Studies on Composite Beams

Dr.N.Arunachalam[1] P.Prakash[2] K.Jayakarthik[3] M.Narmadha[4]
[1]Professor & Dean [2,3]PG Scholar [4]Associate Professor
[1,2,3,4]Department of Civil Engineering
[1,2,3]Bannari Amman Institute of Technology [4]Karpagam Academy of Higher Education

Abstract— In this investigation an attempt has been made to study various aspects in the design of RCC-Steel and RCC-PSC (T-section) composite beams. The RCC-Steel, RCC-PSC (T-section) composite beams have been designed for the following parameters: Live Load: 2kN/m^2, 3kN/m^2, 4kN/m^2, 10kN/m^2, 15kN/m^2, 20kN/m^2, Spans: 10m, 15m, 18m, 20m, 22m, Spacing: 0.5m, 1m, 1.5m, 2m, 3m, 4m, 5m, Grade of concrete: M20 for RCC and M40 for PSC, Steel Used: Fe 415 steel and 5mm HTS wires. The designs were carried out manually and using MS-Excel program. IS-456:2000 code, IS-1343:1980 code, IS-800:2007 code, IS-3935:1966 code and IS-11384:1985 code have been used for design.

Key words: Composite, Prestress, RCC, Steel

NOTATIONS USED

A. *RCC-STEEL Composite*

- A_f - Area of top flange of steel beam
- A_s - cross sectional area of the steel beam of composite beam
- A_{st} - area of tension reinforcement
- A_t - cross sectional area of the transverse reinforcement in composite beam
- a-Stress ratio
- b – breadth of top flange of steel beam
- b_{eff} – effective flange width
- D – overall depth of the section
- d – effective depth of slab
- d_c – vertical distance between centroid of concrete slab and steel beam in a composite section
- d_g – vertical distance between top of the concrete slab and centroid of the steel beam in a composite beam
- d_s – depth of slab
- E_c – modulus of elasticity of concrete
- E_s – modulus of elasticity of steel
- F_{cc} – total concrete compressive force in composite beams
- f_{cb} – elastic critical stress in the beam
- f_{ck} – characteristic compressive strength of concrete
- f_y – characteristic strength of reinforcement
- I_t – moment of inertia of transformed section
- I_{xs} , I_{xy}– moment of inertia of steel beam
- L – span
- L_s – length (in mm) of the shear surface at the shear connectors
- M – design moment
- M_u – design ultimate moment
- M_{ulim} – limiting moment of resistance of a section without compression reinforcement
- m – modular ratio between steel and concrete
- N_c – number of shear connectors per m length
- P_c – design ultimate strength of shear connector
- Q – horizontal shear force
- r_y – radius of gyration of the steel section
- t_f – thickness of flange of the steel section
- t_w – thickness of web of the steel section
- W_{ds} – dead load of the slab per m^2
- W_l – live load per m^2
- X – depth of elastic neutral axis
- X_u – depth of plastic neutral axis of composite section
- X_{umax} – limiting value of X_u
- Z_{xs} – section modulus of steel beam
- δ_d - deflection due to dead load
- δ_l - deflection due to live load
- σ_{bc} - maximum stress at top flange of the steel section
- $(\sigma_{bc})_{max}$ - maximum permissible bending compressive stress in concrete

B. *RCC-PSC Composite*

- A_{pc} – cross sectional area of prestressed section
- A_{st} - area of tension reinforcement
- b_f – breadth of flange of prestressed section
- b_w – breadth of web of prestressed section
- D – overall depth of the composite beam
- d_s – depth of slab
- d_w – depth of web of prestressed section
- E_c – modulus of elasticity of in-situ concrete
- E_p – modulus of elasticity of prestressed concrete
- e – eccentricity of prestressing force
- f_{ck} – characteristic compressive strength of in-situ concrete
- f_y – characteristic strength of non prestressed reinforcement
- I_t – moment of inertia of transformed section
- I_p – moment of inertia of prestressed section
- L – span
- M_{dsb} – dead load bending moment in beam due to slab weight
- M_{dp} – dead load bending moment in beam due to prestressed concrete
- M_{lb} – live load bending moment in beam
- M_t – total bending moment
- M_u – design ultimate bending moment
- M_{ulim} – limiting moment of resistance of slab section
- m – modular ratio between cast in-situ concrete and prestressed concrete
- N_c – number of shear connectors per m length
- P_i – initial prestressing force
- q_u – shear stress at junction of web and in-situ slab
- V – shear force due to ultimate load
- V_c – shear resistance of the beam
- W_{lb} – live load on beam m^2
- W_{dsb} – dead load due to in-situ slab
- W_{dp} – dead load due to prestressed unit

