STRENGTHENING OF RUNWAY BRIDGE AT MUMBAI AIRPORT USING FRP

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SUMMARY

This paper describes application of fibre-reinforced polymer (FRP) composite laminates to strengthen a reinforced cement concrete (RCC) T-beam bridge at the Mumbai Airport, over the Mithi River in Mumbai, India. The bridge was earlier designed for smaller aircrafts. But the capacity evaluation of the superstructure showed that it is not sufficient to carry the loads of the current design of aircrafts. Hence, a need for strengthening the bridge was realized. Considering all the available techniques of strengthening, FRP laminate bonding was suggested. This was in view with the overall repair costs and anti corrosion properties of the FRP materials. The design of strengthening using FRP for the girder and slab for increase in the moment and shear capacities was made. A minimum strengthening was provided for slab even though it was safe for the increased loading.

Keywords: Debonding, peeling effect, strengthening, FRP, concrete bridge.

1. INTRODUCTION

Strengthening of RCC structural elements is a common task for maintenance now days. For the purpose of strengthening, several materials and methods are available such as sprayed concrete, ferro-cement, steel plate and fibre reinforced polymer (FRP). Sprayed concrete is the oldest materials amongst the group and is the most common method of repairing and strengthening of reinforced concrete structures. Ferrocement is another material which is used for strengthening of RCC structures. It has the same cementitious material as reinforced concrete. The incorporation of fine wire mesh beneath the surface of repair mortar has long been practiced although these methods were not identified as ferrocement. This method was mainly used as relining membranes for the repair of liquid

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retaining structures, such as pools, sewer lines and tunnels. Among all of the strengthening materials, steel plate and FRP laminate are the most common and effective materials due to their several advantages.

FRP for civil engineering structures are being increasingly studied in recent years. These materials are being used in the aerospace, automotive and shipbuilding industries for almost two decades. In general, FRP offer excellent resistance to corrosion, good fatigue resistance (with the possible exception of some glass-based FRP), low density, high stiffness and strength, and a very low coefficient of thermal expansion in the fibre orientation. FRP materials as having superior mechanical and physical properties than steel, particularly with respect to tensile and fatigue strengths. The FRP is usually considered only for special applications, such as in non magnetic structures, or for use in aggressive corrosive environments. However, the usage of FRP can be more economical than using steel plates. This is because the material costs in a rehabilitation project rarely exceed 20 percent of the total cost of the repair. Several fibre reinforced polymer (FRP) systems are now commercially available for the external strengthening of concrete structures. The fibre materials commonly used in these systems include glass, aramid, and carbon.

2. MUMBAI AIRPORT RUNWAY BRIDGE

The bridge under consideration is the one at the Mumbai Airport, over the Mithi River. The bridge structure is a reinforced concrete structure, earlier designed for smaller aircrafts. But the bridge won't be sufficient to carry the loads of the current design of aircrafts. Hence a need for strengthening the bridge arose and considering all the available techniques, FRP laminate bonding was suggested. This was in view with the overall repair costs and anti corrosion properties of the FRP materials. The bridge is a T-beam type bridge with two main beams running through the length of the bridge. The superstructure of the bridge consists of T-beam bridge with T-beams at 2470 mm c/c. the beams are supported on two column piers intermediately and two abutments at either ends. The distance of the nearer pier from either abutment is 9700 mm and the center to center distance between the piers is 11700 mm. Thus the total length of the bridge is 31100 mm. The bridge behaved as a T-beam in the mid span and as a rectangular beam at the supports. 11 bars of 32mm diameter was provided as reinforcement in the tensile zone near the mid span and 14 bars of 32mm diameter near the supports. 8 bars of 32mm diameter was provided as steel reinforcement in the compression zone.

