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Analyses of Box Bridge and Comparison of Structural Behavior using 3D Finite Element and Typical 1D Line Models

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***Abstract:** In civil engineering practice, 1D modeling (also called line modeling) is often the most common method of modeling used for the analyses of structures. It is easy to create the model and saves time without loss of significant accuracy in the results. However, these line models are ideally not a true representation of the behavior of the structure as they are overly simplified versions. Though this simplification leads to quick modeling and reduces analyses-design cycle time, this over-simplification can lead to inaccuracies and over- design that can impact the economy of construction in repeat projects. Also, in the current era of precast modular construction, it would be prudent to analyze a structure as precisely as it can be so that optimal solution is achieved before designing as standard member that can be reused across an array of projects. In this study an effort is made to model a box bridge structure to analyze and compare the behavior of the bridge under railway vehicular train loading. A Road under Bridge (RUB) of 25m barrel length is considered and analysis is carried out by creating two models subjected to IRS vehicular rail axle loading using STAAD.PRO commercial software. A comparison of flexural forces in the culvert structure is made between results of 1D line model versus 3D box finite element model. It was found that flexure at the critical sections of the box based on line model analysis are much higher than those from 3D finite element analysis. In this particular example, a 14% excess of flexural reinforcement and a 40% excess shear reinforcement are required if we design the structure based on line model of analysis. Thus it is inferred that a design based on line model analysis can be overly conservative and uneconomical. It is suggested that detailed 3D finite element analysis be performed for the design of modular and reusable members especially for precast construction and engineering.*
***Keywords:** Finite element analysis, Finite element modeling, STAAD.PRO, Road under Bridge, Box culvert, Bridges*

I. INTRODUCTION

Modeling is the foremost step in the computerized structural analysis for any structure. Modeling refers to, generating the geometry of the structure in the analysis software and simulating similar loading environment and support conditions that the structure in real is expected to be subjected to. Proper modeling of the structure results in good analysis and yields accurate results. Poor modeling leads to erroneous results and may lead to unsafe design or, over conservative design which is not economical. Thus, modeling plays a key role in delivering cost optimized and safe designs especially in the field of civil engineering where the cost of mega projects like railway and road projects touch sky high.

Minor bridge is a bridge having a total length up to 60m [1]. Box bridge comes under minor bridges category. Box bridge is an integral structure consisting of a top slab, bottom slab and side walls of definite thickness with a vent in it to allow passage of vehicles (Underpass) or water (Box culvert). The box is rested on the level ground. Road under bridge is an under pass where trains will be passing on the top slab of the box and road is laid beneath the railway track. IRC:5 – 2015 specifies that box culverts are minor bridges whose span, i.e., distance between outer faces of side walls, is less than 6m. Road under bridges are being constructed to bridge even up to 10m span due to their robustness and ease of erection [2]. From mid 19th century, Structural analysis programs have been the most common tool for analyzing structures. Pertaining to box bridges, analysis can be performed in two ways. The first and the most commonly employed method is two dimensional (2-D) line modeling method. The second one is highly sophisticated method called finite element modeling method.

In 2-D line modeling method, the cross section of the box is modeled in a 2-D plane by joining the centre line of top slab, side walls and bottom slab. The width or the barrel length considered is 1m. Thus a 1m segment of barrel is considered for the analysis. Here, the 1m wide top slab, bottom slab and side walls are considered acting as beams. Loading is applied as uniformly distributed load (UDL) per unit width of the slab. Fig. 1 shows a typical line model and 1m width box segment from STAAD.PRO.

