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Structural Engineering Aspects of Metro Rail Projects

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Abstract - *Rapid growth and growing population in Indian metropolises demand the effective means of the Mass Rapid Transport System (MRTS). The metro rail system becomes more effective and economical medium of MRTS in terms of passenger transport in the cities to reach the last mile. Various aspects of the metro rail system from the structural engineering point of view needs to be considered for the safe and cost-effective engineering solution. The work carried out on the various alternatives and their effect on the project cost shows that the elevated metro rail system results in the popular adopted configuration in India. At the same time the advantage of pre-stressed concrete elements in the superstructure to use the material in the most efficient manner helps to preserve the esthetic of the constructions. In case of the metro rail structures the loading is always in a uniform manner as compared to road structures/viaducts. To realize the structural behavior of the metro rail viaduct, typical design of the 24 m span of the viaduct with substructure and the purpose of the pre-tensioned I-Girder and cast-in-situ deck slab configuration has been taken out and demoed in this paper. It also shows the highlights of the pre-cast superstructure elements in the elevated viaduct considering the construction ease and safety.*

Key Words: Metro Rail, Superstructure, Viaduct, pre-stressed, I-Girders, Pre-tensioned

1. INTRODUCTION

Rapid growth and growing population in Indian metropolises demand the effective means of the Mass Rapid Transport System (MRTS). Many of the developed countries are having the proven MRTS system to cater the growing population and its transportation demands.

One of the oldest metro rail in the world is London Tube Rail which started its operation in 1890 whereas India got it its first metro in 1984, as Kolkata Metro. This 100-year gap seems very small as compared to the growth of the Indian metropolises.

Considering the economic growth as well as population growth of India, it becomes the need of the hour for India to adopt the world models of MRTS.

In India there are various means of the MRTS like sub-urban railways in Mumbai, Monorail system, Metro Rail System. The brief of metro projects in India is described below,

Table -1: Brief of Metro Projects in India

Sr. No.	Metro Project	Operational Length (in km)	Operational Year
1	Kolkata Metro	27.22	1984
2	Delhi Metro	343.36	2002
3	Bangalore Metro	42.30	2011
4	Chennai Metro	45.00	2015
5	Kochi Metro	18.40	2017
6	Lucknow Metro	23.70	2017
7	Mumbai Metro	11.40	2014
8	Nagpur Metro	13.50	2019

Above mentioned metro rail projects are just the some of the examples, lot of Tier-II cities are now getting their own metro projects.

Proposed metro rail project in Mumbai city is having last mile connectivity covering all the major suburbs and adjoining cities like Thane, Kalyan, Mira Bhayndar etc. The network plan of the proposed Mumbai metro rail projects is as below,

Fig -1: Mumbai Metro Rail Network

The type adopted for these metro projects adopted is either elevated metro viaduct or underground tunneling or the combination of both. The study of the various elements of the metro rail projects is discussed subsequently in the other sections of the paper. Also, the typical design of the superstructure of the metro rail viaduct with pretensions, I-Girder system comprising of the cast-in-situ slab is discussed.

1.1 Objective

The objective of this paper is,

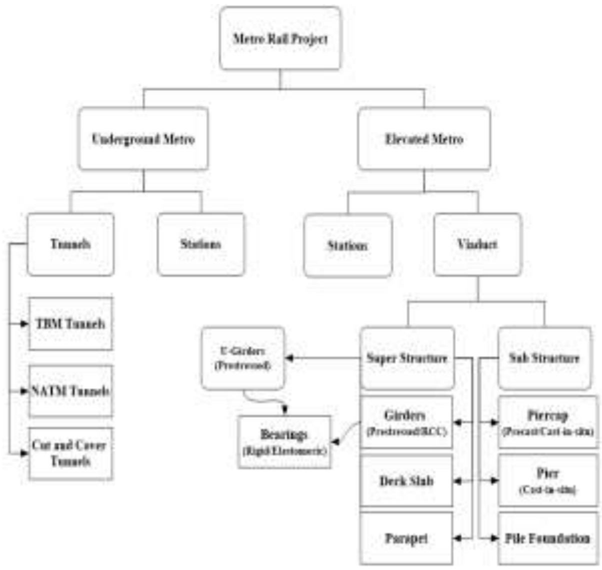
1. To study the aspects of the elevated metro rail system

2. To carry out the analysis of the typical 24 m span of the elevated metro viaduct subjected to the loading from the various elements of the metro system

3. To carry out the design of the 24 m span of the metro viaduct with pre-tensioned girders and cast-in-situ deck system.

