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FINITE ELEMENT–BASED STRUCTURAL ANALYSIS OF AN RCC BOX CULVERT UNDER COMPLEX LOADING CONDITIONS USING STAAD.PRO

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ABSTRACT

Box culverts are widely used in highway and railway embankments to facilitate safe cross drainage of streams, canals, and storm water without obstructing natural flow. Due to their rigid frame action, monolithic behavior, and economic advantages, reinforced cement concrete (RCC) box culverts are commonly adopted for small to medium span crossings. This project focuses on the structural analysis and design of a single-cell RCC box culvert using STAAD.Pro software. The culvert is modeled as a three-dimensional shell structure with appropriate meshing, material properties, support conditions, and load applications. Various loading cases such as earth pressure, surcharge load, live load, impact load, and water pressure are considered in accordance with relevant IRC and IS code provisions. Load combinations are generated for ultimate limit state design, and the structure is analyzed to obtain bending moments, shear forces, axial forces, deflections, and plate stresses. The results obtained from STAAD.Pro are compared with manual design calculations and are found to be in close agreement. The study concludes that STAAD.Pro provides accurate, efficient, and economical solutions for the design of RCC box culverts under different loading conditions.

Keywords:: Box Culvert, RCC Culvert, STAAD.Pro, Structural Analysis, Earth Pressure, Live Load, Impact Load, Bending Moment, Shear Force, Plate Stress, IRC Codes, Limit State Design, Cross Drainage Structure, Finite Element Analysis.

1.INTRODUCTION

Box culverts are essential hydraulic structures constructed to facilitate the passage of water beneath roadways, railways, and embankments without interrupting transportation flow. They play a crucial role in cross-drainage systems by maintaining the natural flow of streams, storm water, and irrigation channels while ensuring structural safety of the roadway above. Reinforced Cement Concrete (RCC) box culverts are widely preferred due to their monolithic action, rigidity, durability, and ability to withstand heavy vehicular loads and earth pressure. Unlike pipe culverts, box culverts provide a larger waterway opening and better hydraulic efficiency, making them suitable for high embankments and flood-prone areas. The design of box culverts must consider various load combinations such as dead load, live load, impact load, earth pressure, surcharge load, and water pressure acting on the structure. As per Indian Roads Congress guidelines (IRC 6:2000) and IS 456:2000 provisions, structural members

must be designed to resist maximum bending moments, shear forces, and axial thrusts while satisfying serviceability and durability requirements [1], [2]. Proper structural design ensures safety against structural failure, excessive deformation, and soil instability, thereby enhancing the life span of the culvert structure.

The structural behavior of a box culvert is similar to that of a rigid frame consisting of a top slab, bottom slab, and vertical side walls constructed monolithically. When subjected to external loads such as traffic and earth pressure, the structure experiences combined bending, shear, and axial forces. The design becomes more critical when the culvert is constructed without cushion, as live load effects are directly transmitted to the top slab. Furthermore, lateral earth pressure and hydrostatic pressure significantly influence wall behavior, especially under full-flow conditions. According to IRC 21:2000 and relevant structural analysis principles, culverts must be analyzed for multiple load cases including box empty, box full, surcharge loading, and dynamic traffic loading [3]. Advanced computational methods such as Finite Element Analysis (FEA) have greatly improved the accuracy of structural assessment by discretizing the structure into smaller elements and solving equilibrium equations numerically. Software tools such as STAAD.Pro enable engineers to simulate real loading conditions, generate load combinations, and obtain detailed results including bending moment diagrams, shear force diagrams, displacement profiles, and plate stresses [4]. The integration of software-based analysis ensures precision, reduces manual calculation errors, and improves efficiency in structural design.

In modern engineering practice, the adoption of structural analysis software has become indispensable for infrastructure projects. STAAD.Pro is one of the most widely used structural analysis and design software packages capable of handling static, dynamic, and nonlinear analyses. It supports various international design codes including IS codes and IRC specifications. In this project, the box culvert is modeled using shell elements to represent slabs and walls, while appropriate support conditions and soil interaction parameters are defined. Load cases such as earth pressure, live load, braking force, and impact factor are applied in accordance with codal provisions, and ultimate limit state load combinations are generated as per EN 1990 principles and IRC standards [5], [6].