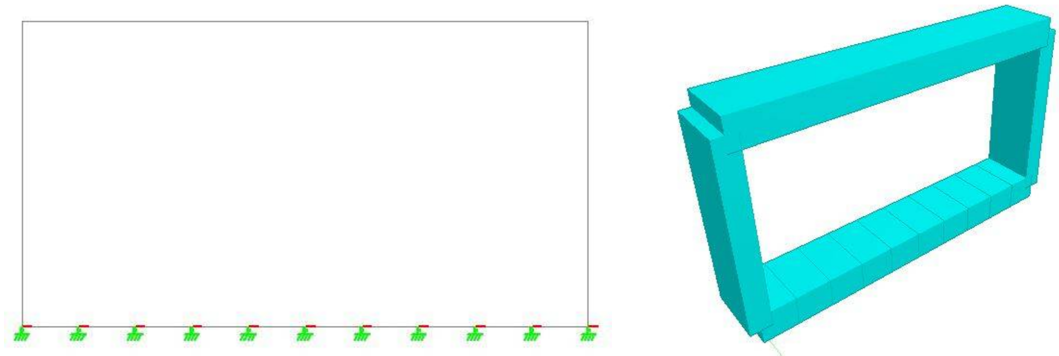

Fig. 1 Line model of the box structure

Invention of finite element analysis (FEA) dates back to early 1940's. The invention of finite element analysis has ignited the fuel and lead to rapid development in the mechanical, civil and material science industry. Finite element analysis is mathematically intensive. The basic principle involved in finite element analysis is finding the solution of a differential equation. Every physical phenomenon in this earth at least, has a governing differential equation associated with it. The solution of the differential equation is also a function of some variable. So, in brief to say, in FEA, a solution function for the differential equation is assumed and that solution function is taken as sum of weighted functions at finite number of variable points which is nothing but called as interpolation function. This division at finite variable points is equivalent to division into finite elements. Followed by that, the assumed solution is substituted in the differential equation back to satisfy the equation. Since, the solution is assumed one, the equation leaves some residual. Then from method of weighted residuals, the weighted functions are solved and final solution is obtained. Thus FEM is highly useful in solving any differential equation, explicitly analyzing any physical phenomena. FEM is even used in simulating fluid flow which is used in wind analysis of tall buildings, popularly known as computational fluid dynamics [3, 4].
In finite element modeling, the entire box structure is modeled in 3-D space and reflecting the exact geometry of the structure. The top slab, bottom slab and side walls are considered as plate elements. The plates are again discretized into smaller plates to capture the analysis results accurately. The loads are applied in the form of uniformly distributed load per unit area. Fig. 2 shows the finite element model of the box structure. Anil K. Garg and Ali Abolmaali conducted a parametric study to develop design equations from a three dimensional verified finite-element model of culverts [5].

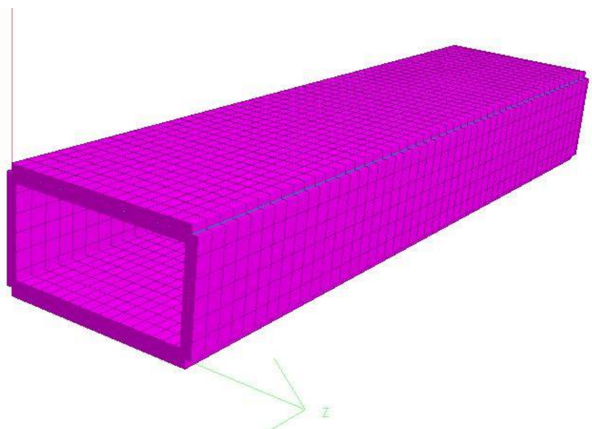

Fig. 2 Plate modeling of the box structure in STAAD.PRO

In the next section, details of a Road under Bridge (RUB) considered for structural analysis under railway loading are provided. Followed by that, structural analysis is carried out using 2-D line modeling method and then by FEM method. Later results and discussion follows and finally conclusions are presented.

II. DETAILS OF THE RUB CONSIDERED FOR ANALYSIS

An RUB is considered for analysis under railway loading. The clear vent height is 2.65m and width is 5.5m. The barrel length is 25m. The depth of top slab is taken as 500mm. Since, the vent clear height is less than the vent width, the depth of the side walls is limited to 350mm as that itself satisfies the ultimate limit state criteria of design. The cross section of the RUB is shown in Fig. 3.

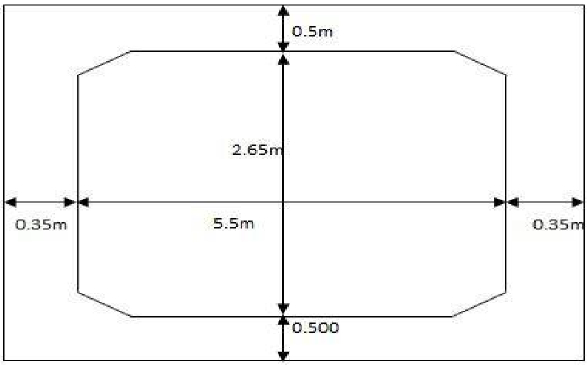

Fig. 3 Cross section of RUB

The earth cushion considered above the top of top slab is equal to 2.0m. The details of the box are given in Table 1 along with loading conditions. The unit weight of soil back fill is 20KN/m^3 and angle of internal friction is 30°. The soil parameters are shown in Table 2.

Table 1 Details of the Box

Clear width of the box	5.5m
Clear height of the box	2.65m
Barrel length	25m
Thickness of top slab	0.5m
Thickness of bottom slab	0.5m
Thickness of side walls	0.35m
Effective height of the box	3.15m
Effective width of the box	5.85m
Super imposed dead load on top slab	60KN/m^2
Super imposed dead load on bottom slab	3.75KN/m^2
Rail loading	25T axial load
Earth cushion	2m
Modulus of sub-grade reaction of soil	8000KN/m^3

Table 2 Soil parameters

Saturated unit weight of soil	20KN/m^3
Angle of internal friction	30°
Safe bearing capacity of soil (SBC)	200KN/m^2
Settlement at SBC	25mm

The loads to be considered are Dead load that includes self weight of the structure, Superimposed dead load on top slab that includes weight of rails, ballast, sleepers, etc, super imposed dead load on bottom slab due to wearing coat, earth pressure on walls, dead load surcharge, live load surcharge and live load due to train. The earth pressure, dead load surcharge and live load surcharge are calculated using the formulations mentioned in IRS substructure code [6]. The live load considered for the design is rail loading confirming to IRS Bridge rules [7]. A 25T axle train is considered and its axle configuration is shown in Fig. 4. The coefficient of dynamic augment is a function of depth of cushion and is worked out from IRS bridge rules.