- X_u – depth of neutral axis of composite section
- Y_{1p} , Y_{2p} – distances of top and bottom fibres respectively of prestressed section from its horizontal centroidal axis
- Y_{1t} , Y_{2t} – distances of top and bottom fibres respectively of composite section from its horizontal centroidal axis
- σ_c ' - allowable compressive stress of concrete
- σ_c - final permissible stress of concrete

II. INTRODUCTION

In conventional composite construction, concrete slabs rest over steel beams and are supported by them. Under load these two components act independently and a relative slip occurs at the interface if there is no connection between them. With the help of a deliberate and appropriate connection provided between the beam and the concrete slab, the slip between them can be eliminated. In this case the steel beam and the slab act as a "composite beam" and their action is similar to that of a monolithic Tee beam. Though steel and concrete are the most commonly used materials for composite beams, other materials such as pre-stressed concrete and timber can also be used. Concrete is stronger in compression than in tension, and steel is susceptible to buckling in compression. By the composite action between the two, we can utilize their respective advantages to the fullest extent. Generally in steel-concrete composite beams, steel beams are integrally connected to prefabricated or cast in situ reinforced concrete slabs. There are many advantages associated with steel concrete composite construction. Some of these are listed below:

- The most effective utilization of steel and concrete is achieved.
- Keeping the span and loading unaltered; a more economical steel section is adequate in composite construction compared with conventional non-composite construction.
- As the depth of beam reduces, the construction depth reduces, resulting in enhanced headroom.
- Because of its larger stiffness, composite beams have less deflection.
- Composite construction provides efficient arrangement to cover large column free space.
- Composite construction is amenable to "fast-track" construction because of using rolled steel and pre-fabricated components, rather than cast-in-situ concrete.

III. DESIGN PROCEDURE

A. RCC-Steel Composite Beam

1) Step: 1 Design of cast in-situ slab

Depth of the in-situ slab is assumed. Bending moments at mid span and support of the slab are computed. The greater of these two moments is taken as the design moment. Limit state moment of resistance of the slab is calculated using the expression.

$$M_{u,\lim} = 0.36 \frac{X_{u\max}}{d}\left(1 - 0.42 \frac{X_{u\max}}{d}\right) bd^2 f_{ck}$$

If M_{ulim} is less than that of the design moment, the depth of in-situ slab is increased. The area of the steel is obtained using

$$M_u = 0.87 f_y A_{st} d\left(1 - \frac{A_s f_y}{b d f_{ck}}\right)$$

The area of the steel obtained is compared with the required minimum steel and if it is less, then A_{stmin} is provided. The distribution steel is provided as recommended by IS-456:2000 code.

2) Step: 2 Design of Steel Section

Steel section is assumed.

a) Load Calculation

The load is calculated in two stages. They are

- Construction stage
- Composite stage

1) Construction stage

The loads considered in this stage are:

- Self-weight of the slab
- Self-weight of the beam
- Construction load

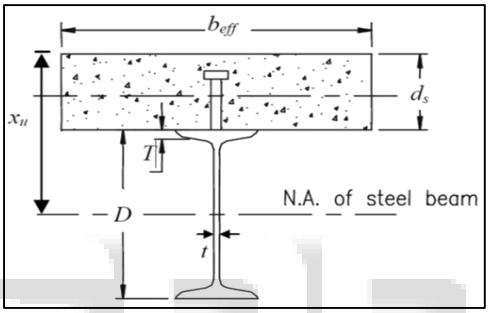

Fig. 1: Construction stage

The total design load at the construction stage is obtained by calculating the sum of the product of the construction load with the partial safety factor and self-weight with the partial safety factor. The partial safety factor adopted is according to IS-800:2007.

