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Structural and Economical Analysis of Cable-Stayed Bridges

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Abstract: *Cable-stayed bridges have emerged as prominent structures in modern civil engineering, renowned for their aesthetic appeal, structural efficiency, and economic viability. This review paper provides a comprehensive analysis of the structural and economic aspects of cable-stayed bridges. It encompasses a thorough examination of various design considerations, construction techniques, material selection, and economic factors influencing the feasibility and performance of cable-stayed bridges. Through the synthesis of existing literature and case studies, this paper aims to offer insights into the key factors driving the design, construction, and economic evaluation of cable-stayed bridges, thereby aiding engineers, planners, and decision-makers in making informed choices in bridge infrastructure development projects.*

Keywords: *Cable-stayed bridges, Structural analysis, Economical analysis, Design considerations, Construction techniques, Material selection.*

I. INTRODUCTION

Cable-stayed bridges have gained immense popularity in the realm of civil engineering due to their unique structural form, which efficiently balances aesthetic appeal, span length, and structural performance. The distinctive feature of cable-stayed bridges lies in their cable-supported deck, where cables transmit the bridge loads to towers, allowing for longer spans with fewer supports compared to traditional bridge types. This section provides an overview of the historical development, structural configuration, and key advantages of cable-stayed bridges, setting the stage for a detailed exploration of their structural and economic aspects. This structured review paper provides a comprehensive analysis of the structural and economic aspects of cable-stayed bridges, offering valuable insights for engineers, researchers, and policymakers involved in bridge infrastructure development projects.

II. LITERATURE REVIEW

Cable-stayed bridges represent a sophisticated engineering marvel, embodying a harmonious fusion of structural elegance and functional efficiency. This literature review navigates through the multifaceted domains of structural analysis, economic evaluation, design considerations, and construction techniques pertinent to cable-stayed bridges.

Structural Analysis of Cable-Stayed Bridges: The structural analysis of cable-stayed bridges stands as a cornerstone in their design and implementation. Scholars have extensively investigated the fundamental principles underlying their structural behavior, encompassing load distribution mechanisms, cable arrangements, tower types, and deck configurations. This body of research underscores the intricate interplay between these design elements and their influence on the bridge's performance under diverse loading conditions. Advanced analysis methodologies, ranging from finite element modeling to analytical techniques, have been employed to assess the stability and structural integrity of cable-stayed bridges. Notable attention has been directed towards optimizing structural efficiency and safety through the judicious selection of configurations and materials.

Economic Analysis of Cable-Stayed Bridges: Economic considerations occupy a central position in the discourse surrounding cable-stayed bridges. Scholars have delved into various aspects of economic analysis, including cost estimation, life-cycle assessment, maintenance requirements, and economic evaluation techniques. Through comprehensive case studies and comparative analyses, researchers have illuminated the cost-effectiveness and long-term economic viability of cable-stayed bridges relative to alternative bridge typologies. Key factors influencing economic feasibility, such as construction duration, environmental impact, and transportation benefits, have been scrutinized to provide nuanced insights into their economic implications.

Design Considerations and Construction Techniques: Designing and constructing cable-stayed bridges entail a confluence of creativity, precision, and innovation. Scholars have elucidated critical design considerations, encompassing span length, geometry, wind and seismic effects, among others, to ensure structural robustness and safety. Furthermore, researchers have explored innovative construction techniques and materials, showcasing exemplary case studies from around the globe.

These endeavors have not only advanced the frontiers of cable-stayed bridge engineering but have also underscored the significance of sustainable and resilient infrastructure development.

In conclusion, the literature surrounding cable-stayed bridges is characterized by a rich tapestry of interdisciplinary research, spanning structural analysis, economic evaluation, design innovation, and construction methodologies. This review encapsulates the collective wisdom gleaned from scholarly endeavors, offering a holistic understanding of the complexities inherent in the planning, design, and execution of cable-stayed bridge projects.

III. EXPERIMENTAL WORK OBSERVATION

Load Calculation (for typical 1m segment)

1) Dead load and Superimposed loads

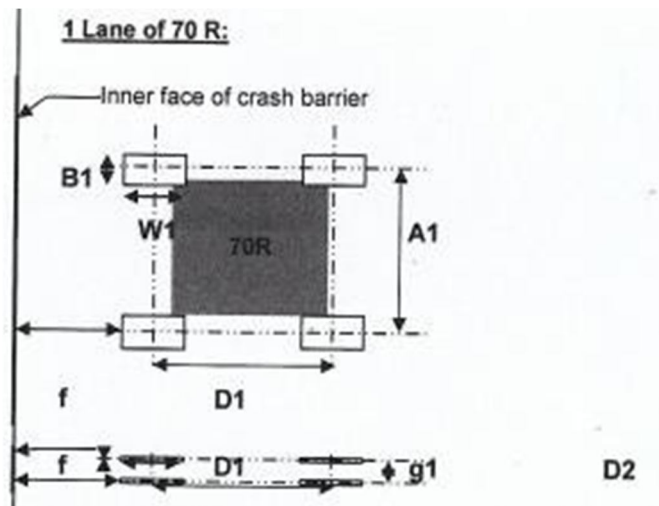
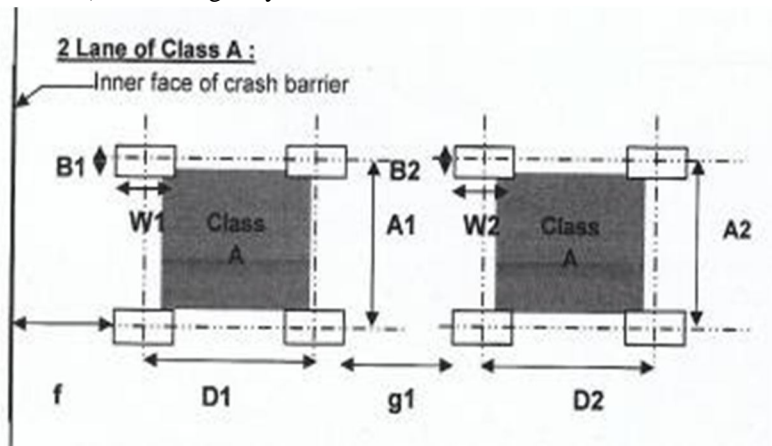
Dead load for box girder is applied as self-weight in software.