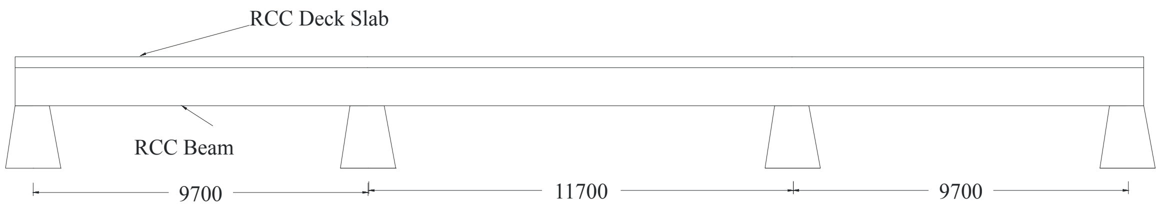

Fig. 1 Support arrangement for Girders.

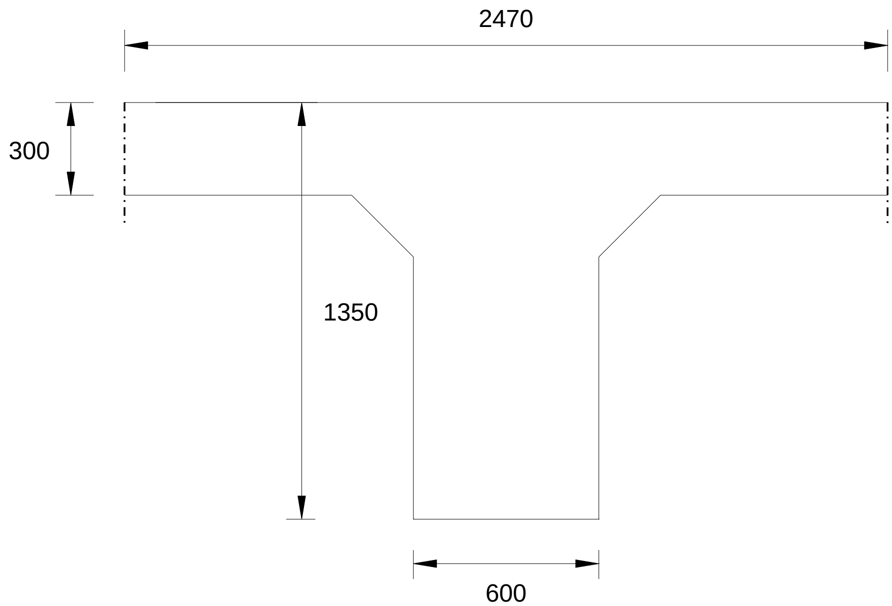

Fig. 2 Typical Cross-Section of T- Beams.

An FRP-laminate strengthening system was selected based on its application being the least intrusive with traffic and the most practical. Rehabilitation work, including erection of a full-size platform underneath the bridge, surface preparation, and installation of the laminates was conducted.

The objectives of this work are

- To evaluate the capacity of the existing bridge following IS code recommendations
- To verify the capacity of the bridge against the demand posed by stipulated loads.

- To design a strengthening using FRP composites following international standards recommendations.

2.1 Reinforcement Details

At mid span (Behavior as T-Beam):

A_{st} = 11-32Φ (8846.75 mm^2)

A_{sc} = 8-32Φ (6434 mm^2)

Shear Reinforcement: 4-lgd 12 Φ at 250 c/c.

At Support (Behavior as Rectangular Beam):

A_{st} = 14-32Φ (11259.5 mm^2)

A_{sc} = 8-32Φ (6434 mm^2)

Shear Reinforcement: 4-lgd 12 Φ at 250 c/c.

2.2 Material Properties

Grade of Concrete:	M 20 (f_{ck} = 20 N/ mm^2)
Grade of Steel:	HYSD (f_y = 415 N/ mm^2)
Carbon Laminates:	S&P CFK Laminates
Carbon FRP:	S&P C-Sheet 240
Glass FRP:	S&P G-Sheet 90/10
Leveling Mortar:	S&P Resin 230 leveling mortar
Primer:	S&P Resin 20 Primer
Epoxy Resin:	S&P Resin Epoxy 55/50

2.3 Loads on Superstructure

2.3.1 Bending Moments

The bending moment values for dead loads and live loads on for the structure. The maximum support moment is found to be as 351 T-m and the maximum span moment as 356 T-m.