2) Composite stage

The loads considered in this stage are:

- Self-weight of the slab
- Self-weight of the beam
- Imposed load

The total design load at the composite stage is obtained by calculating the sum of the product of the imposed load with the partial safety factor and the self-weight with the corresponding partial safety factor. The partial safety factor adopted is according to IS-800:2007.

3) Step: 3 Calculation of bending moment

The two different stages for the calculation of bending moment are

- Construction stage
- Composite stage

$$M = \frac{wl^2}{8}$$

Where,

w-load and l -span of beam.

4) Step: 4 Calculation of moment of resistance of steel section

The moment of resistance of steel section is obtained by

$$M_r = \frac{f_y * Z_{xs}}{1.15}$$

If the moment of resistance of steel section is greater than design moment at the construction stage, then the section is safe.

5) Step: 5 Check for the adequacy of the section at the composite stage

The effective flange width of RC portion is found out as the least of the following (IS-3935:1966 code)

- $\frac{1}{4}$ th span of the beam.
- Centre to Centre distance of beams.
- Web thickness of steel section + 12 times the thickness of slab.

a) Determination of the position of plastic neutral axis and ultimate moment of resistance

In a section of homogeneous material, the plastic neutral axis coincides with the equal area axis of the section, that is, the axis which divides the section into two equal areas on either side. The same concept can be used in the case of composite beams also, provided steel is converted into equivalent concrete area by multiplying it with the stress ratio.

$$a = \frac{0.87 f_y}{0.36 f_{ck}}$$

The position of the neutral axis and ultimate moment of resistance is calculated with respect to the following three cases.

- Case 1: Plastic neutral axis within concrete slab.
- Case 2: Plastic neutral axis within top flange of steel beam.
- Case 3: Plastic neutral axis within the web of the steel beam.

The formulas given in clause 8.2 of IS-11384:1985 and Appendix-A are used to calculate the position of neutral axis and ultimate moment of resistance.

6) Step: 6 Design of shear connectors

If the position of the neutral axis is within the slab, the total load is carried by connectors is,

$$F_{cc} = 0.36 * b_{eff} X_u f_{ck}$$

If the position of the neutral axis is within the top flange of steel beam, the total load is carried by connectors is,

$$F_{cc} = 0.36 * b_{eff} d_s f_{ck}$$

If the position of the neutral axis is within the web of steel beam, the total load is carried by connectors is,

$$F_{cc} = 0.36 * b_{eff} d_s f_{ck}$$

As per Table-1 of IS-11384:1985, the design shear strength of the headed stud is taken. The number of shear connectors required for the half of the span is ratio of the total load carried by the connector and the design strength of the stud.

The spacing is calculated by the ratio of half span and the number of studs in half span.

7) Step: 7 Serviceability check

From clause 12.1 of IS-11384:1985 code the beam is analyzed using the elastic theory adopting a modular ratio of 15 for live load and 30 for the dead load, and neglecting the tensile stress in concrete. The deflection should not exceed the value for the steel structures as $\frac{L}{325}$.

a) Deflection

For dead load, deflection is calculated using moment of inertia of steel beam only.

$$\delta_d = \frac{5 * w_d l^4}{384 * E_s I_{xs}}$$

For live load, deflection is calculated using moment of inertia of composite section. To find the moment of inertia of the composite section we have to locate the position of the neutral axis.

There are two cases:

1) Neutral axis lies within the slab.

(i.e.) when

$$A_s(d_g - d_s) < \frac{b_{eff} d_s^2}{2m}$$

The actual neutral axis depth X can be found out from,

$$A_s(d_g - X) = \frac{b_{eff} X^2}{2m}$$

The moment of inertia of transformed section is,

$$I_t = I_{xs} + A_s(d_g - X)^2 + \left[\frac{b_{eff} X^3}{3m}\right]$$

2) Neutral axis depth exceeds depth of slab (ds).