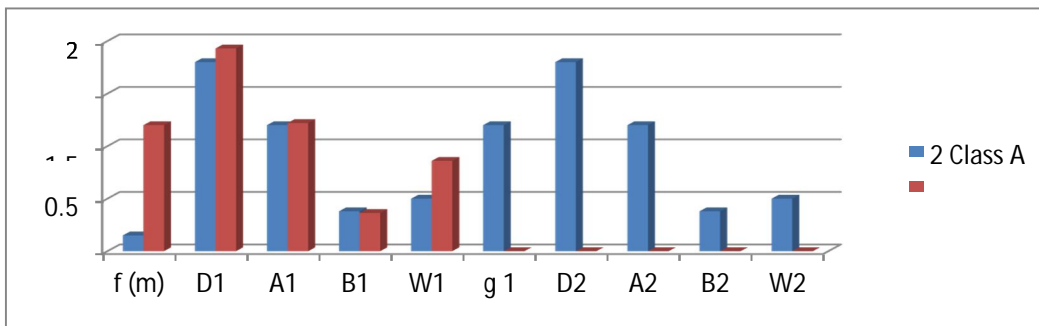
The calculation of load for typical 1m segment is 10.55 kN/m value of load due to crash barrier, 11.55 kN is Load due to utility, Total load is 11.55 kN. Calculation of load for typical 1m segment is 14.28 kN value of load due to footpath, 16.5 kN is value of load due to wearing coat.

2) Vehicular Loads

Live load (LL) analysis is carried out with maximum axle load for the following loading of IRC -6: 2017. Following IRC vehicles are considered-

- 3 Lane of Class A (each carriageway)
- 1 Lane of 70 R + 1 Lane of class A (each carriageway)
- Lane of class A + 1 Lane of 70 R (each carriageway).





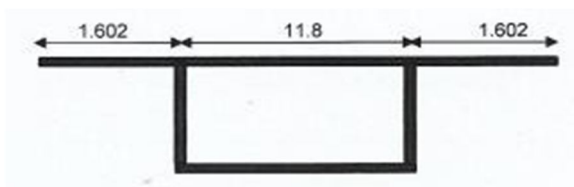
Graph 4.1

| Load | 2 Class A | 70R |
|---------|-----------|-------|
| f (m) | 0.15 | 1.2 |
| D1 (m) | 1.8 | 1.93 |
| A1 (m) | 1.2 | 1.22 |
| B1 (m) | 0.38 | 0.364 |
| W1 (m) | 0.5 | 0.86 |
| g 1 (m) | 1.2 | 0 |
| D2 (m) | 1.8 | 0 |
| A2 (m) | 1.2 | 0 |
| B2 (m) | 0.38 | 0 |
| W2 (m) | 0.5 | 0 |

Table 4.1 Loading due to trains placed at different position.

Loading due to trains placed at different position with 0.2m increment in transversedirection is calculated and presented in Annexure B

Sample Calculation for Live Load



Effective width of each wheel load is calculated as per Annexure B3 of IRC: 112-2011.

➤ For continuous span,

$$b_{eff} = \alpha \cdot a \cdot \left(1 - \frac{a}{l_0} \right) + b_1$$

➤ For cantilever span,

$$b_{eff} = 1.2 a + b_1$$

b_{eff} = Effective width of slab on which load acts b = width of slab = 45.25 m

l_o = effective span = 1.602 m. $b/l_o = 45.25/1.602 = 28.25 > 2.0$

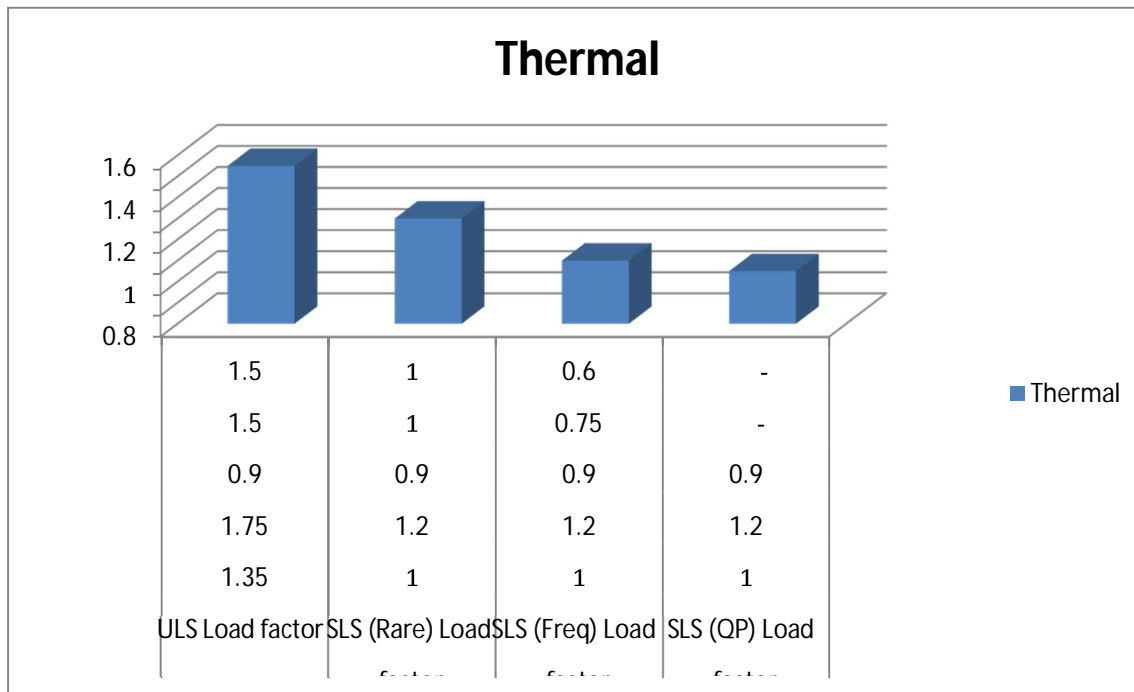
$a = 2.6$ (for condition slab)

Load Combination

Box girder analyzed for various load cases, using load factors described for various combinations of load.