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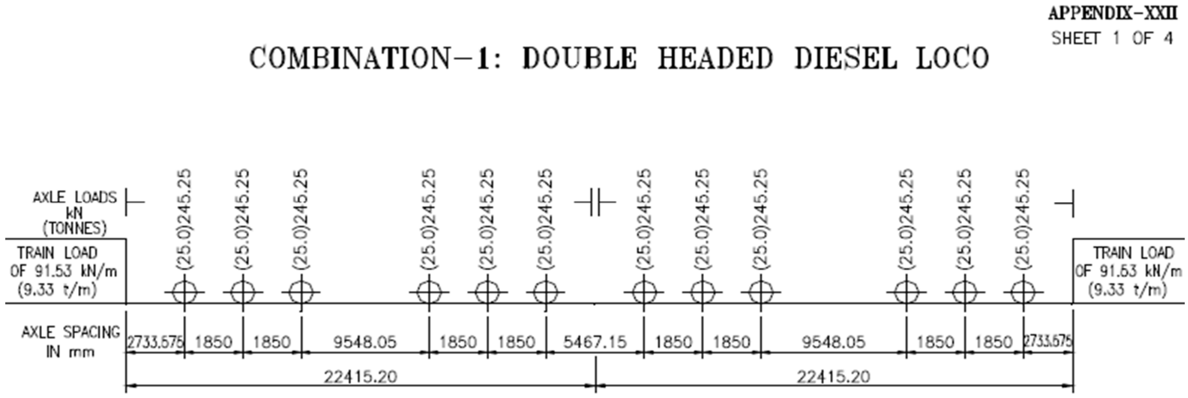

Fig. 4- 25T axle wheel configuration from IRS Bridge rules

As per IRS bridge rules, railway load gets dispersed at the top of ballast over the width of contact 2745 x 254 mm and the load under the sleeper shall be assumed to be dispersed by the fill including ballast at a slope not greater than half horizontal to one vertical. The box barrel is supposed to carry three rail tracks.

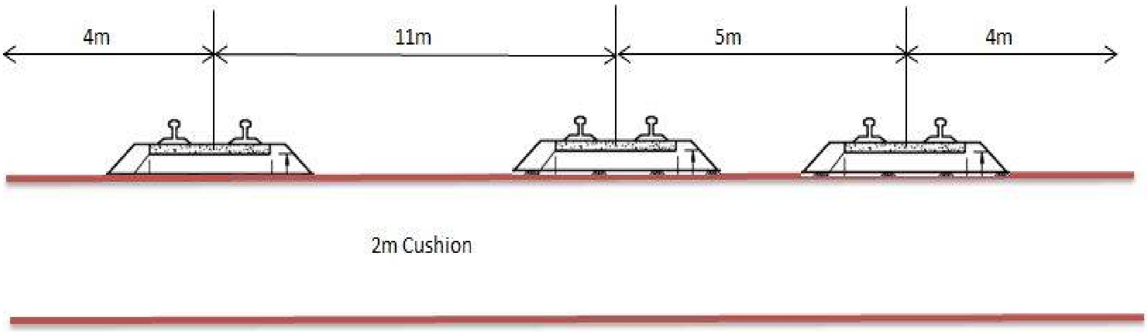

Fig. 5 General arrangement of rail track position

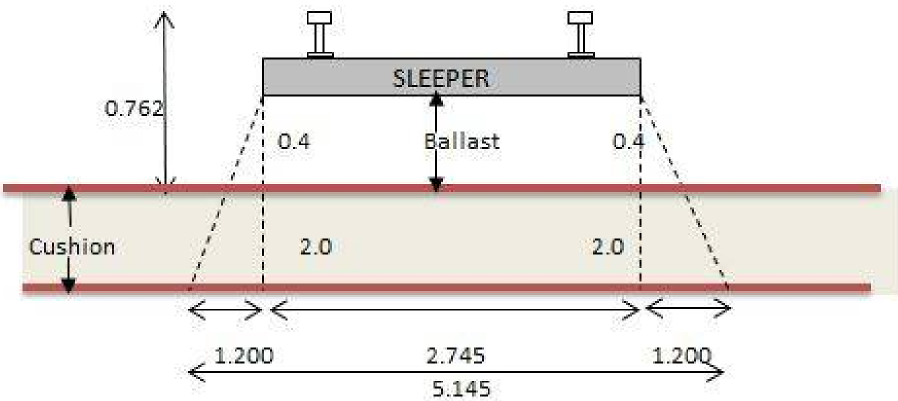

Fig. 6 Dispersion of axle load along the length of the barrel

The arrangement of tracks on the barrel is shown in Fig. 5 and Fig. 6 displays the dispersion of the load from sleepers.