(i.e.) when

$$A_s(d_g - d_s) > \frac{b_{eff} d_s^2}{2m}$$

The actual neutral axis depth X can be found out from,

$$A_s(d_g - X) = \frac{b_{eff}}{m} d_s \left(X - \frac{d_s}{2}\right)$$

The moment of inertia of transformed section is,

$$I_t = I_{xs} + A_s(d_c - X)^2 + \frac{b_{eff} d_s}{m}\left[\frac{d_s^2}{12} + \left(X - \frac{d_s}{2}\right)^2\right]$$

For distributed live load w_{lb} over a simply supported composite beam, the deflection at mid span is,

$$\delta_l = \frac{5 * w_l l^4}{384 * E_s I_t}$$

The total deflection is the sum of dead load deflection and live load deflection.

$$\delta_d + \delta_l < \frac{L}{325}$$

If the deflection obtained satisfies the above condition, then section is safe. If not section to be redesigned.

b) Stress

For dead load, stress is calculated using moment of inertia of composite section. First we have to locate the position of neutral axis.

There are two cases:

- Neutral axis lies within the slab.
- Neutral axis depth exceeds depth of slab(d_s)

The neutral axis depth can be found using same formula given in deflection calculations.

For live load also stress is calculated like same as dead load stress calculations.

If the sum of dead load and live load stresses is less than allowable stress for the steel, then the section is safe. If not, the section is redesigned.

8) Step: 8 Transverse reinforcement

Transverse reinforcement is designed as per the Clause 9.7 of IS-11384:1985 codal provisions.

B. RCC-PSC (T-section) Composite beam

1) Step: 1 Design of cast in-situ slab

Depth of the in-situ slab is assumed. Bending moments at mid span and support of the slab are computed. The greater of these two moments is taken as the design moment. Limit state moment of resistance of the slab is calculated using the expression.

$$M_{u,\lim} = 0.36\frac{X_{u\max}}{d}\left(1-0.42\frac{X_{u\max}}{d}\right)bd^2 f_{ck}$$

If M_{ulim} is less than that of the design moment, the depth of in-situ slab is increased. The area of the steel is obtained using

$$M_u = 0.87 f_y A_{st} d\left(1-\frac{A_s f_y}{bdf_{ck}}\right)$$

The area of the steel obtained is compared with the required minimum steel and if it is less, then A_{stmin} is provided. The distribution steel is provided as recommended by IS-456:2000 code.

2) Step: 2 Dimensions of prestressed unit

Dimensions of the prestressed units are assumed.

The effective flange width is found out as the least of the following (IS-3935:1966 code)

- $\frac{1}{4}$ th span of the beam.
- Centre to Centre distance of beam.
- Web thickness + 12 times the thickness of slab.

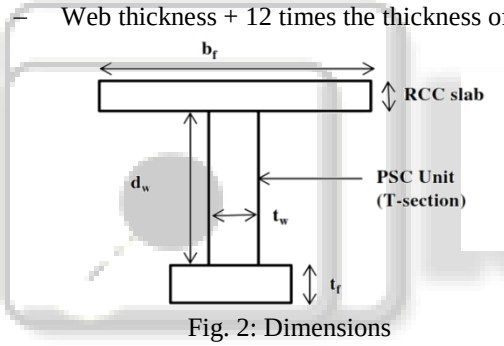

Fig. 2: Dimensions

Total maximum bending moment due to weight of slab, weight of prestressed unit and live load is found out. In post tensioned composite beam, the lever arm between the final prestressing force P in the cable and resultant compressive force is approximately equal to 0.65D, where D is the total depth of the composite section.

The initial value of prestressing force P_i, can be obtained assuming a linear stress distribution with maximum permissible stress σ_c' at bottom and zero at top of prestressed unit.

Hence

$$P_i = T_i = 0.5 * \sigma_c' * b_w (D - d_s)$$

Hence total bending moment M_t is given by

$$M_t = \eta * P_i * 0.65 * D$$

$$M_t = \eta * 0.5 * \sigma_c' * b_w (D - d_s) * 0.65 * D$$

Using the above equation, value of D is obtained and compared with the assumed depth D. If the calculated depth is more than the assumed depth, D is increased.