1.2 Approach and Methodology

Major component of the elevated metro system are the elevated stations and elevated viaduct connecting these stations. In this paper the study of the metro rail system and specially viaduct has been carried out. The typical type/component of the metro rail projects are shown below.



For the design guidelines the parameters defined in the design basis report of the metro rail viaduct for the Mumbai metro rail project has been followed.

Initially the superstructure has been considered as pretensions, I-Girder with cast-in-situ deck slab. Analysis has been carried out in STAAD. Pro and then design has been done based on the design parameters specified.

2. ANALYSIS OF VIADUCT SUPERSTRUCTURE

The viaduct superstructure consisting of pretension I-girder system which supports the cast-in-situ slab and precast walkway. This entire superstructure is supported by RCC pier, founded on pile foundations. This analysis has been done for the typical span of 24 m. The span arrangement adopted for the viaduct is simply supported span. Analysis parameters are discussed below,

2.1 Basic Data

The superstructure configuration is for the typical span is taken as below,

- Span Length (c/c pier) = 24.0 m
- c/l of bearing from center of Pier = 0.3 m
- Overall Width of the Deck = 9.06 m
- Span Length (c/c of Bearing) = 23.4 m

2.2 Loading

Following are the loads considered during the analysis of the superstructure of the viaduct,

1) Dead Load

Dead load of various components of the superstructure are considered by adopting a standard unit weight based on the code provisions. This comprises of self-weight of the girders and deck slab. The section of the girders and deck slab is given in the analysis model to consider this in the analysis.

2) Superimposed Dead Load

As per the design guideline of the metro rail project the superimpose load shall not be taken less than 8.0 Ton/m. This load is for the various elements which are to be provided on the deck slab for the service purpose. Some of the elements which are taken into consideration are as below,

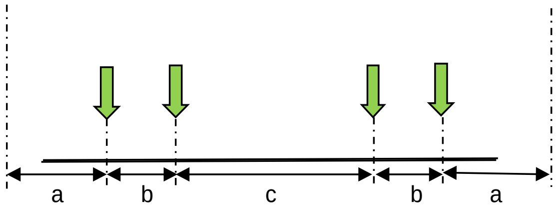
- Cables
- Cable Trays
- Handrail
- Parapet
- Miscellaneous (E&M)
- Rail + Pad
- Track Plinth

During the analysis the load is distributed as per provision of the above mentioned elements on the deck slab.

3) Live Load

The footpath Live load on the walkway portion is taken as 5 kN/m2. Generally, this load is not critical for any structural member except parapet

Vehicular Live load (i.e. Train Load)



Basic Train Data is taken as below,

- Type of Rolling Stock = Modern Rolling Stock
- Axel Load = 17 Ton
- Maximum no. of Cars = 8

This load is applied in the configuration as described below,

Axel load spacing

- a = 2.25 m
- b = 2.5 m
- c = 12.6 m

One car dimension = 2a + 2b +c = 4.5 +5+12.6 = 22.1 m

In this case the Coefficient of Dynamic Impact is taken as below,

- Longitudinal Direction = 1.2
- Transverse Direction = 1.67

2.3 Material Properties

The basic material properties used for the analysis and design of the structure are given in the below table,

Table -2: Material Properties

Parameters	Concrete	Reinforcement Steel (Rebars)	Prestressing Steel for Tendons
Elements	Prestressed I-Girder, Deck Slab and Walkway	Prestressed I-Girder, Deck Slab and Walkway	Prestressed I-Girder
Characteristic Strength	50 MPa	500 MPa	1860 MPa
Modulus of Elasticity	34000 MPa	200 GPa	195 GPa
Density	25 kN/m³ (for prestressed concrete) 24 kN/m³ (for reinforced concrete)	7850 kg/m³	7850 kg/m³
Poisson's ratio	0.15	0.3	0.3
Thermal Expansion Coefficient	1.17 X 10^{5} /°C	11.4 X 10^{5} /°C	11.4 X 10^{5} /°C
Jacking Stress	-	-	1395 MPa

2.4 Modelling

The superstructure is modelled as a grillage model in STAAD.Pro. The center to center spacing of the girder is 3.0 m. The deck slab thickness is considered as a 240 mm and corresponding properties are considered for modelling. The diaphragm is provided at the end of the span and these are in between girders only. The general arrangement of the structure is as shown below,

