUND OF THE STUDY

Reinforced Concrete structures with exposed reinforcement paved the way to the researchers and scientists to repair or strengthen the RC structures with external rebar. In addition, it was assumed that the exposure of reinforcement may enhance ultimate load carrying capacity of a beam deficient in shear [2,3]. Use of two rods one at each side face of the beam kept at the level of embedded rods which were secured at the ends using 'end yokes' witnessed that the beams with external reinforcement reduced deflections (10%-20%) and more flexural strength($\approx 85\%$) [4]. A study on the use of anchoring pins with single deflector (V –shaped) and two deflectors (U – shaped) as shown in Fig. 1(a) and 1(b) proved that U-shaped method yielded better performance (≈ 1.47 times) than V-shaped deflectors. High-tension bars used in this method of flexural strengthening decreased the stiffness before cracking and was found to be effective in increasing the strength [5]. Another study conducted with similar technique supplemented that the increasing the number of deflectors rather than the area of external bar could significantly enhance the ultimate strength up to 24% [6]. A recent study revisited the concept of external reinforcement technique for retrofitting RC beams. The external bars were attached at the soffit of RC beams and found that the moment carrying capacity was enhanced more than 80% of the reference beam. Use of end yokes and intermediate deflectors to hold external reinforcement was eliminated [7]. The present study was carried out on RC beams by attaching a steel truss. That is, to find out the load carrying capacity of a Trussed-RC-Beam.
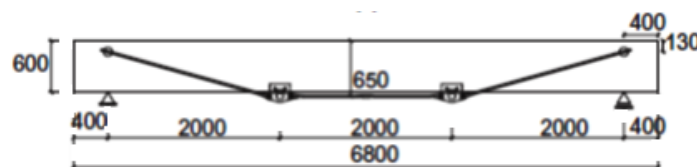

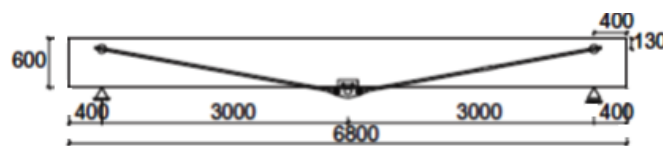Figure 1(a). T/U/L/P type (Source: Shin et al, 2007)

Figure 1(b). T/V/L/P type (Source: Shin et al, 2007)

3. EXPERIMENTAL PROGRAM

3.1 Materials used

Concrete, M25 grade was considered in this work. High yield strength deformed (HYSD) bars conforming to IS:1786 (2008)were used for reinforcement [8]. In addition, steel sections were used for tie members of truss and mild steel flats were used as strut. OPC-43 grade conforming to IS:8112 (2013) was used for concrete [9]. Properties of cement, steel

(bars and sections) and concrete mixture proportion are presented in Tables 1-4.

The truss was designed and fabricated with $42 \times 42 \times 6$ mm angle sections for tie members and 2 pieces of 180×3.4mm flats were used for strut. Two different struts with a varying height of 300mm and 400mm were used. For angles and plates, three samples were tested under tension. Table 3 represents the yield and ultimate stress.

Table 1: Properties of cement

Properties	Value
Specific Gravity	3.1
Standard Consistency	29.4%
Soundness	2.1mm
Setting Time	Initial – 135 min. Final – 255 min.

Table 2: Properties of reinforcing bars

Nominal Bar Diameter	8mm	10mm	12mm
Yielding Stress (MPa)	350	556	530
Ultimate Stress (MPa)	455	590	552

Table 3: Properties of steel used for truss

Sl. №	Specimen	Size (mm)	Stress	
			Yield f_y (MPa)	Ultimate f_u (MPa)
1.	Angle	$42 \times 42 \times 6$	316	341
2.	Flat	180×3.4	650	671