3) Step: 3 Properties of sections

Properties of prestressed and transformed composite sections are found out. The properties of the composite section are calculated for transformed section in which transformed width of in-situ slab is obtained by multiplying actual width by modular ratio, m of concrete given by

$$m = \frac{\text{Modulus of elasticity of in-situ concrete}}{\text{Modulus of elasticity of prestressed concrete}}$$

4) Step: 4 Initial prestressing force and area of steel

$$P_i = T_i = 0.5 * \sigma_c' * b_w (D - d_s)$$

Area of steel is obtained by dividing P_i with the allowable stress in steel.

5) Step: 5 Determination of eccentricity of prestressing force

Eccentricity of prestressing force is determined using the condition that there is no tensile stress at the top fibre of the prestressed unit at transfer of prestress.

6) Step: 6 Check for stresses

Stresses are then determined under the following conditions assuming the prestressed beam as unpropped while in-situ concrete is placed.

a) Case: 1 Initial stresses in prestressed unit:

Stress at top concrete fibre

$$\sigma_t = \frac{P_i}{A_{pc}} - \frac{P_i * e * y_{1p}}{I_p} + \frac{M_{dp} * y_{1p}}{I_p}$$

Stress at bottom concrete fibre

$$\sigma_b = \frac{P_i}{A_{pc}} + \frac{P_i * e * y_{2p}}{I_p} - \frac{M_{dp} * y_{2p}}{I_p}$$

b) Case: 2 Stresses after losses in prestressed unit:

Stress at top concrete fibre

$$\sigma_t = \frac{\eta * P_i}{A_{pc}} - \frac{\eta * P_i * e * y_{1p}}{I_p} + \frac{M_{dp} * y_{1p}}{I_p}$$

Stress at bottom concrete fibre

$$\sigma_b = \frac{\eta * P_i}{A_{pc}} + \frac{\eta * P_i * e * y_{2p}}{I_p} - \frac{M_{dp} * y_{2p}}{I_p}$$

c) Case: 3 Stresses when in-situ concrete is placed

Stress at top concrete fibre of prestressed unit.

$$\sigma_t = \frac{\eta * P_i}{A_{pc}} - \frac{\eta * P_i * e * y_{1p}}{I_p} + \frac{M_{dp} * y_{1p}}{I_p} + \frac{M_{dsb} * y_{1p}}{I_p}$$

Stress at bottom concrete fibre

$$\sigma_b = \frac{\eta * P_i}{A_{pc}} + \frac{\eta * P_i * e * y_{2p}}{I_p} - \frac{M_{dp} * y_{2p}}{I_p} - \frac{M_{dsb} * y_{2p}}{I_p}$$

d) Case: 4 Stresses in prestressed unit when live load acts

Stress at top concrete fibre

$$\sigma_t = \frac{\eta * P_i}{A_{pc}} - \frac{\eta * P_i * e * y_{1p}}{I_p} + \frac{M_{dp} * y_{1p}}{I_p} + \frac{M_{dsb} * y_{1p}}{I_p} + \frac{M_{lb} * (y_{1t} - d_s)}{I_t}$$

Stress at bottom concrete fibre

$$\sigma_b = \frac{\eta * P_i}{A_{pc}} + \frac{\eta * P_i * e * y_{2p}}{I_p} - \frac{M_{dp} * y_{2p}}{I_p} - \frac{M_{dsb} * y_{2p}}{I_p} - \frac{M_{lb} * y_{2t}}{I_t}$$

e) Case: 5 Stresses in concrete cast in-situ

Actual stress at top fibre

$$\sigma_t = \frac{m * M_{lb} * y_{1t}}{I_t}$$

Actual stress at bottom fibre

$$\sigma_b = \frac{m * M_{lb} * (y_{1t} - d_s)}{I_t}$$

If the stress at any stage exceeds the allowable limit, the section is to be redesigned.

f) Step: 7 Shear reinforcement

Shear resistance at different sections are found out and necessary shear reinforcement is designed (Shear force due to ultimate load can be calculated using Clause 23.4.3 of IS-1343:1980 code).Horizontal shear resistance is calculated at

the interface of prestress and cast in-situ concrete and if horizontal shear force is more than horizontal shear resistance, additional reinforcement is designed.