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III. STRUCTURAL ANALYSIS USING 2-D LINE MODELING

The box structure is modeled in 2-D plane as line model in STAAD.PRO as shown in Fig. 7. The soil structure interaction is reflected in the model with elastic soil springs attached at the bottom of the base slab.

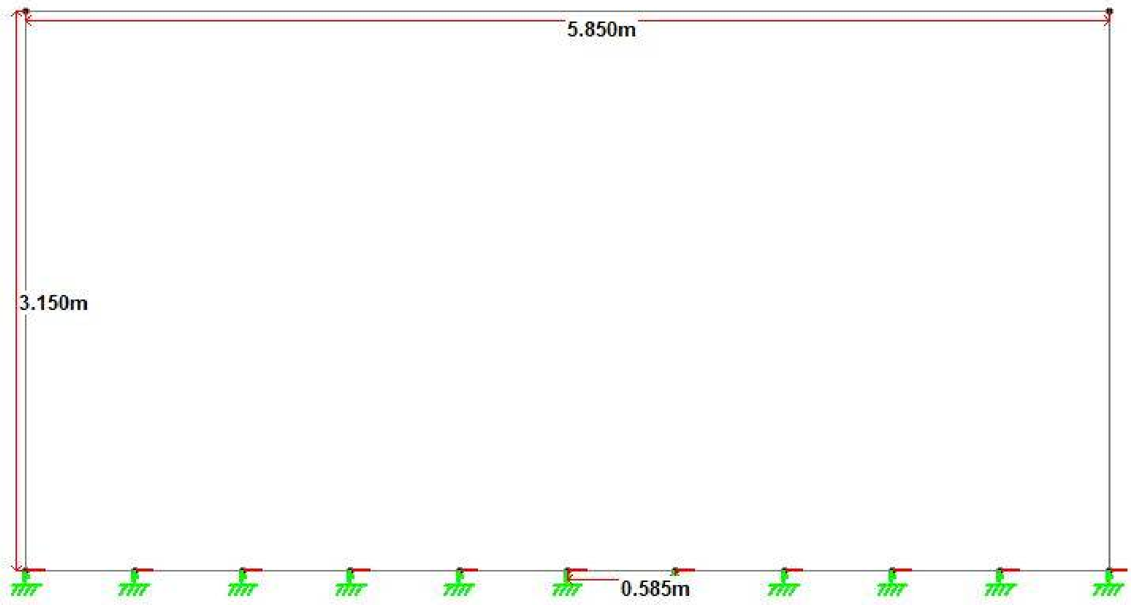

Fig. 7 Line model in STAAD.PRO

The springs are considered at spacing of 585mm. The corresponding stiffness of each spring is worked out from the given modulus of sub grade reaction. Thus, the supports are assigned. The structure is loaded with the above mentioned loads as shown in Fig. 8.

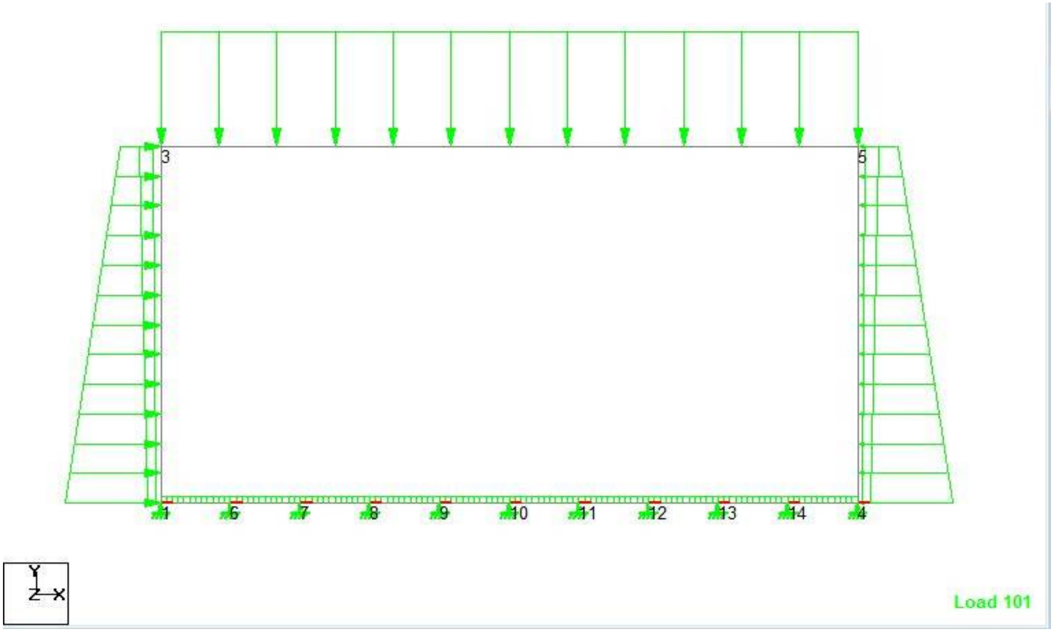

Fig. 8 Loads applied on the line model in STAAD.PRO

The live load is run on the top slab using moving load analysis in STAAD.PRO. The load combinations for ultimate limit state with partial safety factors are considered from IRS concrete bridge code [8]. Analysis is performed and results are obtained.