Table 4.2 Box girder analyzed for various load cases.

| Load type | DL & SIDL | Surfacing | Prestress | Live Load | Wind Load | Thermal |
|------------------------|-----------|-----------|-----------|-----------|-----------|---------|
| ULS Load factor | 1.35 | 1.75 | 0.9 | 1.5 | 1.5 | 1.5 |
| SLS (Rare) Load factor | 1.00 | 1.20 | 0.9 | 1.0 | 1.0 | 1.0 |
| SLS (Freq) Load factor | 1.00 | 1.20 | 0.9 | 0.75 | 0.6 | 0.6 |
| SLS (QP) Load factor | 1.00 | 1.20 | 0.9 | - | - | 0.5 |

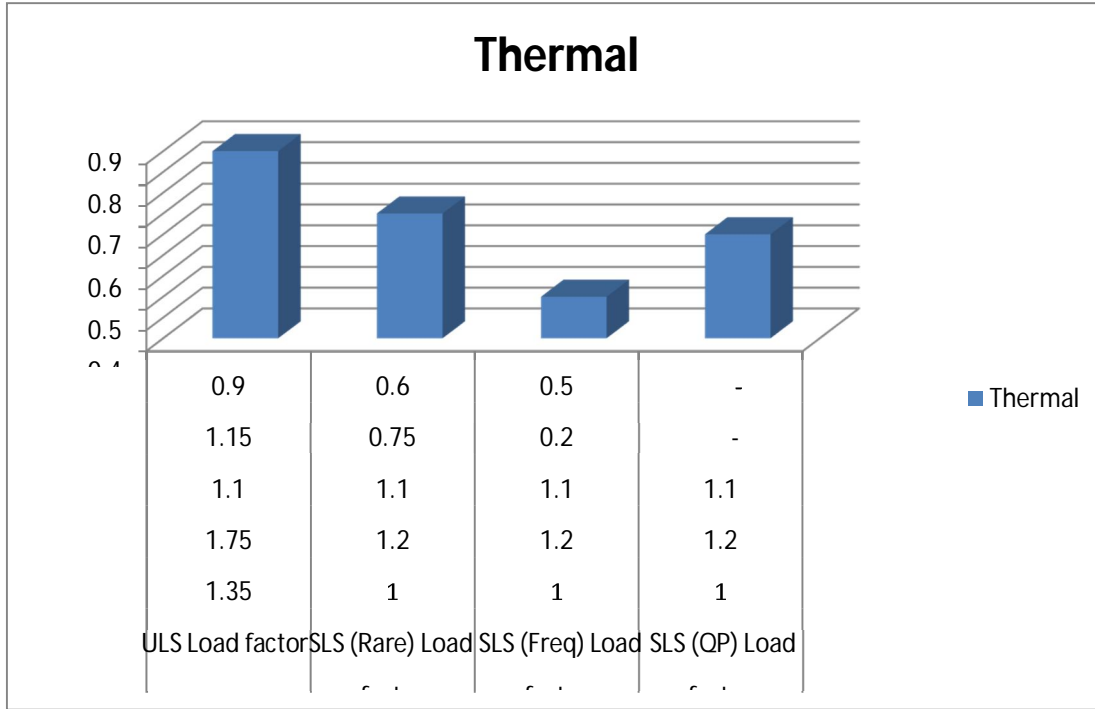


Graph 4.2

Table 4.3 Wind load and thermal load

| Load type | DL & SIDL | Surfacing | Prestress | Live Load | Wind Load | Thermal |
|------------------------|-----------|-----------|-----------|-----------|-----------|---------|
| ULS Load factor | 1.35 | 1.75 | 1.1 | 1.15 | 0.9 | 0.9 |
| SLS (Rare) Load factor | 1.00 | 1.20 | 1.1 | 0.75 | 0.6 | 0.6 |
| SLS (Freq) Load factor | 1.00 | 1.20 | 1.1 | 0.2 | 0.5 | 0.2 |

| | | | | | | |
|----------------------|------|------|-----|---|---|-----|
| Load factor | | | | | | |
| SLS (QP) Load factor | 1.00 | 1.20 | 1.1 | - | - | 0.5 |



Graph 4.3 Wind load and thermal load

Note:- Wind load and thermal load need not be taken simultaneously

Design for flexure.

Critical sections are identified for the design of segment as marked in figure 4.1 these sections are checked for flexure for the ultimate load combinations.

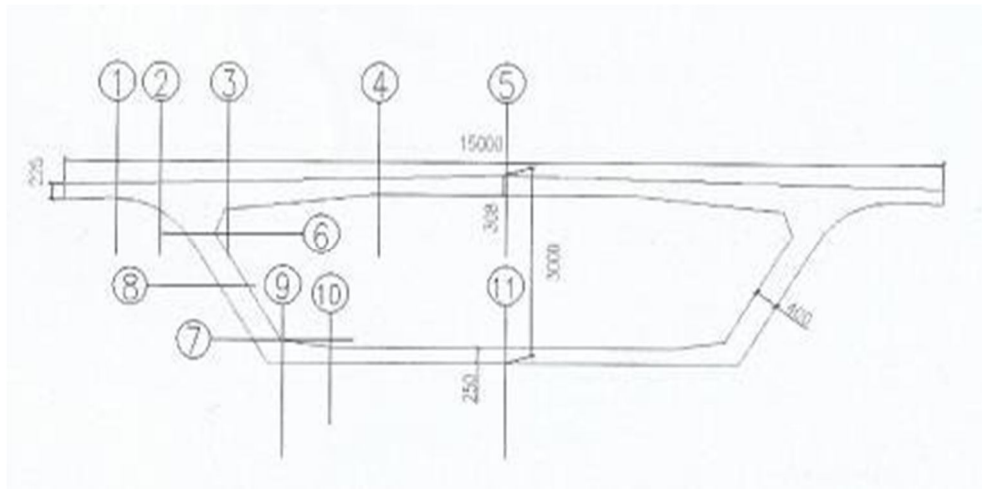
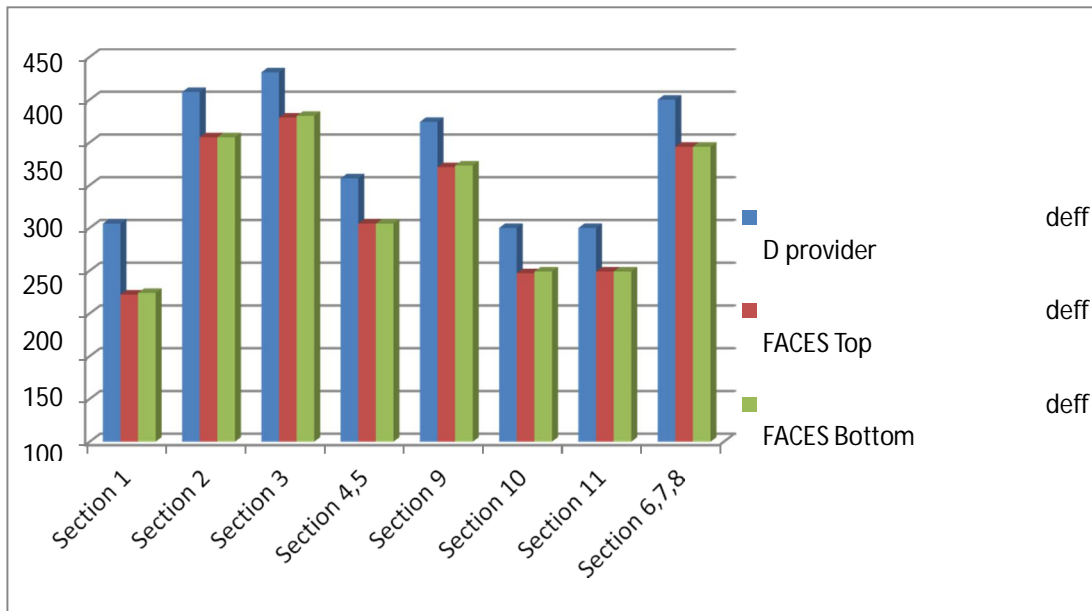


