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Lifting and Handling Precast Tunnel Segments

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Abstract—In this research paper, the authors have dealt the design criteria for precast tunnel segments handling and lifting both in the factory as well as at the site of Tunnelling mostly done with the help of TBM now a days. Tunnel lining segments have to be handled from the factory or storage site and carried to the tunneling site for placing the lining segment at the right place in the underground tunnels with the help of TBM. Therefore, lifting, moving, handling and placing the tunnel lining segment without any damage and with full safety, is a major challenge for site engineers. In this research paper an effort has been done to calculate the max. Moments and shear forces that develop in tunnel lining segments while lifting and handling them in various combinations as per the need at site. If the moments /shear force induced in segment while handling them is known, the engineers can procure the correct type of tunnel handling equipments of required capacity in order to handle the movements of lining segments without compromising the safety standards and thus avoiding any mishap at site.

Index Terms— Criteria for Design for Tunnel Segment, Handling of Tunnel Segments, Lifting of Tunnel segments, Loads & Moments in Tunnel Segments, Safety check for Tunnel Segments, Tunnel Segments Handling Design.

1.0 INTRODUCTION

The article elaborates the design criteria for Lifting and Handling Precast Tunnel Lining Segments.

1.1 TUNNEL SEGMENTS LIFTING & HANDLING

In the market various machines working on vacuum with suction pads are available for handling and lifting tunnel lining segments. The required type of machinery to lift and handle the RCC tunnel lining segments smoothly are purchased and brought at site by the field managers and TBM manufacturers. However for proper tunnel lining segment handling and movement it is necessary to calculate the moments and shear forces which are induced during such process. In order to meet the challenge, exact analysis of moments/shear force calculations are required for the design of multifunctional vacuum beams which are being used in the handling of tunnel segments. Handling of tunnel lining segments thus includes the devices that can handle lining segments in order to lift, tilt, turn and stock the concrete segments with full safety. For a safety measure in practice in case of a power failure or otherwise, the lifting and handling machines hold the lining segments for 30 minutes even when power goes off. Since the RCC tunnel lining segments are precast at a separate site, the removing of a concrete lining segment from the original mould is always a critical activity. After curing the lining segments in water and during opening of covers of mould, the segment inside are quite hot and sensitive, and thus they are to be handled very carefully so that no damage is done to segment. Any damage to segment while handling or lifting leaves a permanent damage to it. Thus not only extra care during handling of segments is required but the machines for handling them should be safely designed for any combination of moments and shear forces during the process. Tunnel lining segment handling machines which are available in the market are both hydraulic and electrical operated on vacuum mechanism.

1.2 Evacuation & Storage of Tunnel Segments

Evacuation and storage of concrete tunnel segments is always an important activity in handling of lining segments. Various stages involved in this process are:

i)Removing of the segments from the mould .
ii)Storage of segments at factory and at tunnel site.
iii)Transferof the segments from the factory to the tunneling site.
iv) Shifting, moving and handling the segments at tunnel site.

2.0 TUNNEL SEGMENTS LIFTING & HANDLING – DESIGN CRITERIA

2.1 Design parameters and safety checks for Handling

Design parameters for safely lifting and moving Tunnel lining segments are as per following
Self-weight of one standard Segment , W =37 kN.
Plan length of standard Segment , L(plan) = 3.318 meter
Uniformly Distributed Loading(UDL) from self- weight of segment , w= W/Lplan = 37/3.318=10.53kN/m

2.2 Design of Vacuum Lifter

Now for the design of Vacuum Lifter which are used to lift the Tunnel Lining segment:
Assume edges of segment projecting beyond the vacuum lifter acting as a cantilever:
Moment at A , Bending Moment (BM_A)= $wL^2/2$ for Cantilever length of 0.515 m at both ends of a segment (refer Fig 1(a) on below page)
BM_A= 10.53 x 0.515 ^{2}/2 = 1.4 kN/m
Shear Force at A, V_A= wL= 10.53 x 0.515 = 5.4kNm

2.3 Temporary Frame (while gaskets are attached)

Moment at center of Segment,
Here, L= 2.288+0.515+0.515 = 3.318 mete (Total length of the segment)
Thus Bending Moment at center point B is = BM_B = (wL/2) x 2.288/2 –($wl^2/8$) . (Refer Figure 1(b) on page below)
Thus BM_B= 1.144(10.53 x 3.318)/2 – 10.53($3.318^2/8$) = 5.5 kNm.
For calculation of Moment at Support, L= 0.515m
Bending Moment at point C (refer figure 1(b) below)