IV. STRUCTURAL ANALYSIS USING FEM METHOD

As mentioned earlier, the box is modeled in 3-D plane with top slab, side walls and bottom slab as discretized plate elements shown in Fig. 9. The smaller the plate size, the more accurate the results will be.

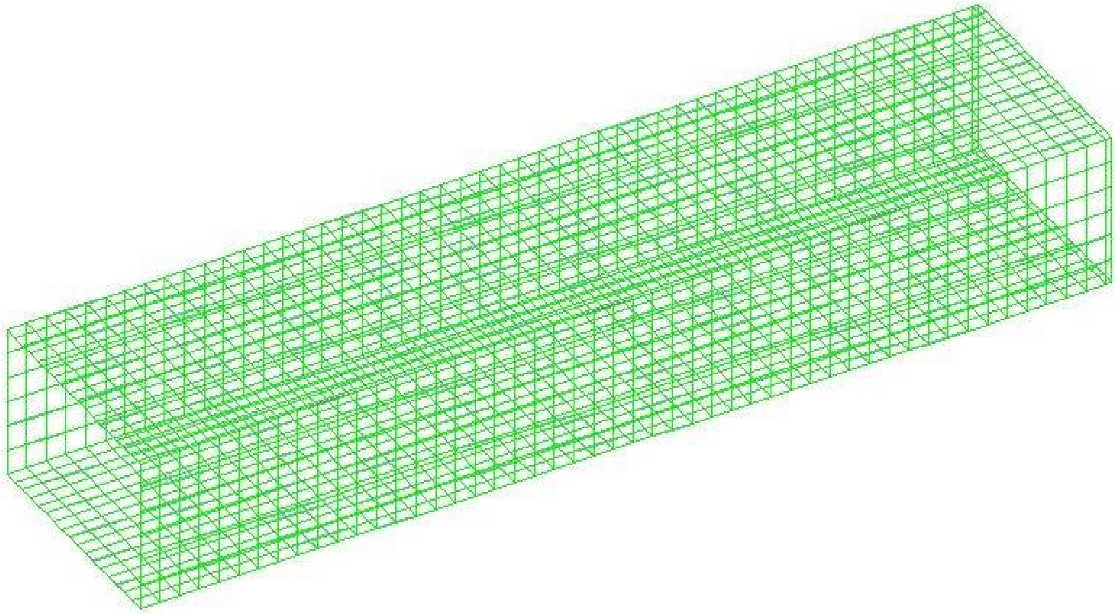

Fig. 9 Discretized finite plate element modeling in STAAD.PRO

The computational capacity limitation has constrained the author in limiting the plate element sizes. The following Fig. 10 and Fig. 11 shows the plate element sizes considered for computation. Meshing is done with quadrilateral elements of good aspect ratio.

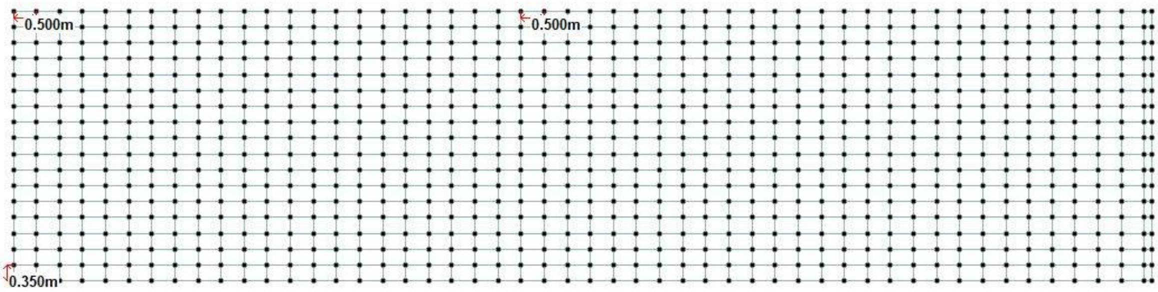

Fig. 10 Plate element sizes for the top slab and bottom slab

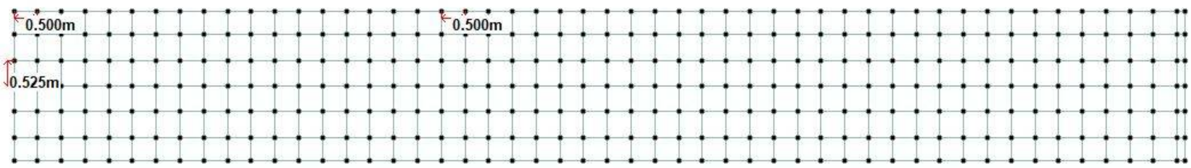

Fig. 11 Plate element sizes for the side walls

The analysis is carried out using moving load analysis for the live load and results are obtained.