Figure 4.1: Girder cross section marked with critical sections

Table 4.4

| Deff. | | | |
|---------------|------------|-------|--------|
| | | FACES | |
| Section | D provider | Top | Bottom |
| Section 1 | 255 | 172 | 174 |
| Section 2 | 409 | 356 | 356 |
| Section 3 | 432 | 379 | 381 |
| Section 4,5 | 308 | 255 | 255 |
| Section 9 | 374 | 321 | 323 |
| Section 10 | 250 | 197 | 199 |
| Section 11 | 250 | 199 | 199 |
| Section 6,7,8 | 400 | 345 | 345 |

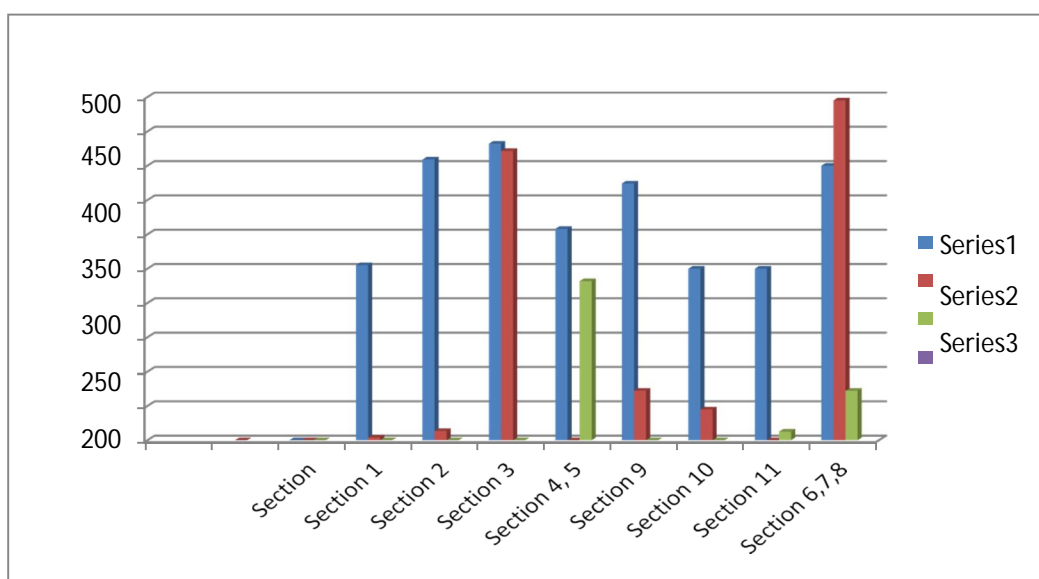


Graph 4.4

Table 4.5

| Bending Moment { ULS (kN - m) } | | | |
|---------------------------------|------------|-------|--------|
| | | FACES | |
| Section | D provider | Top | Bottom |
| Section 1 | 255 | 3.87 | 0.10 |
| Section 2 | 409 | 13.47 | 0.00 |

| | | | |
|---------------|-----|--------|--------|
| Section 3 | 432 | 421.41 | 0.00 |
| Section 4, 5 | 308 | 0.00 | 231.71 |
| Section 9 | 374 | 72.09 | 0.00 |
| Section 10 | 250 | 44.88 | 0.00 |
| Section 11 | 250 | 0.00 | 12.57 |
| Section 6,7,8 | 400 | 495 | 72.09 |

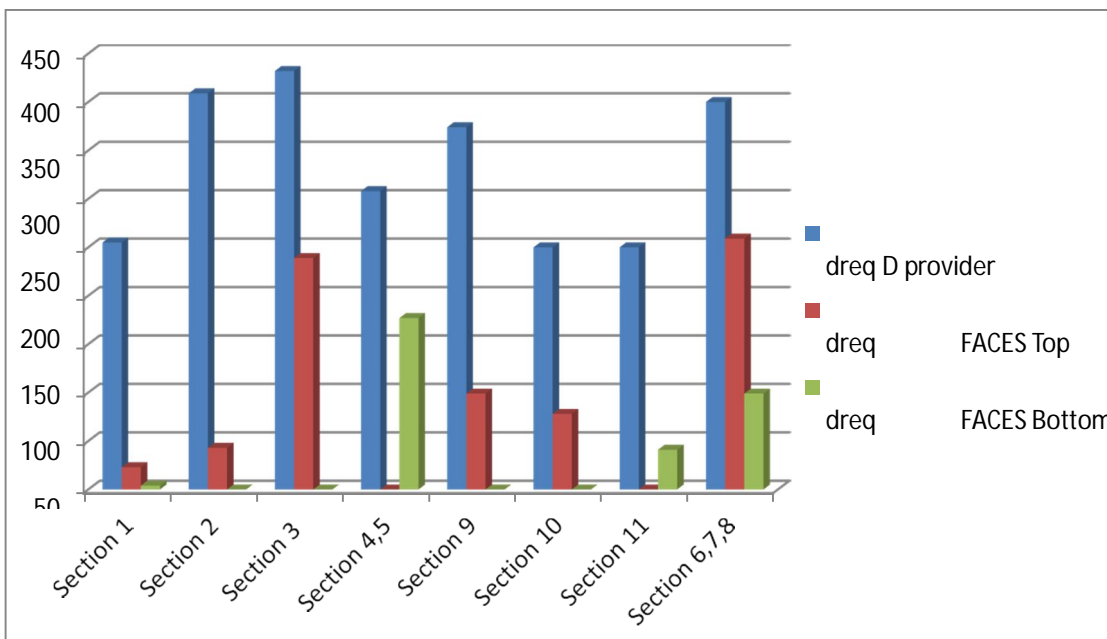


Graph 4.5

Table 4.6

| dreq | | | |
|-------------|------------|-------|--------|
| | | FACES | |
| Section | D provider | Top | Bottom |
| Section 1 | 255 | 23 | 4 |
| Section 2 | 409 | 43 | 0 |
| Section 3 | 432 | 239 | 0 |
| Section 4,5 | 308 | 0 | 177 |
| Section 9 | 374 | 99 | 0 |
| Section 10 | 250 | 78 | 0 |

| | | | |
|---------------|-----|-----|----|
| Section 11 | 250 | 0 | 41 |
| Section 6,7,8 | 400 | 259 | 99 |