Table 4: Concrete mixture proportion

Cement (kg/m^3)	Aggregate (kg/m^3)		Water (l/m^3)
	Fine	Coarse	
320	775	1160	170

(a) Longitudinal Section

(b) Cross Section
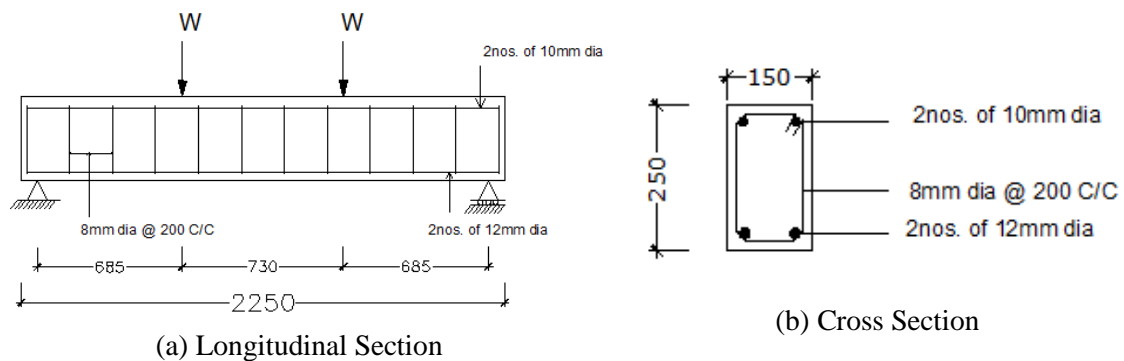
Figure 2. Details of beam specimens (dimensions in mm)

3.2 Test specimen

In this experimental program, six number of RC beam specimens,150 × 250 mm cross section and 2.25m long were cast. All the beams were identically reinforced, 2-12# at bottom as tension reinforcement and 2-10# as hanger bars. Plain bars of 8mm dia were used for stirrups and the beams were adequately reinforced to avoid shear failure. Out of six beams, two beams were designated as BB representing basic (reference) beams; two beams were designated as RB-A representing retrofitted beams in which the truss was attached at 33mm below the neutral axis of the beam; and the balance two beams were designated as RB-B representing retrofitted beams in which the truss was attached at 137mm below the neutral axis. The schematic diagram of the truss is shown in Fig. 3.
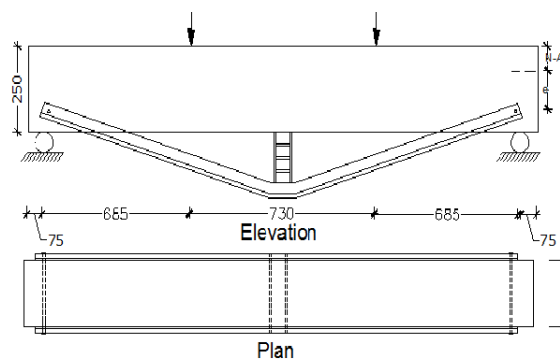
Figure 3. Details of Trussed Beam (dimensions are in mm)

3.3 Attaching truss with RC beam

In order to attach single-strut-truss to the RC beam, 22mm diameter through hole was made, one above each support but below the neutral axis. In RB-A specimens the hole was made 33 mm below the neutral axis and in RB-B specimens it was 137mm below the neutral axis. Keeping one angle section as tie member on each face of the beam the truss was attached. To attach the truss, 16mm bolts were used. The strut was inserted in between the beam soffit and the tie as shown in Fig. 4. The slope of the tie was 22.8° with horizontal in both RB-A and RB-B. The height of strut was suitably increased while increasing the eccentricity of the truss from 33mm to 137mm.
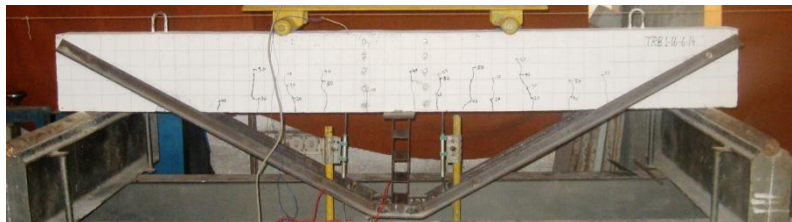
Figure 4. External truss attached with the beam