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V. RESULTS AND DISCUSSION

With about 113 load combinations generated, the analysis results of both the methods are obtained from post processing in STAAD.PRO. The bending moments for ultimate limit state are obtained at critical sections of the box for the design. Fig. 12 displays the critical sections in the box, considered for design.

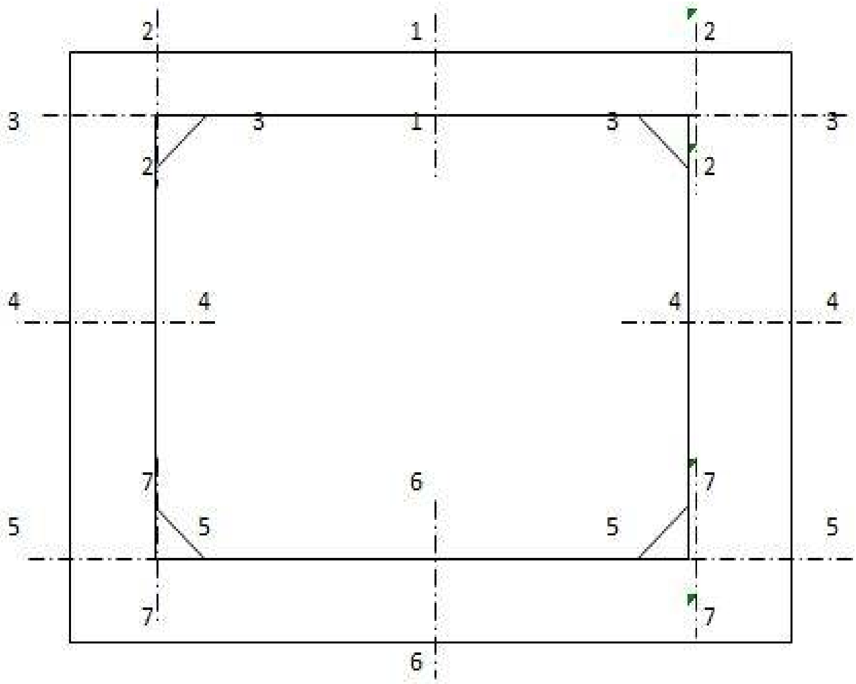

Fig. 12 Typical cross-section of box showing critical sections for design

The bending moments at those corresponding critical sections are obtained from both the analysis methods. Fig. 13 shows the bending moment profile for one of the load cases generated, from line model method.

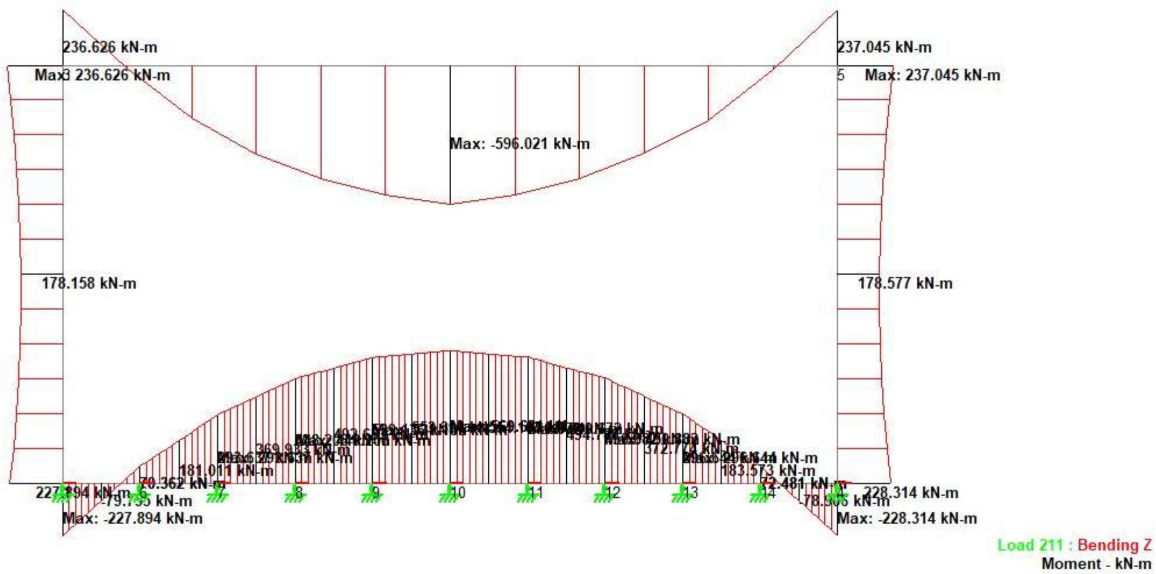

Fig. 13 Bending moment profile for one of the load combinations (Line Model Method)

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In case of FEM analysis, STAAD.PRO generates bending moment contours for all the load combinations. Maximum bending moment of all the combinations can be obtained from STAAD.PRO results tab. Fig. 14 shows the bending moment contours for one of the load combinations. The bending moment values can be