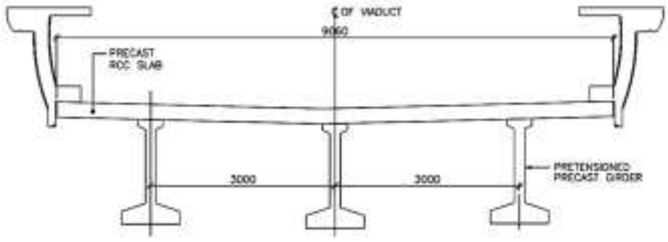


Fig -2: General Arrangement of Superstructure

Static analysis of the viaduct portion is carried out by considering the dead load and superimposed loads and live load. For static analysis under dead load, the dead load values are calculated from the basic section properties and material properties considered for modeling and this is assigned as a member load command in STAAD. For the girder, composite section properties at various locations are assigned by considering the volume of the deck and the density of the concrete. The structure is also analyzed for various live load cases (Train Load) e.g. single track loaded, both spans loaded. The analysis model i.e STAAD.Pro model is as shown below,

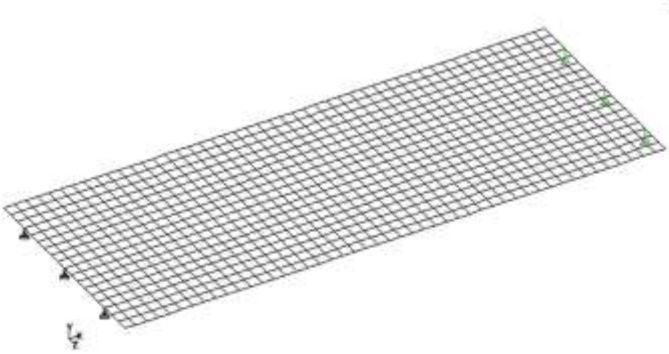


Fig -3: Grillage model of 3-Girder System

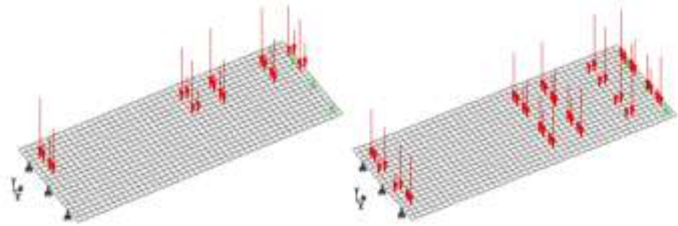


Fig -4: Train Load (STAAD.Pro model)

2.5 Analysis Results

Summary of the analysis carried out in the software program has been sorted out for the sections under consideration i.e. midspan of the I-Girder section. The summary of the results for the various load cases is as shown in the below table,

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Table -3: Summary of the Analysis at mid span

Load		End Girder		Mid Girder	
		SF in ton	**BM in t-m**	**SF in ton**	**BM in t-m**
DL	Girder	0	88	0	88
	Deck Slab	0	122	0	122
	Diaphragm	0	0	0	0
SIDL	Parapet + Track Plinth	0	181	0	158
Total Dead Load		0	210	0	210
Total SIDL		0	181	0	158
Live load (case 1)		12	127	6	93
Live load (case 2)		13	184	13	186
Maximum Vertical Load (With CDI)		16	221	16	223
DL+SIDL+LL		16	612	16	591

Graphical view of the bending moment in different load cases is as shown below,

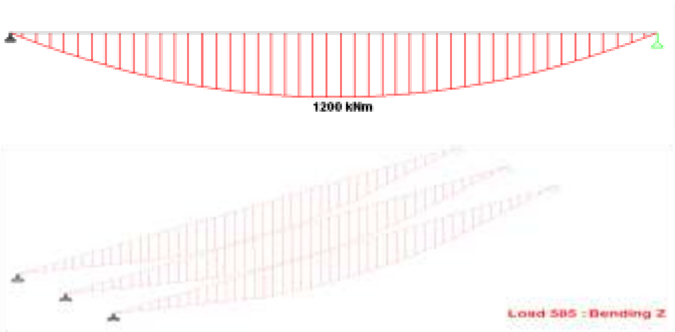

Fig -5: Typical Bending Moment of Girders

3. DESIGN OF VIADUCT SUPERSTRUCTURE

The design is carried out based on the guideline stipulated in the latest IRS and IRC standards. The design stress is to be kept within the limits as specified in the IR S Concrete Bridge Code and IRC codes. Permissible stress values considered while carrying out this design are as below,