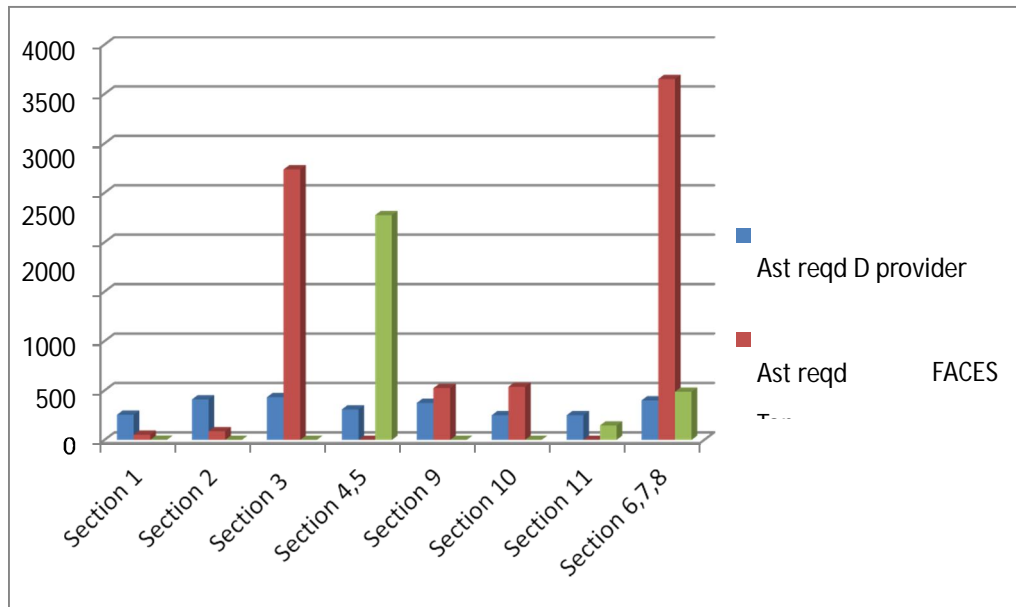


Graph 4.6

Table 4.7

| Ast reqd | | | |
|-------------|------------|-------|--------|
| | | FACES | |
| Section | D provider | Top | Bottom |
| Section 1 | 255 | 52 | 1 |
| Section 2 | 409 | 87 | 0 |
| Section 3 | 432 | 2737 | 0 |
| Section 4,5 | 308 | 0 | 2274 |
| Section 9 | 374 | 524 | 0 |
| Section 10 | 250 | 537 | 0 |
| Section 11 | 250 | 0 | 146 |

| | | | |
|---------------|-----|------|-----|
| Section 6,7,8 | 400 | 3651 | 487 |
|---------------|-----|------|-----|

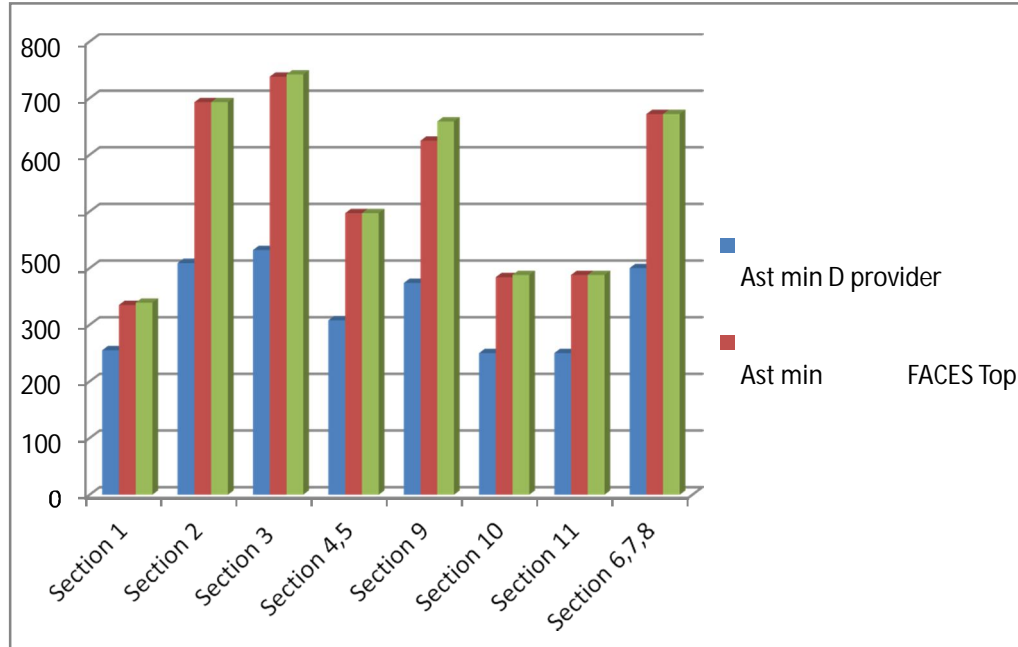


Graph 4.7

Table 4.8

| Ast min | | | |
|-------------|------------|-------|--------|
| | | FACES | |
| Section | D provider | Top | Bottom |
| Section 1 | 255 | 335 | 339 |
| Section 2 | 409 | 693 | 693 |
| Section 3 | 432 | 738 | 742 |
| Section 4,5 | 308 | 497 | 497 |
| Section 9 | 374 | 625 | 659 |
| Section 10 | 250 | 384 | 388 |
| Section 11 | 250 | 388 | 388 |

| | | | |
|---------------|-----|-----|-----|
| Section 6,7,8 | 400 | 672 | 672 |
|---------------|-----|-----|-----|



Graph 4.8

Hidden extra reinforcement in web, Additional reinforcement is provided in case of webs to satisfy the shear and torsion effects as described. The reinforcement required as per shear and torsion combined.