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BM_C=wL^2/2, and since L=0.515m =1.4 kNm

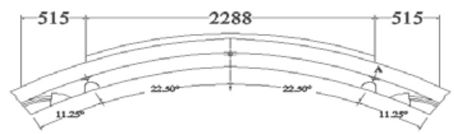

FIG. 1(a)

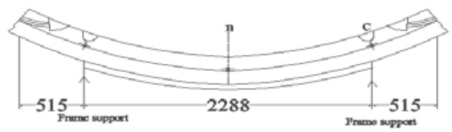

FIG. 1(b)

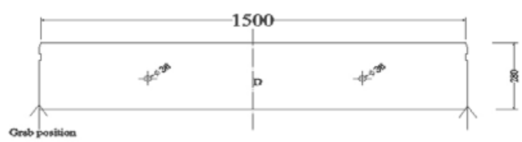

FIG. 2

Maximum Shear taken at Support L= 3.318 m
Shear Force = wL/2 = V_C .Thus V_C= 10.53 x 3.318/2 = 17.5 kN

2.4 Lifting of Single Segment off Frame using Grabs

Bending moments for this case are the same as those for the Temporary Frame as calculated above.

However, this is the additional bending moment induced across the width of the segment owing to the nature of the grab (Refer Fig 2 above).

Moment at center of Segment , (Fig 2)
Total weight of Segment W= 37 kN. And L= 1.5m
Unit weight of Segment = Total Weight/1.5= 37/1.5= 24.67kN/m= Ws
Bending Moment at point D (Refer plan of segment as per Fig 2 above) BM_D=Ws x L^2 = 24.67 x 1.5 ^{2}/8 = 6.9 kNm

2.5 Stack of Two Counter-Key Segments and one Key Segment (Refer Fig 3 & 4 below)

The Total Length of the Counter Key Segments = 3.365m.
The Total weight of 68.5^0 Counter Key Segment = 37.5 kN
The location of key battens has been assumed as shown in Fig 3 & Fig 4 below. Weight of 20.5^0 Key = 11.2kN
Thus Reaction at Support ,R = (37.5+ 11.2)/2= 48.7/2=24.35kN

Thus Unit weight of Counter Key Segment= Total weight/L= 37.5/3.365= 11.1kN/m= Wc

Bending Moment at center of Counter Key Segment at point E, BM_E,

BM_E= (R)x (2.249)/2 – Wc x L^2/8 = 24.35 x 1.1245 – 11.1x (3.365^2)/8 = 9.9 kNm

Max. Shear Force= R= 24.4 kN.

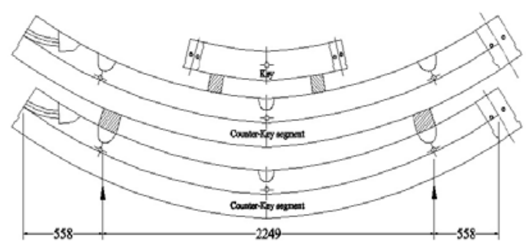

FIG. 3

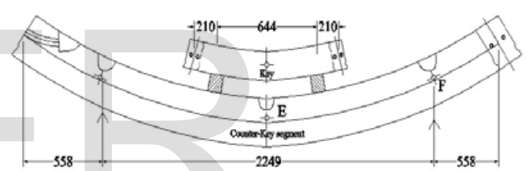

FIG. 4

2.6 Full Stack of Six Segments (Refer Fig 5 below)

With the full stack of 6 Segments in place, the Moments induced are calculated due to batten misalignment with ± 100 mm tolerance as shown in Fig 6 below.

In this case, top 3 Segments(one key and two counter key segments) are stacked onto the bottom three(ordinary segments), a load factor of 5 is used for the load of the top three segments while the load factor of 1.4 is applied to the self -weight of the lower three segments.

Weight of Key Segment = 11.2 kN, weight of one Counter Key Segment = 37.5 kN.
Thus weight of top 3 Segments = 11.2 + 37.5+37.5 =86.2 kN.
Weight of one individual (Ordinary) Segment = 37 kN.