3.4 Testing trussed beam

The beams were simply supported over an effective span of 2.1m and subject to four-point

loading system. A 300kN capacity hydraulic jack was used for applying load. On every increment of load deflection, concrete strain was measured and recorded. LVDT was used to measure the deflection at their mid-span and one-third of the span in the specimen. DEMEC strain gauge was used to measure the strain of concrete at the level of tensile and compressive reinforcing bars at the mid-span and one-third of the span of specimens. To record the output data, data acquisition system was used.
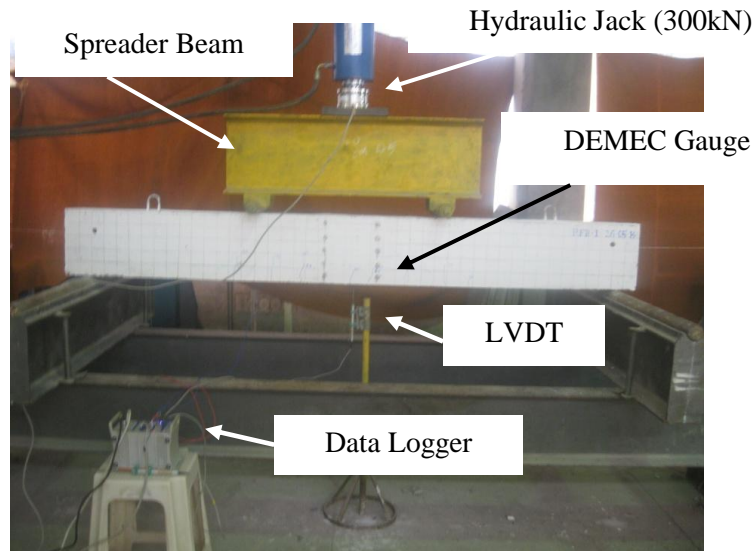

Figure 5. Test setup

4. RESULTS AND DISCUSSION

4.1 Failure Modes

All the beam specimens failed due to flexure. In basic beams, the load was 20 kN when the first crack (cracking moment=7 kN.m) occured. In both the retrofitted beam specimens (RB-A&RB-B), the first cracking moment was at 3.3 kN.m and the corresponding load was 30kN. In basic beams, a large number of cracks were formed at closer intervals (Fig. 6(a) & (b)) and on further increase of load the basic specimens, BB1 and BB2 failed at a load of 72kN and 75kN respectively against the estimated failure load of 75kN. In retrofitted beams, after formation of first crack the beam continued to take further load without showing much of cracks. When the beam started undergoing additional deflection further cracks were formed symmetrically on either side of strut. As depicted in Fig. 6(c) & 6(d), a wide crack was formed in RB-B at 150kN load in both the specimens while there was no evidence of such crack formation in RB-A specimens. In RB-A the truss was attached to the beam at 33mm below the neutral axis and in RB-B it was at 137mm.

Figure 6(a). Basic beam (BB1)

Figure 6(b). Basic beam (BB2)

Figure 6(c). Retrofitted beam (RB-A)

Figure 6(d). Retrofitted beam (RB-B)

4.2 Load deflection behavior
Deflection was recorded continuously from the starting of load application up to failure state. In basic beams the maximum deflection was measured at mid-span and in retrofitted beams at the points of application loads. The maximum deflection noted for various specimens are given in Table 5 and the load versus deflection has been shown in Fig. 7. At every 10 kN load increment, deflection of beams at mid-span was recorded. The maximum (mid-span) average deflection for basic beam was 28mm. Whereas in retrofitted beam the maximum deflection point was shifted to the point of maximum bending moment, that is at the load application points. The average maximum deflection in RB-A was 24.0 mm and it was 23.6mm for RB-B specimens. Further, the retrofitted beams had a very narrow crack width.

Table 5: Use of external truss: test results

Beam Type		Concrete Cube Compressive Strength (MPa)	Load at initial crack (kN)	Ultimate Load (kN)		Ultimate Moment (kN.m)		Deflection		Crack Width (mm)	Ductility Index d_u/d_y
				Tested	Calculated	Tested	Calculated	yielding stage	ultimate stage		
BB	1	38	20	72	75	25.5	26.5	8.3	25.6	5.0	3.1
	2	38	20	75	75	26.5	26.5	11.1	30.3	4.5	2.7
RB-A	1	42	30	175	150	37.6	30.9	11.3	24.0	2.5	2.1
	2	42	30	185	150	38.1	30.9	11.1	24.7	2.6	2.2
RB-B	1	42	30	192	185	31.7	30.6	10.1	23.9	2.0	2.3
	2	45	30	200	185	32.8	30.4	11.1	23.4	3.0	2.1