2.3.2 Shear Forces

The shear force values for the structure. The maximum shear force in beam is found to be as 247 T. In addition to this the slab shall be checked against a punching shear force due to ESWL of 54 T.

2.4 Design Checks (Capacity Evaluation)

2.4.1 Known Data

$b_f = 2470$ mm

$b_w = 600$ mm

$D = 1350$ mm

$D_f = 300$ mm

At mid span (Behavior as T-Beam):

$A_{st} = 11\text{-}32\Phi$ (8846.75 mm^2)

$A_{sc} = 8\text{-}32\Phi$ (6434 mm^2)

Shear Reinforcement: 4-lgd 12 Φ at 250 c/c.

A_t Support (Behavior as Rectangular Beam):

$A_{st} = 14\text{-}32\Phi$ (11259.5 mm^2)

$A_{sc} = 8\text{-}32\Phi$ (6434 mm^2)

Shear Reinforcement: 4-lgd 12 Φ at 250 c/c.

2.4.2 Design Parameters

For evaluating capacity of the slabs and beams, the following properties and design parameters as per IRC: 21 are considered

Grade of Concrete:	M 20 ($f_{ck} = 20$ N/ mm^2)
Grade of Steel:	HYSD ($f_y = 415$ N/ mm^2)
Modular ratio, m:	10
$\sigma_{cbc:}$	6.7 MPa
σ_{st}:	200 MPa
NA depth coefficient, k:	0.25
Lever arm factor, j:	0.91
Moment of Resistance coefficient, Q:	0.762

2.4.3 Bending Moment Capacity

The bending moment capacity of the beams at supports (negative moment capacity) and mid span (positive moment capacity) are calculated using working stress method as recommended by IRC codes.

$$M_{(-),all} = 2086.65 \text{ kNm}$$

$$M_{(+),all} = 1971.78 \text{ kNm}$$

2.4.4Shear Force Capacity

We have, 100 A_s/bd = 100*11259.5/(600*1280) = 1.47

Corresponding permissible shear stress in concrete for M20, τ_c = 0.45 MPa

Thus concrete shear force capacity, V_c = 0.45*600*1280/1000 = 345.6 kN

For 4-lgd 12 Φ at 250 c/c (A_{sv} = 452 mm^2), we get,

Stirrups Shear force capacity, V_s = 519.8 kN

Thus, Shear force capacity = 345.6 + 519.8 = 865.4 kN

2.4.5 Design Check against Demand

As given in chapter 3, the maximum bending moments at support and mid span and shear force are found as

At support:

$$M_{u(-)} = 351 \text{ tm} = 3443.31 \text{ kNm} < 2086.65 \text{ (UnSafe)}$$

At mid span:

$$M_{u(+)} = 356 \text{ tm} = 3492.36 \text{ kNm} > 1971.78 \text{ kN-m (Unsafe)}$$

Shear Force:

$$V_u = 247 \text{ t} = 2423.07 \text{ kN} > 865.4 \text{ kN (Unsafe)}$$

Thus, it is found that the beams are unsafe against both bending moments and shear forces.

2.4.6 Punching Shear Capacity and Design check of Slab

Let us conservatively assume a wheel contact with pavement as 150 mm by 300 mm as shown in Fig 7. The bridge deck is covered with a 200 mm layer of wearing course and a

200 mm thick concrete pavement. The load will be distributed at an angle of 45^o through the two layers to the bridge deck. Thus the load will be distributed in an area of 1100 mm (300 + 400 + 400) by 950 mm (150 + 400 + 400) and therefore the critical section for punching shear will be at a distance of d/2 (= 150 mm) from the face of distributed load area i.e. 1400 mm by 1250 mm.