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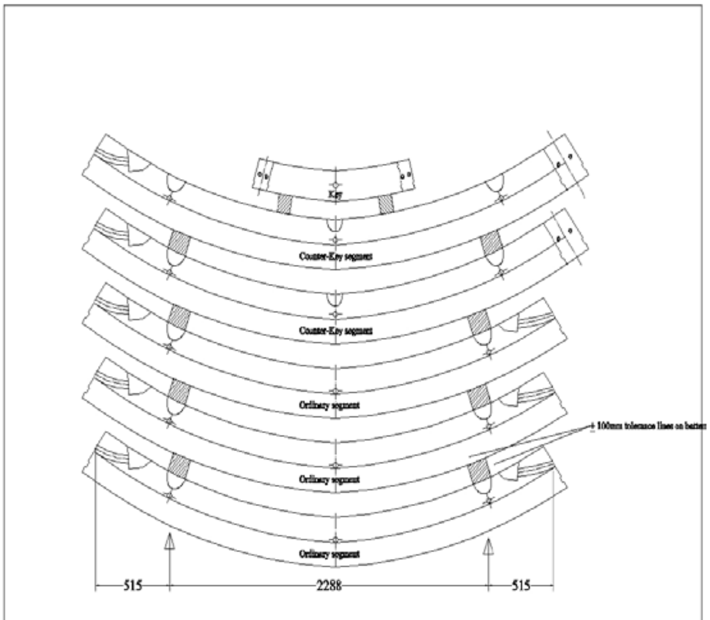


FIG. 5

2.7 Analysis of Bottom most Segment

Refer Fig 6 (a) below

Total factored load on bottom segment = Factored load of top 5 segments

= 86.2 x 5 + 2x37 x 1.4 = 534.6 kN

Thus Reaction or Shear Force on bottom segment, F = 534.6/2= 267.3 kN

UDL w = (37 x 1.4)/3.318 (where 3.318 is the length of ordinary segment)= 15.6 kN/m

Thus Maximum Shear Force on bottom Segment , V (Under Point Load)

V= F +(w x 0.415) (Considering 100 mm tolerance, thus 515-100= 415 mm)

V= 267.3 + 15.6 x 0.415 = 273.8 kN

Now Max. Bending Moment is calculated as, BM_G

BM_G = (F x 0.1) + (w x 0.515^2)/2

= 267.3 x 0.1 + 15.6 x 0.515^2/2 = 28.8 kNm

2.8 Upper Batten – 100 mm out of Position

Refer Fig 6 (b) below

Total Shear Force ,F= 279.4 kN , As self weight of Segment is 37 kN with a factor load of 1.4,

Thus Reaction R = 279.4+ (37 x1.4)/2= 305.3 kN/m

UDL , w= 15.6 kN/m , Then as per Fig 6(b) below,

Thus Bending Moment at H(i.e. location of max. moment from differentiation), BM_H

BM_H=(R x 0.69) – (F x 0.59) - (w x1.205^2/2) = 34.5 kNm.

2.9 Considering Segment Second from Bottom Segment

(i.e. Two Segments from bottom)

Upper batten + 100 mm out of position and also lower batten – 100 mm out of Position .Refer Fig 6 (c) below