Check for Crack Width in Deck slab.

$$Wk = Sr, \max(\epsilon_{sm} - \epsilon_{cm})$$

$$Wk, \lim = 0.2 \text{ mm}$$

Where, Sr, \max = the maximum crack spacing

= the mean strain in ϵ_{sm} reinforcement under the relevant combination of loads, including the effect of imposed deformation and taking into account the effects of tension stiffening

= the mean strain in the concrete between cracks

$$\epsilon_{cm,n} - \epsilon_{cm} = \frac{\sigma_s - k_t \frac{f_{ct,eff}}{\rho_{p,eff}} (1 + \alpha_e \rho_{p,eff})}{E_s} \geq 0.6 \frac{\sigma_s}{E_s}$$

Where,

σ_s = the stress in the tension reinforcement assuming a cracked section α_e = the ratio E_s/E_{cm}

= the effective $A_{c,eff}$ of concrete in tension surrounding the reinforcement or prestressing tendons of depth, h_c , h_t , where h_c , h_t is the lesser of $2.5(h-d)$, $(h-x)/3$ or $h/2$

$$\rho_{p,eff} = A_s / A_{c,eff}$$

k_t = a factor dependent on the duration of the load

$$S_{r,max} = 3.4 c + 0.425 k_1 k_2 \phi / \rho_{p,eff}$$

k1 = a coefficient which takes account of the bond properties of the bonded reinforcement.

STRESS CHECK

SLS BM (Rare Combination) = 158 kN-m The Concrete Stress at top of section:

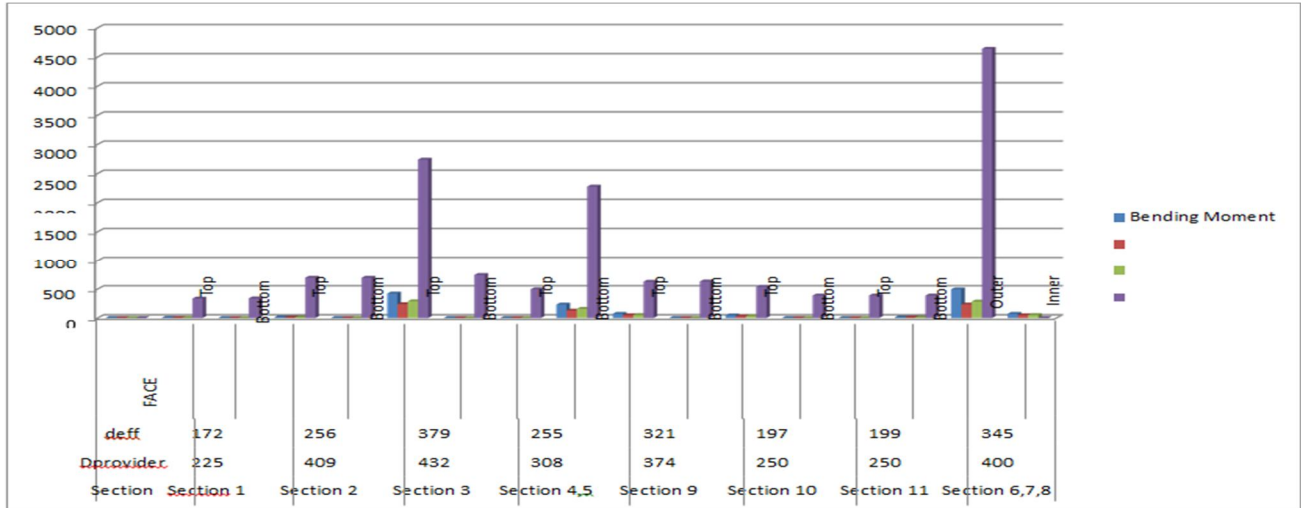
$$\sigma_c = \frac{M_{ED} E_{c,eff}}{z_c E_s}$$

The Reinforcement Stress:

$$\sigma_s = \frac{M_{ED}}{z_s}$$

Table 4.9

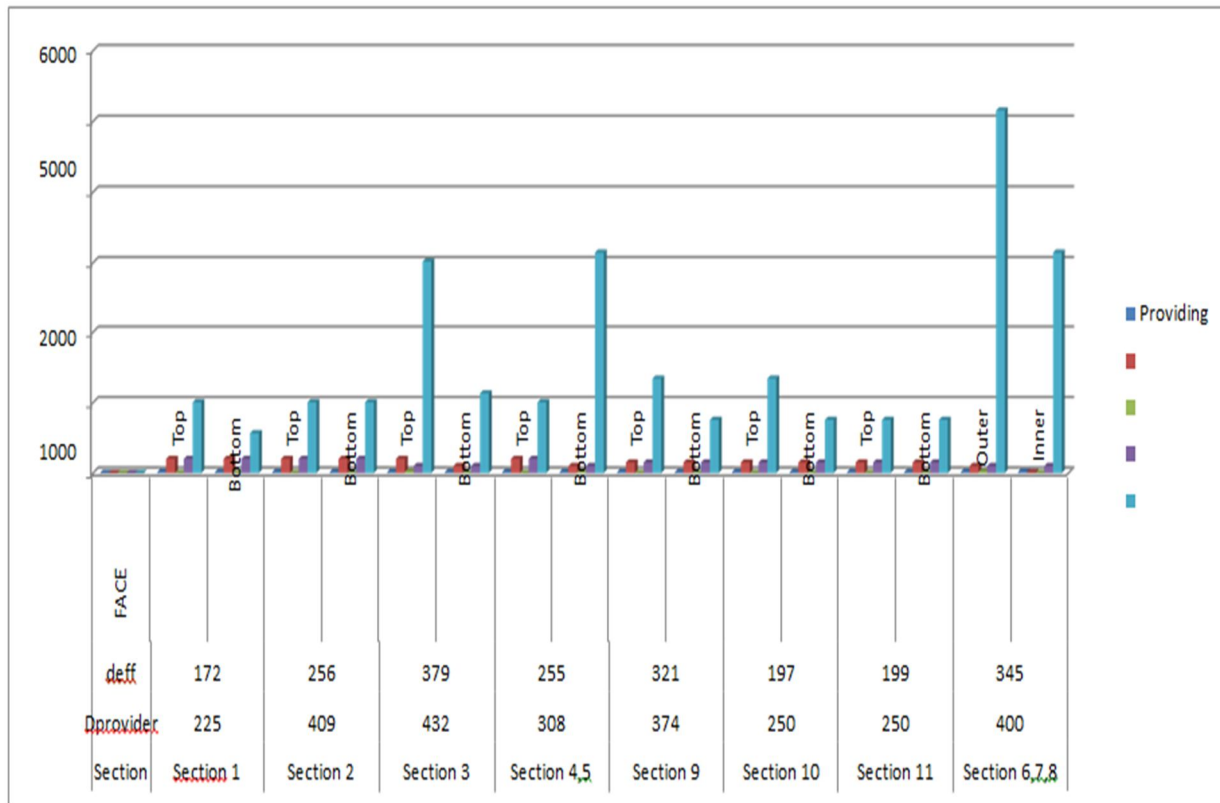
| | Section | Section 1 | | Section 2 | | Section 3 | | Section 4,5 | | Section 9 | | Section 10 | | Section 11 | | Section 6,7,8 | |
|----------------|------------------------------------|-----------|--------|-----------|--------|-----------|--------|-------------|---------|-----------|--------|------------|--------|------------|--------|---------------|---------|
| | D _{provide} | 225 | | 409 | | 432 | | 308 | | 374 | | 250 | | 250 | | 400 | |
| | d _{eff} | 172 | | 256 | | 379 | | 255 | | 321 | | 197 | | 199 | | 345 | |
| | FACE | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Outer | Inner |
| Bending Moment | ULS | 3.87 | 0.10 | 13.47 | 0.00 | 421.41 | 0.00 | 0.00 | 231.71 | 72.09 | 0.00 | 44.88 | 0.00 | 0.00 | 12.57 | 495.00 | 72.09 |
| | SLS(Freq) | 2.59 | 0.08 | 9.06 | 0.00 | 238.61 | 0.00 | 0.00 | 128.69 | 48.31 | 0.00 | 28.62 | 0.00 | 0.00 | 11.61 | 232.78 | 48.31 |
| | SLS(Rare Comb) | 2.81 | 0.08 | 9.78 | 0.00 | 288.13 | 0.00 | 0.00 | 157.77 | 51.96 | 0.00 | 31.71 | 0.00 | 0.00 | 9.77 | 283.01 | 51.96 |
| | A _{st} (mm ²) | 335.02 | 338.92 | 693.42 | 693.42 | 2737.07 | 742.11 | 496.69 | 2274.34 | 625.24 | 629.14 | 537.30 | 387.61 | 387.61 | 387.61 | 4639.31 | 14.7485 |



Graph 4.9

Table 4.10

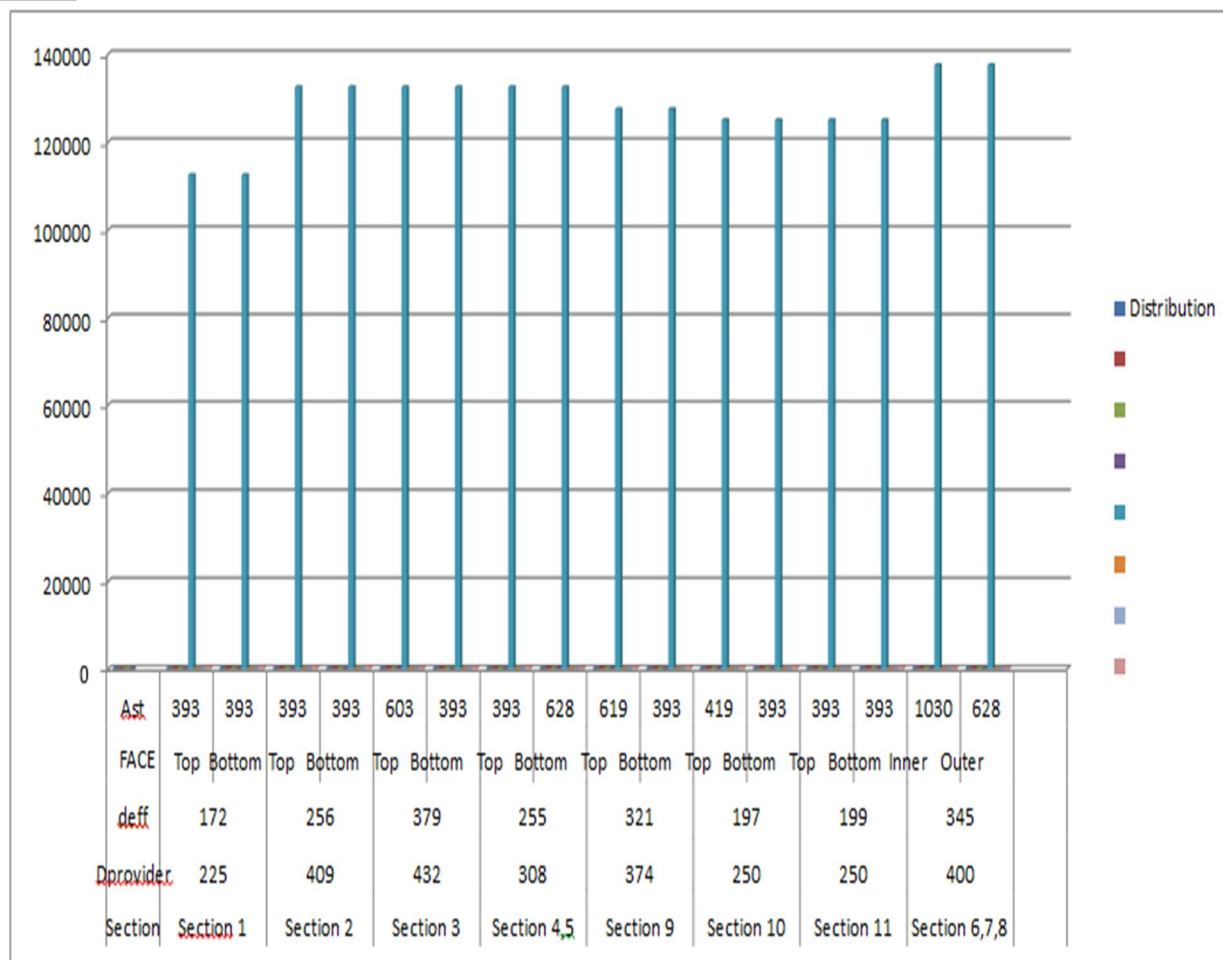
| Section | Section 1 | | Section 2 | | Section 3 | | Section 4,5 | | Section 9 | | Section 10 | | Section 11 | | Section 6,7,8 | | |
|-----------------------------|-----------|--------|-----------|--------|-----------|--------|-------------|--------|-----------|--------|------------|--------|------------|--------|---------------|-------|-----|
| | Dprovider | 225 | 409 | 432 | 308 | 374 | 250 | 250 | 400 | | | | | | | | |
| deff | 172 | 256 | 379 | 255 | 321 | 197 | 199 | 345 | | | | | | | | | |
| FACE | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Inner | Outer | |
| Providing | Φ | 16 | 12 | 16 | 16 | 16 | 12 | 16 | 16 | 16 | 12 | 16 | 12 | 12 | 12 | 20 | 20 |
| | Spacing | 200 | 200 | 200 | 200 | 200 | 100 | 200 | 100 | 150 | 150 | 150 | 150 | 150 | 150 | 100 | 100 |
| | Φ | 0 | 0 | 0 | 0 | 16 | 0 | 0 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 16 | 0 |
| | Spacing | 200 | 200 | 200 | 200 | 100 | 100 | 200 | 100 | 150 | 150 | 150 | 150 | 150 | 150 | 100 | 100 |
| Ast prov (mm ²) | 1005 | 565 | 1005 | 1005 | 3016 | 1131 | 1005 | 3142 | 1340 | 754 | 1340 | 754 | 754 | 754 | 5152 | 3142 | |