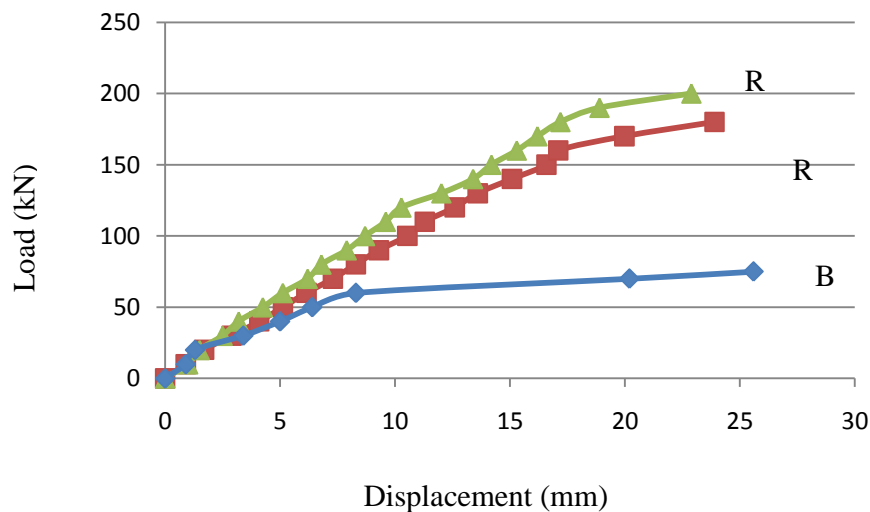*In BB the maximum deflection noted at mid-span and in RBs, it was noted at the load points

Figure 7. Load Vs maximum deflection

4.3 Load carrying capacity

The load carrying capacity of all the beams was observed. It was found that all the beam specimens were loaded up to their ultimate loads. The beams, RB-A and RB-B attained the maximum load carrying capacity as these beams were strengthened with external truss. The ultimate load of basic beams designed conventionally was found to have low. The increase in the strength of beams witnessed due to the effect of truss that varies with height of strut h, ultimate load of 185 kN and 200 kN were obtained due to strengthening. The results of ultimate strength of retrofitted beams with external truss are shown in Table 5 and Fig. 8.

The findings revealed that beams attached with external truss were found to have greater load carrying capacity than the basic beams. It is evident that the beams with external truss have shown an increase of 2.5 times and 2.7 times respectively in the load carrying capacity. However, it can be augmented that by attaching an external truss the load carrying capacity is enhanced by 246% and 260%, respectively.
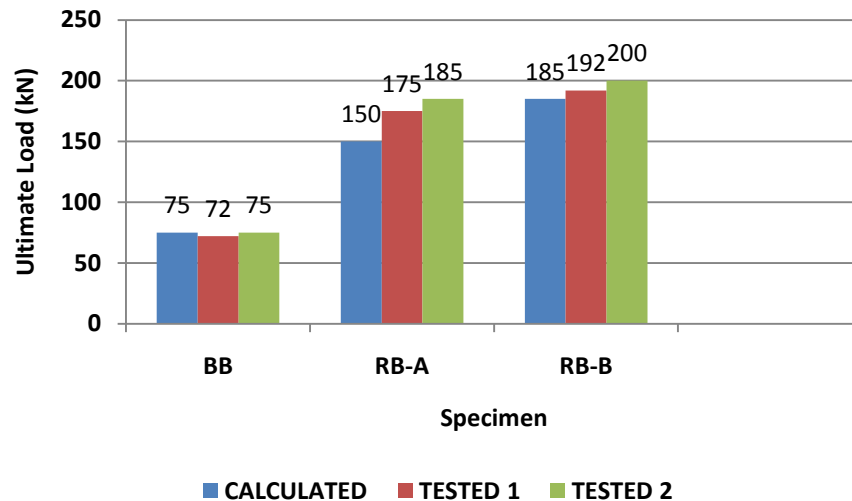
Figure 8. Ultimate load carrying capacity