IV. RESULTS AND DISCUSSIONS

The results of RCC-Steel composite beams and their costs are as follows:

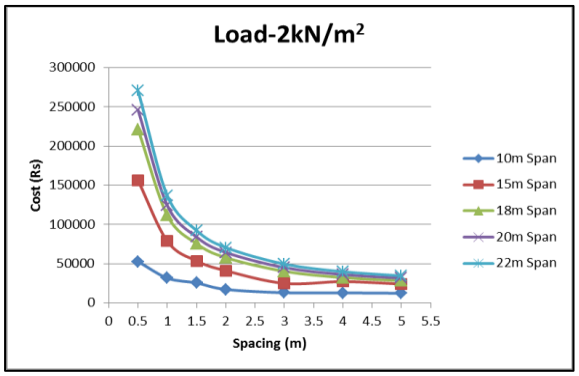

Fig. 3: Load 2KN/m^2

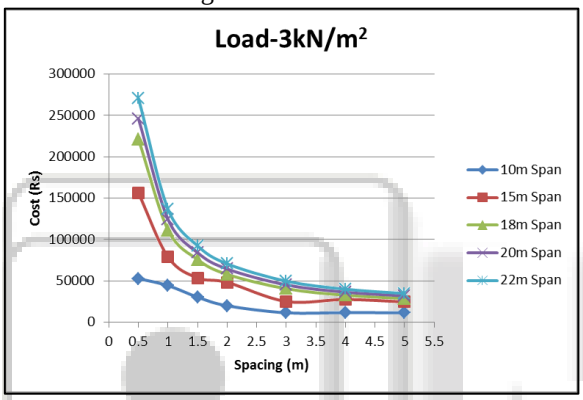

Fig. 4: Load 3KN/m^2

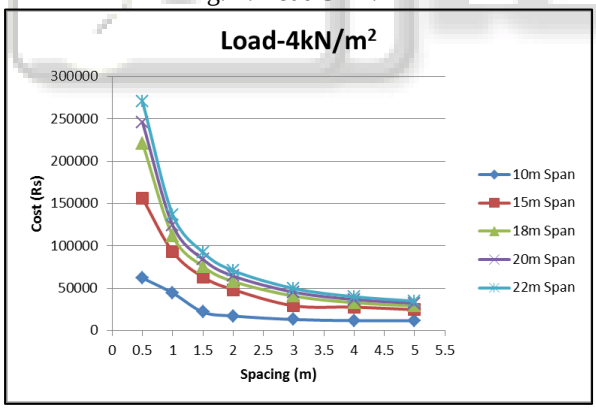

Fig. 5: Load 4KN/m^2

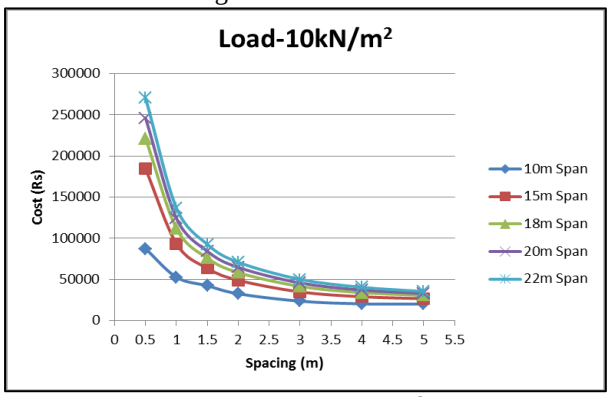

Fig. 6: Load 10KN/m^2

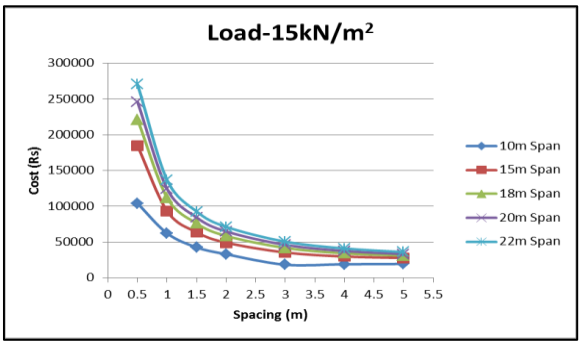

Fig. 7: Load 15KN/m^2

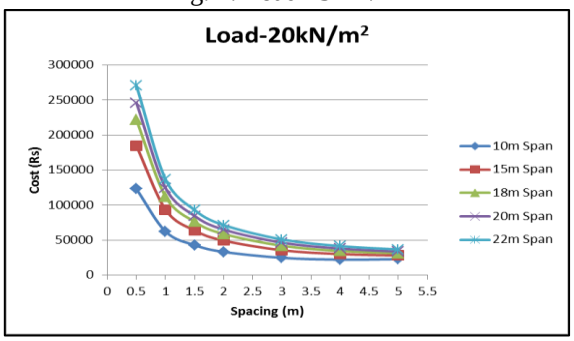

Fig. 8: Load 20 KN/m^2

The results of RCC-PSC (T-section) composite beams and their costs are as follows