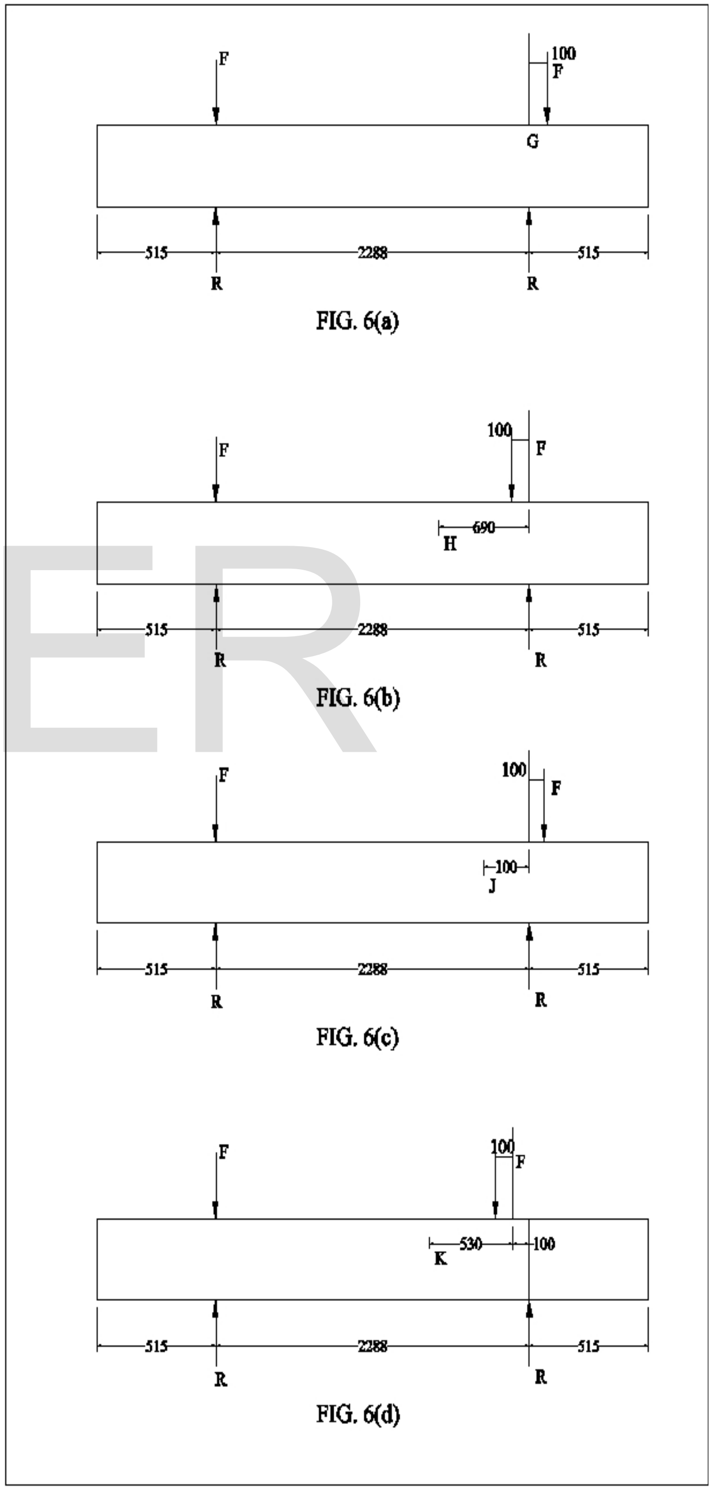


FIG. 6(a)

FIG. 6(b)

FIG. 6(c)

FIG. 6(d)

Thus as per Fig 6 (c) above, Point J is under consideration

Total Load of top three segments = 86.2 kN and Load of 4^{th} segment =37 kN.
Thus considering factored loads, Shear Force , F=(86.2 x5 + 37 x1.4)/2 = 241.4 kN
UDL ,w = (37 x 1.4)/3.318 = 15.6 kN/m
Thus Max. Shear Force (under point load) , V
V= F +w x0.415 = 241.4 +15.6 x 0.415 = 247.8 kN
Calculating Moment at J , BM_J
BM_J=(F x0.2) + (w x 0.615^2/2)= 241.4 x 0.2 + (15.6 x 0.615^2/2) = 51.2 kNm

2.10 Upper Batten -100 mm out of Position & Lower Batten +100 mm out of Position

Refer Fig 6 (d) above
Total Force on Segment, F= 86.2 x 5/2= 215.5 kN
Thus Reaction R = 215.5 + (37 x 1.4)/2= 241.4 kN
UDL =w= 15.6kN/m
Calculate Sagging Moment at K (Location of max moment from differentiation)
BM_K = (R x 0.63) –(F x 0.43) –(w x 1.358^2/2)=(241.4 x 0.63)-(215.5 x 0.43) –(15.6 x 1.358^2/2)
BM_K = 45.03 kNm

2.11 Lifting of one Ordinary Segment by Central Lifting Socket (During Construction)

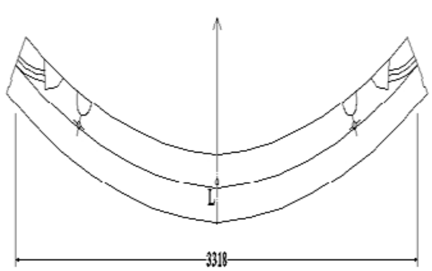


FIG.-7

Refer Fig 7 above.
Here Length of segment, L = 3.318m and considering average weight of one segment as 35kN
UDL , w = 35/3.318 = 10.6 kN/m
Bending Moment at Segment center , BM_L = $wl^2/8$ = 14.5 kN/m
Total Shear Force at supports= 17.5 kN(35/2)
Shear Force at distance d from segment center , V= 15 kN.
Shear Force at distance 2d from Segment center ,= 12.5 kN
Where d is the effective depth of the Segment

2.12 Reinforcement Calculations : Hoop Reinforcement

Determine depth of neutral axis, Xu, using the following Limit State Design formula
Xu/d = 0.87 fy Ast/0.36 fck. bd
Limiting value of Xu/d = 0.48
Mu= 0.87. fy Ast. d(1-α) where α = fy Ast/ fck. bd .
Considering M 50 grade of concrete & Fe 415 Tor steel,
Thus Ast = 1131 mm^2.
Provide 10 nos. T 12 bars (on each face of segment)
Thus for fcu = 50 N/mm^2 . Here Xu/d = 0.075 < 0.48 . Hence OK.
Here α = 0.031 , Thus Bending Moment Capacity of one Segment = 114.4 kNm > Design Moments. Hence O.K.