4.4 Load-strain behaviour

To measure the load strain behaviour, DEMEC gauge with five pins was used. The strain was measured at different stages – near top and bottom of the beam. The loading was applied up to the ultimate load of 180 kN and deflections were monitored for load increments. The strain measured by strain gauge gives the local data that allows to know the local behaviour of the beams while loading. Recording of load versus compressive strain and load versus tensile strain was at 25 mm from top and bottom of the beam, respectively. The basic beams and retrofitted beams showed the development of strain in steel bar in the tensile region [Fig. 9]. One or several cracks occurred in concrete when the tensile stress of concrete reached its ultimate strength,. The cracks due to flexural moment were controlled by internal steel bars and compressive region of concrete. It could be observed from the curves that the strains of all retrofitted beams develop when the applied load increases. Maximum compressive strain found in concrete on the beams attached with external truss (RB-A & RB-B) was 0.0035 and 0.0029, respectively. Whereas the maximum strain in basic beams (BB1 & BB2) was 0.0026 and 0.0028, respectively.
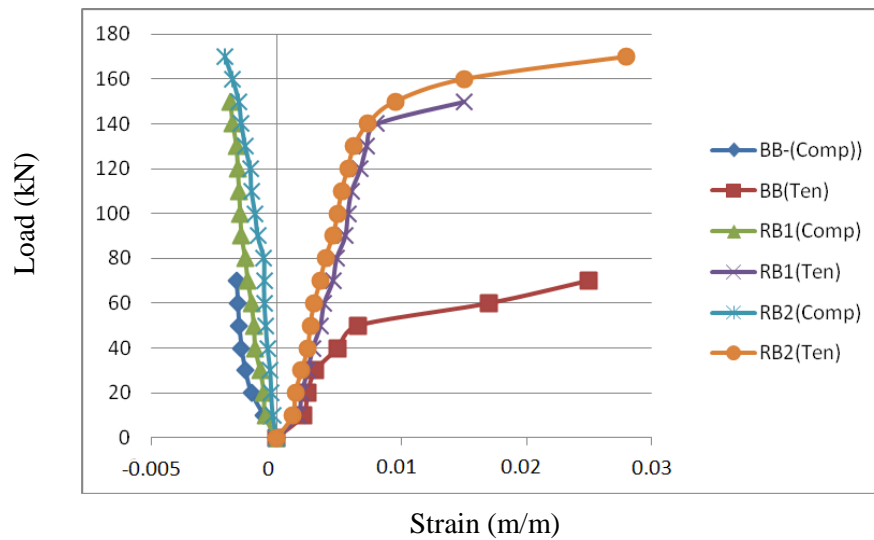
Figure 9. Load vs. strain behaviour

5. CONCLUSION

The findings of the study on retrofitting of RC beams with external truss led to the following conclusions:

- The flexural strength and stiffness of the beams with external truss increased significantly.
- Enhancement of cracking load and ultimate load of retrofitting beams could be achieved.
- The retrofitted beams (RB-A and RB-B), the load carrying capacity witnessed an increase of 2.5 times and 2.7 times respectively compared to the basic beam.
- The anchoring technique enabled to increase the ultimate load carrying capacity of the retrofitted beams.
- Improved performance with respect to initial cracking behavior reduction in crack width during the serviceability and ultimate stage.
- The ultimate moment capacity for the retrofitted beams increased from 26% to 146 % by the provision of external truss.
- The maximum crack width at the ultimate stage was in the range of 2 to 2.5 mm for retrofitted beams when compared to the basic beam (4 to 5 mm).
- The recovery of deflection was found to have more in retrofitted beams than the basic beams.

APPENDIX: ANALYSIS AND DESIGN OF TRUSSED BEAM

Note:
- Energy principle was employed for analyzing the structure.
- Truss was attached to the RCC beam with certain eccentricity. During analysis, this was ignored initially.
- However, at design stage the effect of 'e' was accounted.
- In order to fix the failure load on the trussed beam the modulus of the rupture of the Basic Beam (BB) was equated to the modulus of rupture of the trussed beam. As a matter of fact, both the beams were identically reinforced.
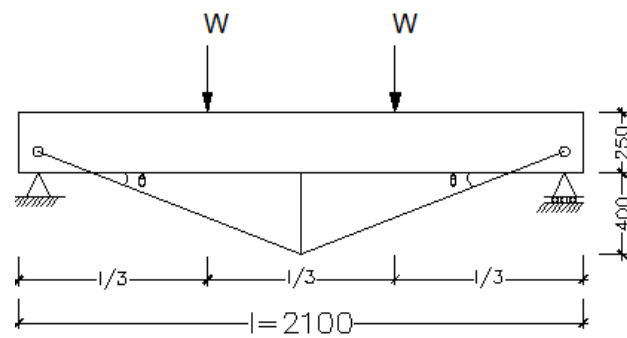
Trussed beam details
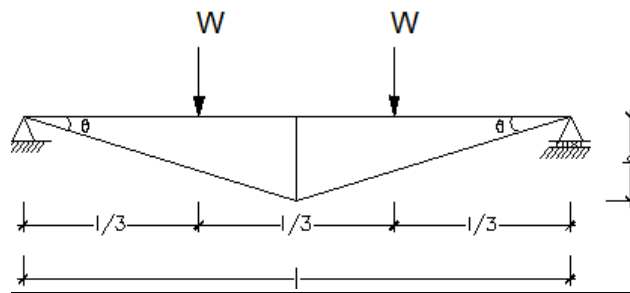
Idealized trussed beam