Thus, the area resisting punching shear is given by,

$$A_{ps} = 2*(1400 + 1250)*279 = 1478700 \text{ mm}^2$$

The allowable shear stress as per IS 456 is equal to $0.16(f_{ck})^{0.5} = 0.716$ MPa

Therefore, allowable punching shear load = 0.716*1478700/1000 = 1058.75 kN =107.93t > 54t (Hence safe).

However, in order to have better load dispersion and thus safety, it is proposed to provide 12 mm dowels at 300 mm c/c to connect the deck slab with pavement.

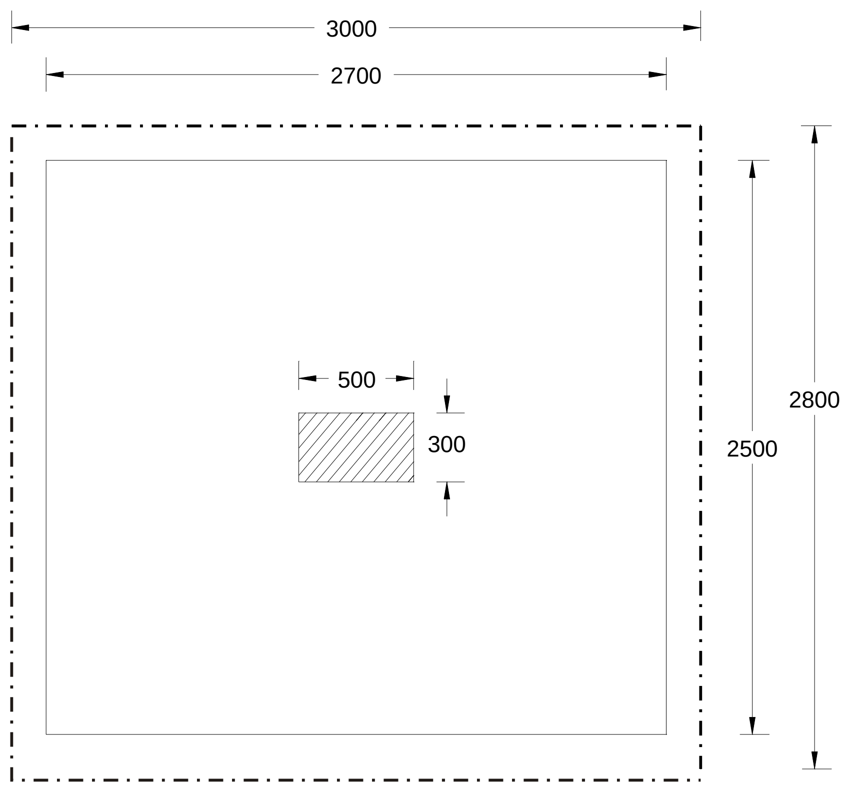

Fig. 7 Load dispersion and critical section for punching shear in slab.

3. DESIGN OF STRENGTHENING

The design of strengthening of beam is again performed following working stress methodology. The S&P CFK laminates are used for the purpose of strengthening of beams against bending moment. The design of strengthening is performed following the recommendations given in various international codes on FRP strengthening namely, ACI code, CEB-FIP code and Eurocode 8.

3.1 Design of Strengthening for Beam

3.1.1 Design of T-beam for Mid-Span Strengthening

The design moment, $Mu_{(+)}$ = 3488.8 kNm

Design stress for S&P CFK laminates, f_f = 1650 MPa

Let the area of the laminates required be A_f

The neutral axis depth for the strengthened section (neglecting compression reinforcement) is given by

$$x_{u,str} = (0.87 f_y A_{st} + f_f A_f)/(0.36 f_{ck} b_f)\text{, thus}$$

$$x_{u,str} = (0.87*250*8846.75 + 1650*A_f)/(0.36*20*2470) = 108.20 + 0.093A_f$$

Now, the moment carrying capacity for the strengthened section is given by,

$$M_{u,str} = 0.87 f_y A_{st}(d - 0.42 x_{u,str}) + f_f A_f(D - 0.42 x_{u,str})\text{, thus}$$

$$M_{u,str} = 0.87*250*8846.75*(1270 - 0.42*(108.20 + 0.093A_f) + 1650A_f*(1350 - 0.42*(108.20 + 0.093A_f))$$