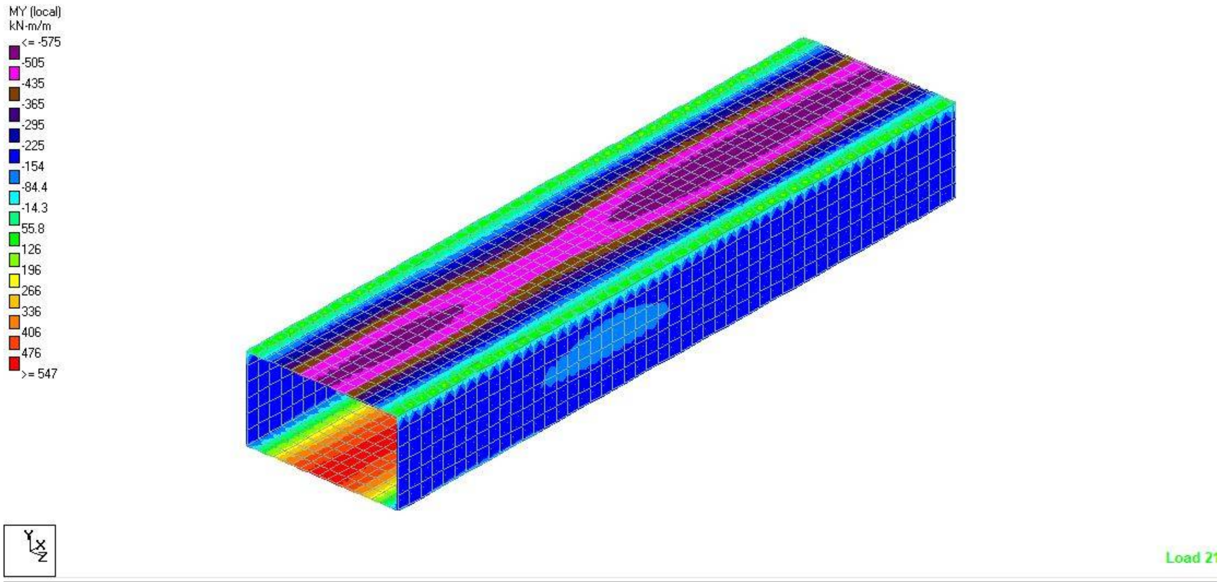

Fig. 14 Bending moment contours from FEM

obtained from those contours by selecting plates at any cross section. Here, cross sections at the extreme edge of the barrel and at the middle of the barrel are considered and bending moments at every plate of that section are obtained and those values are plotted in Fig. 15 and Fig. 16. It is observed that unlike in case of bending moment profile from Line Model Method (LMM), the sum of moments at slab-wall joint is not equal to zero. It clearly says that, in case of 3D modeling, the moments get distributed in all the three directions of the barrel. Thus, reducing the design moments at critical sections. This is taken advantage of in developing economic structural designs.