Graph 4.10

Table 4.11

| | Section | Section 1 | | Section 2 | | Section 3 | | Section 4,5 | | Section 9 | | Section 10 | | Section 11 | | Section 6,7,8 | |
|----------------|----------------------|-----------|--------|-----------|--------|-----------|--------|-------------|---------|-----------|--------|------------|--------|------------|--------|---------------|---------|
| | | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Outer | Inner |
| | Dprovider | 225 | | 409 | | 432 | | 308 | | 374 | | 250 | | 250 | | 400 | |
| | deff | 172 | | 256 | | 379 | | 255 | | 321 | | 197 | | 199 | | 345 | |
| | FACE | | | | | | | | | | | | | | | | |
| Bending Moment | ULS | 3.87 | 0.10 | 13.47 | 0.00 | 421.41 | 0.00 | 0.00 | 231.71 | 72.09 | 0.00 | 44.88 | 0.00 | 0.00 | 12.57 | 495.00 | 72.09 |
| | SLS(Freq) | 2.59 | 0.08 | 9.06 | 0.00 | 238.61 | 0.00 | 0.00 | 128.69 | 48.31 | 0.00 | 28.62 | 0.00 | 0.00 | 11.61 | 232.78 | 48.31 |
| | SLS(Resp) | 2.81 | 0.08 | 9.78 | 0.00 | 288.13 | 0.00 | 0.00 | 157.77 | 51.96 | 0.00 | 31.71 | 0.00 | 0.00 | 9.77 | 283.01 | 51.96 |
| | Ast(m ²) | 335.02 | 338.92 | 693.42 | 693.42 | 2737.07 | 742.11 | 496.69 | 2274.34 | 625.24 | 629.14 | 537.30 | 387.61 | 387.61 | 387.61 | 4639.31 | 14.7485 |



Graph 4.11

Table 4.12

| | | | | | | | | | | | | | | | | |
|-----------|-----------|--------|-----------|--------|-----------|--------|-------------|--------|-----------|--------|------------|--------|------------|--------|---------------|-------|
| Ast | 393 | 393 | 393 | 393 | 603 | 393 | 393 | 628 | 619 | 393 | 419 | 393 | 393 | 393 | 1030 | 628 |
| FACE | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Inner | Outer |
| deff | 172 | | 256 | | 379 | | 255 | | 321 | | 197 | | 199 | | 345 | |
| Dprovider | 225 | | 409 | | 432 | | 308 | | 374 | | 250 | | 250 | | 400 | |
| Section | Section 1 | | Section 2 | | Section 3 | | Section 4,5 | | Section 9 | | Section 10 | | Section 11 | | Section 6,7,8 | |

| | Section | Section 1 | | Section 2 | | Section 3 | | Section 4,5 | | Section 9 | | Section 10 | | Section 11 | | Section 6,7,8 | |
|-------------------------|------------------------------|-----------|--------|-----------|--------|-----------|--------|-------------|--------|-----------|--------|------------|--------|------------|--------|---------------|-------|
| | Dprovid er | 225 | | 409 | | 432 | | 308 | | 374 | | 250 | | 250 | | 400 | |
| | deff | 172 | | 256 | | 379 | | 255 | | 321 | | 197 | | 199 | | 345 | |
| | FACE | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Top | Bottom | Inner | Outer |
| Crack Width Check | Wk | 0.022 | 0.001 | 0.041 | 0.000 | 0.187 | 0.000 | 0.000 | 0.144 | 0.147 | 0.000 | 0.142 | 0.000 | 0.000 | 0.122 | 0.108 | 0.044 |
| | Wk , max | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Stress Check | Stress in Concre te | 0.9 | 0.0 | 1.0 | 0.0 | 17.1 | 0.0 | 0.0 | 17.6 | 5.5 | 0.0 | 7.3 | 0.0 | 0.0 | 2.8 | 16.1 | 3.5 |
| | Stress inSteel | 17.6 | 0.9 | 28.9 | 0.0 | 275.6 | 0.0 | 0.0 | 219.4 | 218.3 | 0.0 | 129.1 | 0.0 | 0.0 | 69.4 | 179.1 | 52.7 |

IV. MATERIAL SELECTION AND SUSTAINABILITY

Material selection plays a crucial role in determining the structural performance, durability, and sustainability of cable-stayed bridges. This section examines the materials commonly used in cable-stayed bridge construction, including steel, concrete, and composite materials, with a focus on their mechanical properties, environmental impact, and long-term sustainability. Advances in material technology and sustainable construction practices are explored to address the growing demand for environmentally friendly and resilient bridge infrastructure solutions.

V. CONCLUSION

The synthesis of structural and economic analyses presented in this review underscores the significance of cable-stayed bridges as versatile and cost-effective solutions for modern bridge infrastructure projects. By integrating innovative design approaches, advanced materials, and economic evaluation techniques, cable-stayed bridges continue to redefine the boundaries of bridge engineering, offering sustainable and aesthetically pleasing solutions to meet the evolving transportation needs of society.

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