Now, for $M_{u,str} = M_{u(+)}$ = 3488.8 kNm, we get,

$$3488.8 \text{ x } 10^6 = 1924168.125*(1224.56 - 0.039A_f) + 1650A_f*(1304.56 - 0.039A_f)$$

Simplifying, we get,

$$0.039A_f^2 - 1259.08A_f + 686391.35 = 0$$

Solving for A_f, we get,

$$A_f = 554.68 \text{ mm}^2$$

Let us provide, 5 Nos. 100 x 1.4 S&P CFK laminates (A_f = 700 mm^2) on the soffit of beam in the middle 6000 mm span.

3.1.2 Design of Rectangular beam for End-Span Strengthening

The design moment, $M_{u(-)}$ = 3439.8 kNm

Design stress for S&P CFK laminates, f_f = 1650 MPa

Let the area of the laminates required be A_f

The neutral axis depth for the strengthened section (considering compression reinforcement) is given by

$$x_{u,str} = (0.87 f_y A_{st} + f_f A_f - f_{sc} A_{sc})/(0.36 f_{ck} b_w),$$

Where, f_{sc} is the stress in compression reinforcement. Let us initially assume that the stress in compression reinforcement is also equal to $0.87f_y$ (that is the compression reinforcement has also yielded)

Thus,

$$x_{u,str} = (0.87*250*11259.5 + 1650*A_f - 0.87*250*6434)/(0.36*20*600),$$

thus

$$x_{u,str} = 242.95 + 0.382 A_f$$

Now,

Compression force in concrete, $C_c = 0.36 f_{ck} b x_{u,str}$

Hence, $C_c = 0.36*20*600*(242.95 + 0.382 A_f)$

$$C_c = (1049544 + 1650 Af)\ \text{N}$$

Compression force in compressive steel, $C_s = 0.87 f_y A_{sc}$

Hence, $C_s = 0.87*250*6434$

$$C_s = 1399395\ \text{N}$$

Tensile force in tension steel, $T_s = 0.87 f_y A_{st}$

Hence, $T_s = 0.87*250*11259.5$

$$T_s = 2448941.25$$

Tension force in laminates, $T_f = f_f A_f$

Hence, $T_f = 1650*A_f$

$$T_f = 1650 A_f\ \text{N}$$

(The force balance may be noted)

Since the reinforcement cannot be placed at the top, it is placed at the soffit of the slab.

That is the distance of the fiber from the mid section depth is equal to $D - Df - D/2$

Thus, the moment carrying capacity for the strengthened section is given by,

$$M_{u,str} = C_c(D/2 - 0.42x_{u,str}) + C_s(D/2 - d') + T_s(d - D/2) + T_f(D - D_f - D/2)$$

Now, for $M_{u,str} = M_{u(-)}$ = 3439.8 kNm, we get, 3439.8 x 106 = (1049544 + 1650Af)*(1350/2 – 0.42*(242.95 + 0.382A_f)) +1399395*(1350/2 – 54) + 2448941.25*(1270 – 1350/2) + 1650A_f*(1350 – 300 – 1350/2)

Simplifying, we get,

$$264.66A_f^2 - 1396206.96A_f + 512310000 = 0$$

Solving for A_f, we get,

$$A_f = 396.77 \text{ mm}^2$$

Let us provide, 4 Nos. 100 x 1.4 S&P CFK laminates (A_f = 560 mm^2), two on each side of beam and very close to beam at the slab soffit along the length of the beam up to 2500 mm from the face of the support on either side.