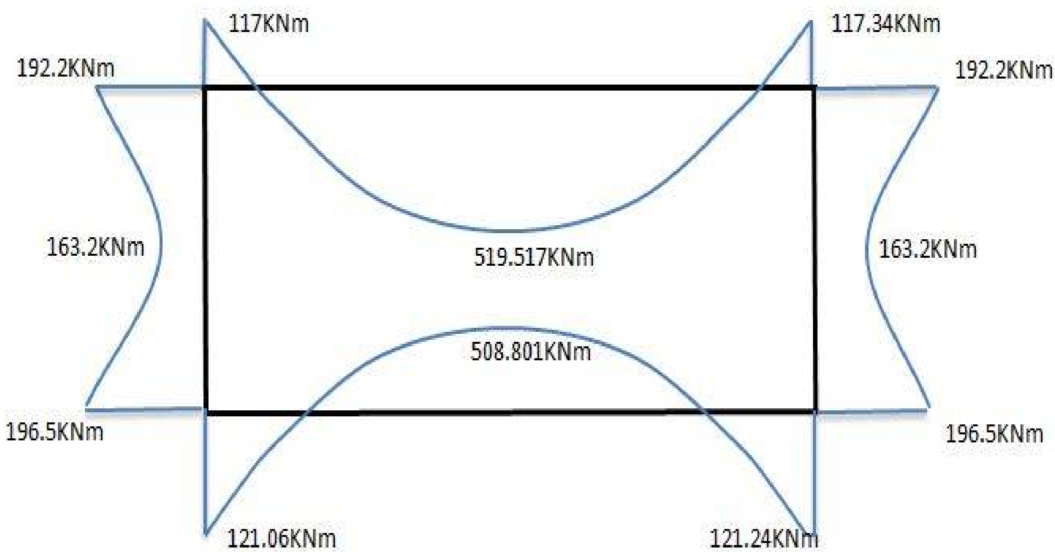

Fig. 15 Bending moment profile at edge section of the barrel

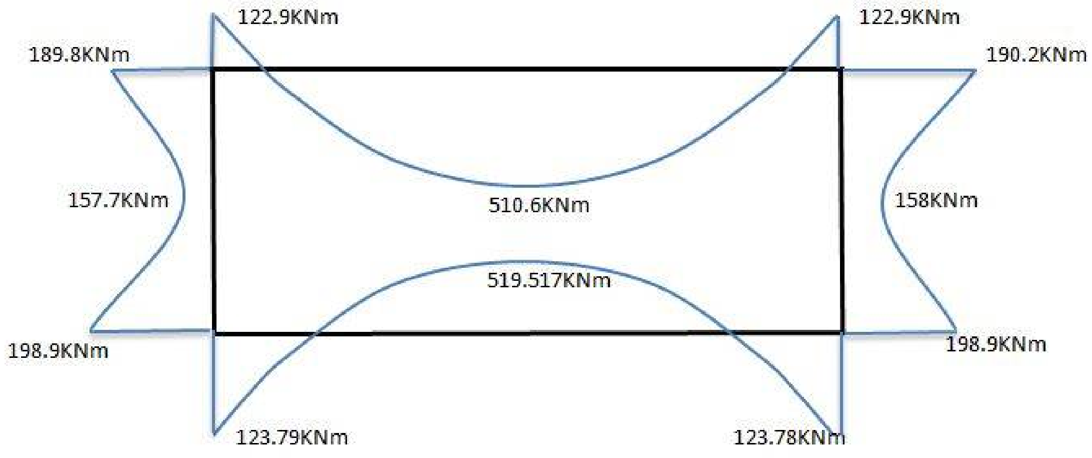

Fig. 16 Bending moment profile at middle section of the barrel

After getting the analysis results and noting down the maximum bending moments at every critical section, structural design is carried out as per IRS Concrete bridge code. The design input data is shown in Table 3.

Table 3 Input design data

Characteristic strength of concrete	35N/mm^2
Characteristic strength of steel	500N/mm^2
Clear cover to any reinforcement (soil face)	50mm
Clear cover to any reinforcement (inner face)	40mm

The maximum of bending moments, shear forces and corresponding required area of tension steel for ultimate limit state of moment resistance from both the FEM and LMM are tabulated in Table 4.

Table 4 Comparison of bending moments, shear forces and tensile steel requirement in LMM & FEM at critical sections

Section		Critical Bending moment (KNm)	Critical Shear force(KN)	$A_{st,req}$ (mm^2) per meter width of slab
1-1	LMM	596.02	-	3688
	FEM	575.86	-	3564
2-2	LMM	260.45	527.6	1565
	FEM	172.44	486	1036
3-3	LMM	260.23	135	2486
	FEM	228.08	82.6	2179
4-4	LMM	178.15	-	1633
	FEM	173.66	-	1597
5-5	LMM	254.25	168.23	2429
	FEM	246.34	98.35	2353
6-6	LMM	569.63	-	3478
	FEM	546.78	-	3341
7-7	LMM	254.25	554.54	1528
	FEM	190.66	549	1146

The above table clearly shows that, the maximum bending moments from line modeling method, at all the critical sections, are greater to those from finite element method.

There is a maximum increase of around 88KNm moment for LMM over FEM at section 2-2. At the joint between the sections, 2-2 and 3-3, the moments obtained by FEM are not equal where as moments obtained from LMM are equal. It is due to the fact that in LMM, the model is considered two dimensional and the moment distribution along the other direction doesn't take place. Where as in FEM moment distribution takes place in three directions as discussed previously. Obviously, corresponding area of tensile steel required for ultimate limit state of moment resistance per meter width of the slab is also higher for LMM over FEM. At section 5-5, the critical shear force from LMM exceeded the shear force from FEM by 70KN which is huge. Thus, shear reinforcement can also be reduced a lot by employing FEM. At section 3-3, there is difference of around 300mm^2 of tensile steel area per meter width of the slab which clearly states that, the design using line modeling method is uneconomical and over conservative. Moreover, FEM also gives more realistic insight into the actual structural behavior of the box bridge.

VI. CONCLUSIONS

In this paper, a Road under Bridge is considered and analyzed for 25T axle Indian Railway Specifications based rail loading in STAAD.PRO using 2-D line model method and finite element method. It is observed that, in this particular example, a 14% excess of flexural reinforcement and a 40% excess shear reinforcement are required if we simplify the structural analysis using 1D line model instead of developing a comprehensive 3D finite element model for the RUB culvert. The increasing cost of construction materials demands for economic structural designs [9,10]. Hence replacing finite element methods over conventional analysis methods can produce quite a considerable cost saving designs. For modular construction projects and in precast construction, it is imperative to achieve even slightest efficiency in form or design [11, 12] because these modules and designs are reused over multiple projects, so very small savings per member could still be large savings when implemented over multiple projects. A constant and continous improvement in efficiency of engineering and construction methods are of paramount significance in achieving goals of sustainable engineering and construction as recommended by Jonnalagadda et al [13] in his doctoral thesis. The models in this study did not include the haunch at the corners of these box culvert units. The haunch provides more rigidity at the wall-slab joint and hence more rotational restraint, so it would be interesting to study its effect on the design economy of these structures. This study can be extended further to include the effect of haunches on the behavior of minor box bridges and their design economy and efficiency.

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