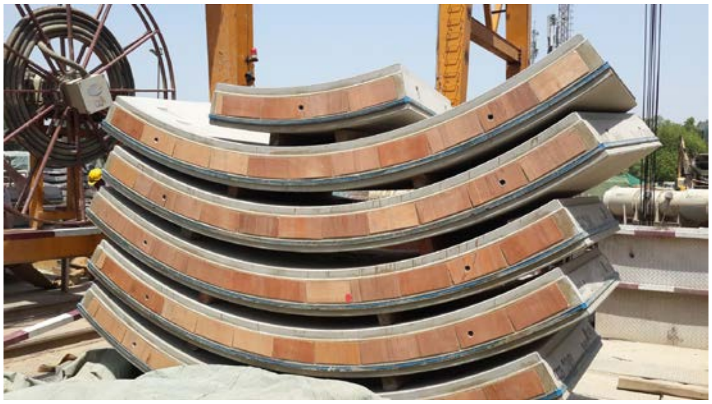
2.13 Longitudinal direction Reinforcement

The Bending Moment induced in the longitudinal direction due to the lifting of the Segment with the Grabs is :
BMo=6.9kNm , and considering load factor as 5
Factored Moment = 34.5 k Nm
Determine depth of neutral axis , Xu , using the Limit State formula, Xu/d = 0.87 fy Ast/0.36 fck. bd
Limiting value of Xu/d = 0.48
For Neutral Axis of the Balanced Section ,Mu= 0.87. fy Ast. d(1-α) where α = fy Ast/ fck. bd .
Considering M 50 grade of concrete & Fe 415 Tor steel,
Thus Ast = 804 mm^2.
Provide 16 nos. T 8 bars (on each face of segment)
Thus α= 0.001
Thus for f cu = 50 N/mm^2 . Here Xu/d = 0.022. Hence Max. Bending Moment Capacity = 105.7kNm
Hence sufficient moment capacity. O.K.

2.14 Shear Forces Calculations for Segments (Before Stacking of 6 segments)

Design Shear Strength of Section :
100As/bd= 0.4275 , for fcu = 50 N/mm^2 ,
Shear Stress, as per design table τ_c= 0.47 N/mm^2
Maximum Shear Stress calculations for Stack of 6 Segments
Max. unfactored Shear Force , V=24.4kN , Load factor =5
Thus Max. Factored Shear Force = 122kN.
Thus Shear Stress =0.34 N/mm^2 < 0.47 N/mm^2. Hence Safe. O.K. Sufficient Shear Capacity.
Maximum Shear in Stack of 6 Segments
Bottom Segment
Max. factored Shear Force , V= 273.8 kN . Thus Shear Stress = 0.76 N/mm^2
Considering Shear enhancement due to proximity of Support = 2d τ_c /av
Where, d=240 mm and average = 100mm. Thus Shear Stress τ_c (2 x240 /100) x 0.47= 2.256 N/mm^2
Shear Stress τ_c = 2.256 N/mm^2 and is > 0.76 N/mm^2 . Hence O.K. Sufficient Shear Capcity.

Photo below taken from DMRC site at Hauz Khas, New Delhi. Photo showing five Ordinary plus one Key Segment at top. (Courtesy DMRC)



3 Conclusion

This research paper thus has analysed the moments and shear forces in various combinations of tunnel lining segments so as to safely design machines used in handling hydraulic clamps & grabs for Tunnel Segments. Several projects require the optimal use of space available not only in the factory but also at the storage point. Tunnel lining segments are piled up, one over the other, and are to be lifted, turned & carried in several combinations of segments as per requirements. Thus moment and shear forces generated in each combination will vary and the handling machines are designed for the worst case, i.e. considering max. Moments/shear forces with a factor of safety of 3 to 5. In DMRC metro project at Delhi, number of segments used are five plus one key segment.
The authors have found it interesting the way tunnel lining segments are handled with the help of hydraulic machines and finally they are carted inside the tunnel with the help of a trailer attached to a locomotive during field visit to DMRC sites in New Delhi.

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