3.1.3 Design of Beam for Shear Strengthening

The design is done as per EuroCode8 part 3. The shear contribution of FRP shear reinforcement for one ply is given by

$$V_f = 0.9d_f b_w \rho_f E_f \varepsilon_{fve}(1+\text{Cot}\beta)\text{Sin}\beta$$

Where,

d_f = section depth over which fiber is laid (for U-wrap, $d_f = D - D_f$)

ρ_f = Shear reinforcement ratio = $2t_f \text{ Sin}\beta / b_w$

t_f = Thickness of one ply of fiber in mm

b_w = breadth of web of the beam in mm

β = angle between principal fiber orientation and longitudinal axis of member

ε_{fve} = Effective strain = min [$0.00065\{f_c^{2/3}/(\rho_f E_f)\}^{0.56}$ and $0.17\{f_c^{\ 2/3}/(\rho_f E_f)\}^{0.30}$] ≤ 0.006

f_c = Concrete cylinder strength, in MPa and

E_f = FRP elastic modulus in principal direction, in GPa

For our case,

b_w = 600 mm

d = 1050 mm

t_f = 0.234 mm (430 gsm fiber)

E_f = 240 GPa

f_c' = 0.8*20 = 16 N/mm^2

$\beta = 90^{o}$

Therefore,

$\rho_f = 2*0.234*1/600 = 0.00078$

ε_{fve}= min [0.00065{$16^{2/3}$/(0.00078*240)}0.56 and 0.17{$16^{2/3}$/(0.00078*240)}$^{0.30}$] =0.0047 $\leq$ 0.006 (Okay)

V_f = 0.9*1050*600*0.00078*240*0.0047 kN = 498.87 kN

Therefore, for two plies of wraps, V_f = 2*498.87 = 997.74 kN

Thus, allowable shear capacity, $V_{uf} = \varphi V_f$ = 0.85*997.74 = 848.08 kN

Hence, total shear resistance capacity of strengthened section, $V_{u,str} = V_{uc} + V_{us} + V_{uf}$ = 548.64 + 499.86 + 848.08 = 1896.58 kN > V_u (1749.40 kN). Thus the beams are safe against shear.

Provide 2 ply S&P C-sheet 430 gsm U-wrap up to 4000 mm from the face of support on either side of beams. This wrap will also act as end anchorage for laminates.

3.2 Design of Strengthening for Slab

Although the slab is safe against bending moment as well as both types of shear, still as an additional safety feature it is recommended to provide 100 x 1.4, 1300 mm long laminates at 500 mm c/c. The laminates should be anchored at the end with mechanical end anchorage system.

4. SURFACE PREPERATION FOR INSTALLATION OF FRP

Areas of the beams with visible cracking were first repaired (by removing loose concrete and replacing it with new patching concrete, and filling the cracks with a cement based grout material) and those with uneven surfaces ground to a smooth finish. Sharp edges around the beam corners were then rounded, and the bridge underneath was sand-blasted and pressure washed with water to remove any loose surface materials that could lead to de-bonding of the laminates. After the surface was dry, laminate locations on the beams and flange soffits were clearly marked. A 15 mm gap was provided between U-jackets laminates to allow an avenue for moisture to escape.

A primer was applied followed by putty at the locations where the FRP laminates were to be installed. The primer is expected to penetrate the concrete surface, increase its strength, and improve laminate bonding to the surface. After primer application, gaps and pinholes greater than 1 mm can be seen on the concrete surface. The putty application smoothed the surface by filling the gaps and pinholes.

Fig. 8 Application of FRP laminates to the T-Beam at the site

5. CONCLUSIONS

Flexural Strengthening

The flexural strengthening of beams is achieved by externally applying S&P CFK Carbon Laminates. The design recommendation is to provide:

1. S&P CFK Laminates 100x1.4 at 450 mm c/c along the length of the beam at the soffit of the slab of T-beam up to 2500 mm from the face of the support on either side.
2. S&P CFK Laminates 100x1.4 at 500 mm c/c across the length of the beam at the soffit of the slab as main reinforcement to slab up to 300 mm from the face of the beam on either side.
3. 5 Nos. S&P CFK Laminates 100x1.4 along the length of the beam at the soffit of the beam as main reinforcement to beam in the middle 6000 mm of the beam.