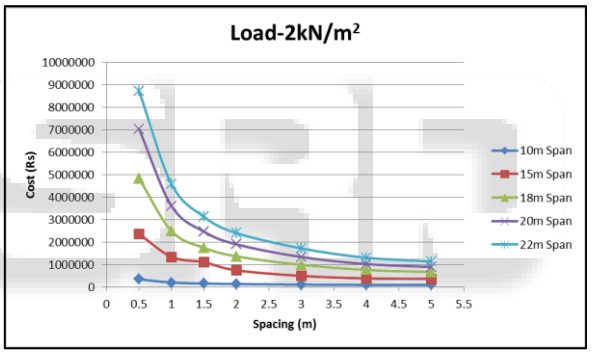

Fig. 9: Load 2KN/m^2

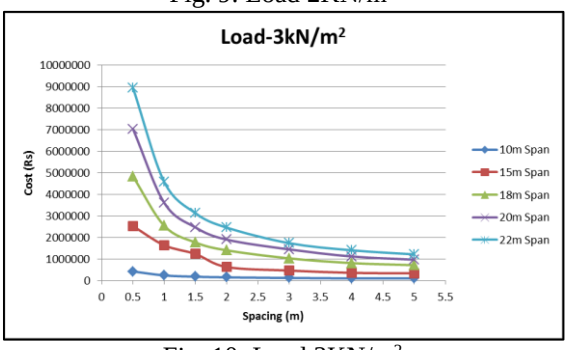

Fig. 10: Load 3KN/m^2

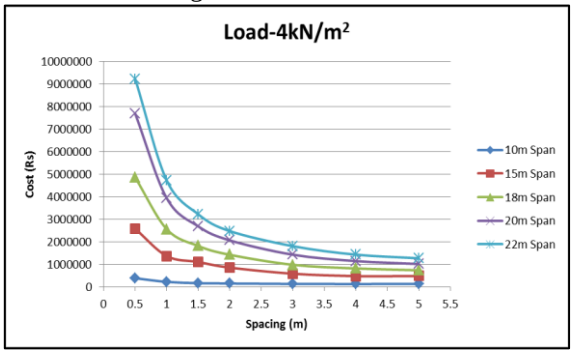

Fig. 11: Load 4KN/m^2

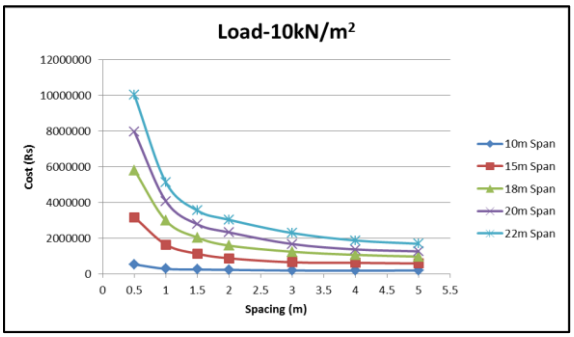

Fig. 12: Load 10KN/m²

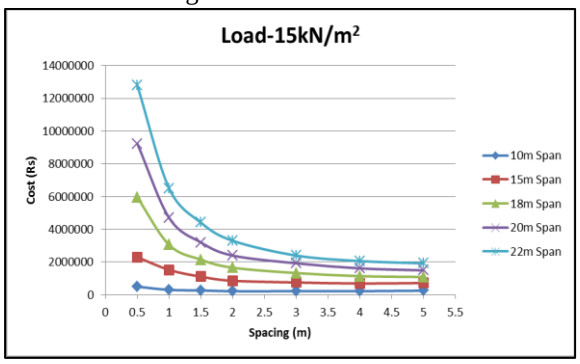

Fig. 13: Load 15KN/m²

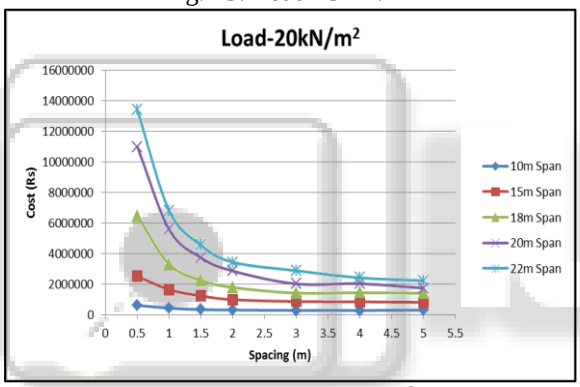

Fig. 14: Load 20KN/m²

V. CONCLUSIONS

- For RCC-Steel composite beam of 10 m,15m,18m, 20m, 22m spans for all loads taken, the cost decreases rapidly for 0.5 m to 3 m spacing and for 3 m to 5 m spacing the cost variation is negligible (Fig 3 to Fig: 8).
- Hence for RCC-Steel composite beams, the spacing between 3m to 5m can be adopted to achieve economy.
- For RCC-PSC(T-section) composite beam of 10 m,15m,18m, 20m, 22m spans for all loads taken, the cost decreases rapidly for 0.5 m to 3 m spacing and for 3 m to 5 m spacing the cost variation is negligible (Fig:9 to Fig:14).
- Hence for RCC-PSC (T-section) composite beams, the spacing between 3m to 5m can be adopted to achieve economy.

REFERENCES

[1] Deepak M Jirage, Prof . V.G. Sayagavi, Prof. N.G. Gore – "Comparative Study of RCC and Composite Multi-storeyed Building"- International Journal of Scientific Engineering and Applied Science (IJSEAS) - Volume-1, Issue-6, September 2015 –pp-236-240.