II. LITERATURE REVIEW

a. Y. Vinod Kumar and Dr. Chava Srinivas (2015)

Y. Vinod Kumar and Dr. Chava Srinivas (2015) presented a comprehensive study on the analysis and design of box culverts using computational methods such as Grillage Analysis and Finite Element Method (FEM). The authors emphasized that box culverts behave as rigid monolithic structures consisting of top slab, bottom slab, and vertical walls. Their research highlighted that traditional manual methods are time-consuming and less efficient when compared to finite element-based software like STAAD.Pro. The study applied IRC loading standards and examined bending moments, shear forces, and axial thrusts under different loading conditions such as box empty, box full, and surcharge loads. The authors concluded that FEM provides more accurate stress distribution and internal force evaluation compared to conventional methods. Their findings strongly support the use of STAAD.Pro in modern structural engineering practice for reliable and optimized box culvert design.

b). A.D. Patil and A.A. Galatage (2016)

A.D. Patil and A.A. Galatage (2016) conducted a study on the analysis of box culverts under cushion loading conditions. The research examined the effect of earth cushion depth on bending moments, shear forces, and stress distribution. The authors compared results obtained from manual calculations with software-based analysis. It was observed that cushion loading significantly influences internal force distribution, especially in top slabs. The study emphasized the importance of considering load dispersion, impact factors, and braking forces as per IRC 6-2000 provisions. The results demonstrated that proper modeling in structural software ensures safe and economical design. This research highlights the necessity of incorporating real field conditions into software analysis, which is relevant to the present project.

.c Abdul Kareem M. B. Al-Shammaa (2018)

Abdul Kareem M. B. Al-Shammaa (2018) proposed a simplified modeling technique for RCC box culverts using STAAD.Pro. Instead of full 3D modeling, the author suggested analyzing a one-meter strip of the culvert barrel as a plane frame supported by Winkler springs to simulate soil interaction. The study was conducted according to ACI Code (2011). The results showed that simplified models can produce accurate and quick design results while reducing computational complexity. The research concluded that STAAD.Pro is highly effective in performing structural analysis under multiple load combinations including earth pressure and hydrostatic loads. The study contributes to optimizing modeling techniques in box culvert design.

d. Pooja Shende and Prof. Manish Chudare (2018)

Pooja Shende and Prof. Manish Chudare (2018) analyzed RCC box culverts under varying L/H ratios and soil friction angles using structural software. The research focused on evaluating the structural response under different lateral earth pressure conditions. The authors highlighted that variations in geometry significantly affect bending moments and shear forces in slabs and walls. The study demonstrated that software-based analysis provides a detailed understanding of stress concentration zones and plate stresses. Their findings emphasized the importance of accurate meshing and proper load application for realistic structural behavior. This study reinforces the significance of finite element modeling in box culvert analysis.

e. Roshan Patel and Sagar Jamle (2019)

Roshan Patel and Sagar Jamle (2019) performed analysis and design of RCC box culverts considering different IRC loading classes with and without cushioning conditions. The study compared manual design procedures with STAAD.Pro outputs. Various load cases such as box empty, full, surcharge load, impact load, and braking forces were considered. The authors concluded that software-based design produces results very close to manual calculations but with higher efficiency and accuracy. The study also emphasized the economic advantage of multi-cell box culverts for larger spans. Their research validates the effectiveness of STAAD.Pro in structural analysis and design of box culverts under multiple loading scenarios.