1) *H. T. Strands*
   - Maximum Jack Pressure = 0.75UTS = 1395 MPa

2) *Concrete*
   - Compressive Stress = 25.0 MPa
   - Tensile Stress = 2.5 MPa
   - Tensile stress during Construction = 2.5 MPa
   - Compressive Stress during service = 16.7 MPa
   - Tensile stress during service = 0.0 MPa
   - Maximum Shear stress = 5.3 MPa

3) *Reinforcement*
   - Characteristic Strength = 500 MPa
   - Permissible Stress (Combined Flex.) = 240 MPa
   - Permissible Stress (Direct Comp.) = 205 MPa

Here the section is designed at the mid span section i.e. at 0.5L to check the stress level in the girder with respect to the reinforcement and concrete section properties considered in the analysis. Basic section properties and design of the girder is described below,

Girder Properties:			
Girder:			
Overall Depth	=	1.6500	m
Area	=	0.5203	m^2
Y top	=	1.0541	m
Y Bottom	=	0.5959	m
I Cg.	=	0.1531	m^4
Z top	=	0.1452	m^3
Z Bottom	=	0.2569	m^3

Eccentricity of Pretensioning strands :

Layer No.	*No. of strands*	*Ecc. From bott.*
1	15	77.6
2	15	142.6
3	7	207.6
4	0	272.6
Top	1	1572

Sr. No	Description	Section at distance (m) from center line of bearing
		0.5L
1	**Girder Properties**	
	Area	0.520
	I_g	0.153
	Y_{top}	1.054
	Y_{bottom}	0.596
	Z_{top}	0.145
	Z_{bottom}	0.257
2	**Composite Section Properties**	
	Area	1.240
	I_g	0.573
	Y_{top}	0.613
	Y_{bottom}	1.277
	$Z_{cie\ top}$	0.935
	Z_{top}	1.538
	Z_{bottom}	0.448

Summary of the stress calculation is as below,

Stresses Due to	Forces	Stresses (kN/sqm)	
		Girder Top	Girder Bottom
Pretensioning			
Force:	742.94	1427.87	1427.87
Moment:	318.98	-2196.68	1241.79
Resultant		**-768.81**	**2669.66**
Self Wt. Moment	88.00	606.02	-342.58
Resultant	--	**-162.79**	**2327.07**
Intial Losses in Strands			
Force:	44.90	-86.29	-86.29
Moment	19.28	132.75	-75.04
Resultant		**-116.33**	**2165.74**
Moment due to Slab	122.00	840.16	-474.95
Resultant		**723.83**	**1690.80**

Stress Due to	*Moment*	*Slab Top t/Sq.m*	*Slab Bottom t/Sq.m*	*Girder Top t/Sq.m*	*Girder Bottom t/Sq.m*
Differential Shrinkage	--	-14.72	-68.92	295.95	-76.72
Resultant		**-14.72**	**-68.92**	**1019.78**	**1614.08**
SIDL	217.20	232.23	141.24	141.24	-484.32
Resultant		**217.51**	**72.32**	**1161.02**	**1129.76**
Due to Final Losses	146.93	-118.46	-118.46	-118.46	-118.46
	63.08	67.45	41.02	41.02	-140.67
Live Load	223.00	238.43	145.01	145.01	-497.25
Resultant		**404.93**	**139.89**	**1228.59**	**373.38**
DS + DL + SiDL		**217.51**	**72.32**	**1161.02**	**1129.76**
DS + DL + SiDL + LL		**404.93**	**139.89**	**1228.59**	**373.38**

4. CONCLUSIONS

As discussed in this paper the among various types of the metro structures, the pre-cast superstructure elements in the elevated viaduct considering the construction ease and safety. As the precast elements give the feasibility in the construction avoiding the interference to the traffic and gives an easy hand to the civil engineer to control the quality of the work.

As the paper gives and basic analysis and design steps followed in the design of the pre-tensioned I girder and shows that the requirement of the prestressing steel is 28-30 kg/m3 with quick launching ability over the cast in situ post tensioned girders or box type girders.
There is the future scope of the value engineering in the design of the precast elements for the metro rail structures

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