Fig. 9 shows the complete design details for the flexural strengthening of the superstructure.

Shear Strengthening

The shear strengthening of beams is achieved by providing Carbon U- Wraps on the beams as shown in Fig. 10. The design recommendation is to provide **2-ply-430 gsm S&P C-240** as U-wraps on beams at L/3 from the face of the support on either side.

Load tests were conducted before and after installation of the laminates to evaluate effectiveness of the strengthening system and investigate its influence on structural behavior of the bridge. The FRP techniques were easily implemented and showed satisfactory performance.

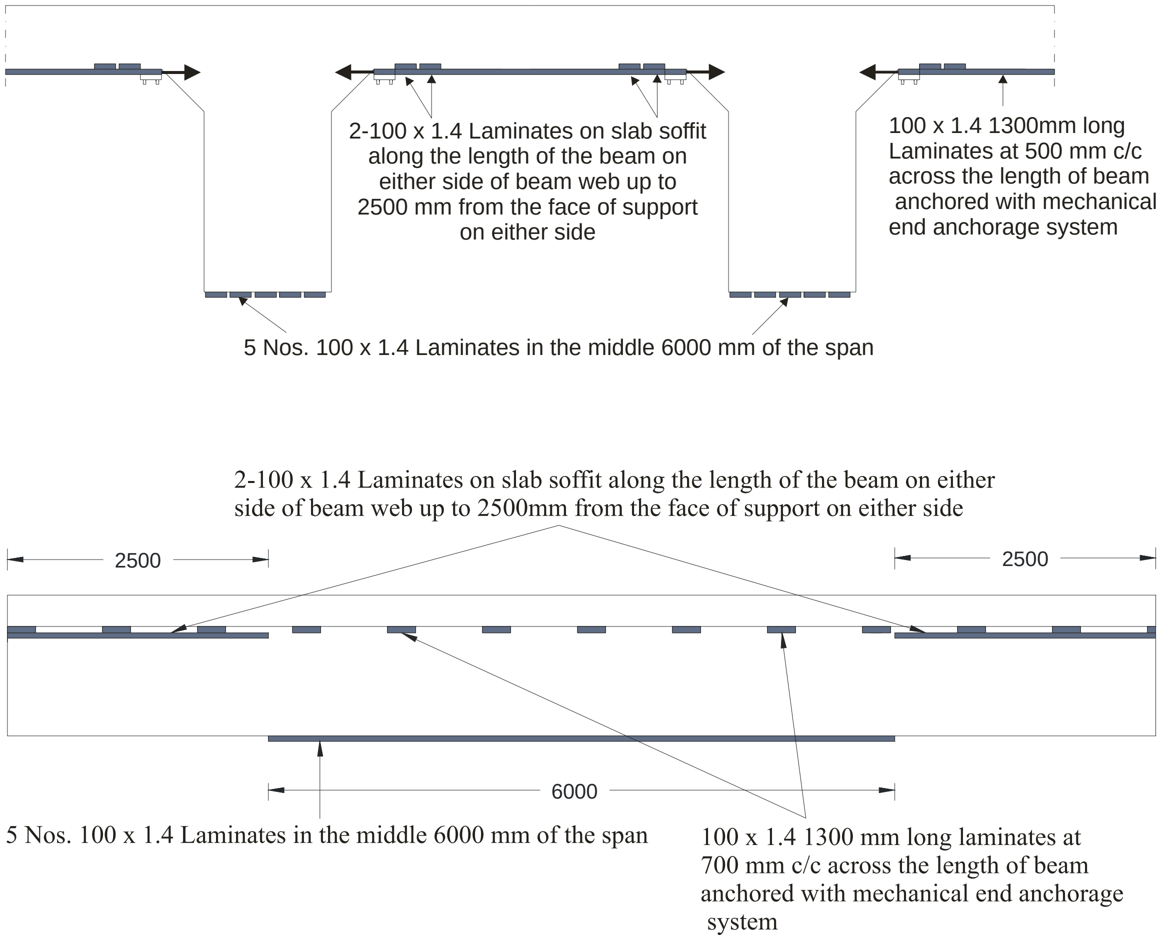

Fig. 9 Flexural strengthening of Superstructure and shear strengthening of slab

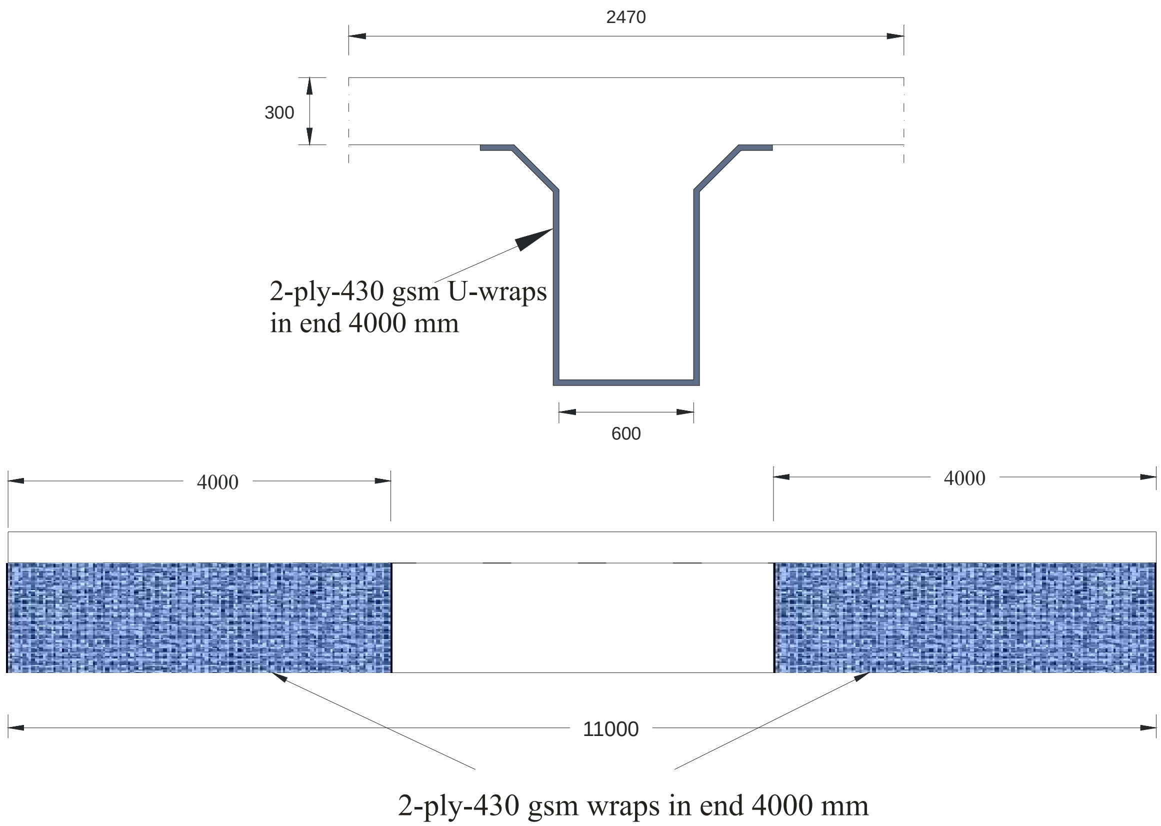

Fig. 10 Flexural strengthening of Superstructure and shear strengthening of slab

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