Section Details
Overall length of RCC beam= 2.25 m
Effective Length   =2.10 m
Breadth, b   = 150 mm
Overall depth, D   = 250 mm
Truss Details
Tie: Single angle 42×42×6 mm
Strut: 2 Nos. - 180×3.4 mm
(composed of two flats kept 60mm apart)
Eccentricity   =137 mm
Height of the strut, h = 400mm

Material Properties
Strength of concrete used, f_{ck} = 38.0 MPa (BB)
                               = 42 MPa (RB)
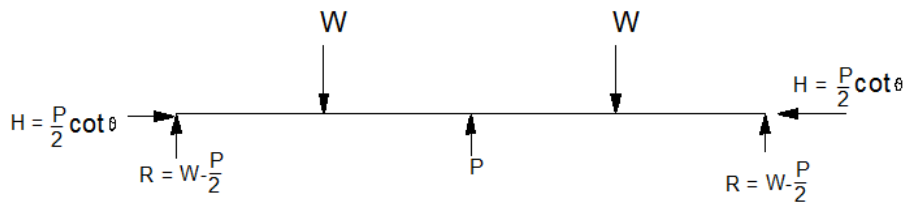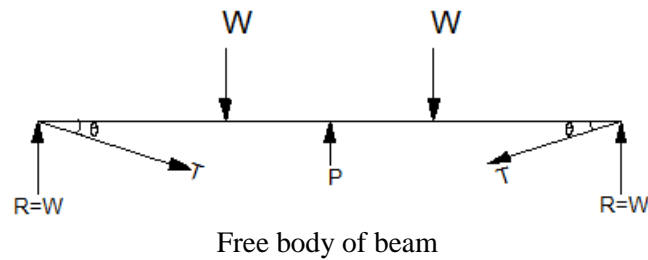
$E_{concrete}$, $5000\sqrt{f_{ck}} \times 10^{-3} = 32.977$ kN/mm²/GPa

E_{Steel} = 200.0 kN/mm²/GPa

Gross moment of inertia of RCC beam, $I_g = \dfrac{1}{12} \times 150 \times 250^3$

$$= 195.313 \times 10^4 \, mm^4$$

∴ Section Modulus $Z = \dfrac{I_g}{250/2}$

$$= 15.625 \times 10^6 \, mm^3$$

By inputting the above data, we find the strut force, P = 0.737w   (w=External − two point loading)

Free body of beam

Note: Eccentricity H is ignored

Maximum Bending Moment (@w) = $R \times \left(\dfrac{l}{3}\right)$

$$M_1 = \left(W - \dfrac{P}{2}\right)\dfrac{l}{3}$$

$M_1 = 0.21wl$
Accounting eccentricity of 'H'
Bending Moment (M_2) = H×e

$$= \left(\dfrac{P}{2}\right)(\cot\theta)\,e \qquad (e=136 \text{ mm})$$

$$= \left(\frac{0.737W}{2} \right) \cot 22.8 \times 137$$

$\therefore$ M2 = 120w kN.mm

$\therefore$ Net BM, M = M$_1$ – M$_2$

= 0.21wl – 120w

= w(0.21 × 2100 – 120)

= 321w kN.mm

Modulus of Rupture for RB

Modulus of Rupture for BB = $17.77 \times 10^{-3} \, kN/mm$

$$f = \frac{M}{Z} = \left[\frac{321w \times 10^3}{156.625 \times 10^4} \right] = 17.77 \times 10^{-3}$$

$\therefore$ w = 86 kN

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