[2] Shashikala. Koppad and Dr. S.V.Itti – "Comparative Study of RCC and Composite Multi-storeyed Buildings" - International Journal of Engineering and Innovative Technology (IJEIT) Volume 3, Issue 5, November 2013- pp-341-345.

[3] Shweta A. Wagh and Dr. U. P. Waghe – "Comparative Study of R.C.C and Steel Concrete Composite Structures" - International Journal of Engineering Research and Applications-ISSN : 2248-9622, Vol. 4, Issue 4 (Version 1), April 2014, pp.369-376.

[4] Sattainathan.A and Nagarajan.N – "Comparative study on the behavior of R.C.C, Steel & Composite Structures (B+G+20 storeys)" - International Journal on Applications in Civil and Environmental Engineering-Volume 1: Issue 3: March 2015, pp. 21-26.

[5] Dr.N.Arunachalam and S. Sri vidhya – "Cost Comparative Studies on Composite Beams" ||unpublished.

[6] IS-456:2000- "Code of practice for plain and reinforced concrete" -Bureau of Indian standards.

[7] IS-3935:1966- "Code of practice for composite construction"- Bureau of Indian standards.

[8] IS-11384:1985- "Code of practice for composite construction in structural steel and concrete"- Bureau of Indian standards.

[9] IS-800:2007-"Code of practice for general construction in steel" - Bureau of Indian standards.

[10] IS-1343:1980- "Code of practice for prestressed concrete" - Bureau of Indian standards.