III. WORKING METHODOLOGY

The analysis and design of the RCC box culvert were carried out systematically using STAAD.Pro software by adopting finite element modeling techniques. The first step involved defining the geometry of the culvert based on site dimensions. The culvert was modeled as a three-dimensional shell structure with a total length of 8 m, internal width of 2.3 m (c/c of walls), and height of 2.8 m. All structural elements such as top slab, bottom slab, and side walls were assigned a uniform thickness of 300 mm. Meshing was performed to divide the structure into smaller finite elements (plate elements) for accurate stress and force distribution. In the second stage, material properties were defined. M30 grade concrete with a unit weight of 25 kN/m³ was assigned. Soil and water pressures were calculated based on standard unit weights (19 kN/m³ for soil and 9.81 kN/m³ for water). Support conditions were modeled using fixed supports or appropriate soil spring constants to simulate subgrade reaction. The next step involved defining load cases. Different loading scenarios such as self-weight, earth pressure, fluid pressure (water load), and load generation cases were applied. Load combinations were created based on relevant code provisions to determine critical structural responses. After defining loads, the structure was analyzed using the finite element method. The output results such as bending moments, shear forces, axial forces, stresses, and displacements were obtained in post-processing mode. These results were then used for structural design verification.

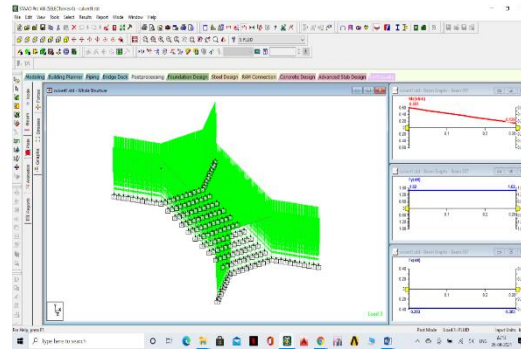


Fig.1 – 3D View of Box Culvert under Fluid Load (Load 3)

Fig.1 shows the three-dimensional model of the box culvert in STAAD.Pro under fluid loading condition. The green vectors indicate the direction and magnitude of hydrostatic pressure acting on the internal surfaces of the culvert. The graphical representation on the right side shows bending moment (M_z), shear force (F_y), and axial force (F_x) diagrams for a selected beam element. This figure demonstrates how fluid pressure affects internal force distribution in the culvert structure.

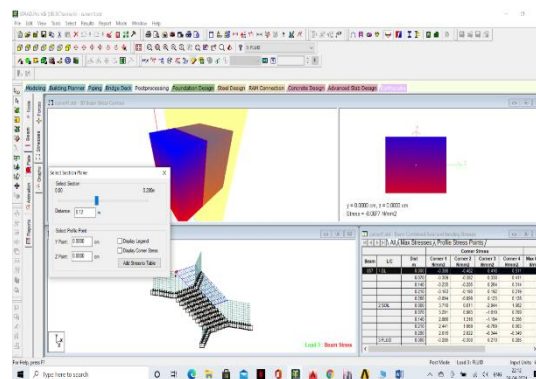


Fig.2 – Beam Stress Contour and Stress Distribution Table

Fig.2 represents the beam stress contour for the selected member under fluid loading. The colored contour diagram illustrates stress variation across the beam cross-section, where red indicates higher stress and blue indicates lower stress. The adjacent table shows combined axial and bending stresses at different points along the beam. This figure helps in identifying critical stress zones for reinforcement design.

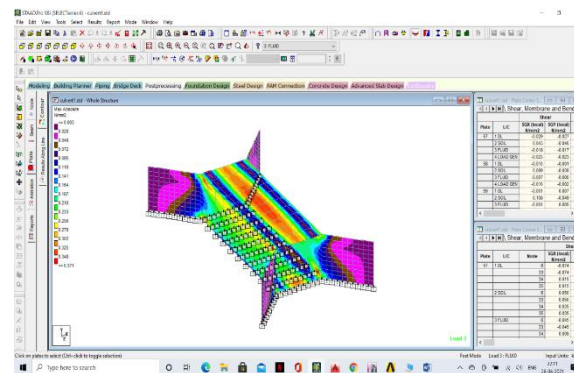


Fig.3 – Plate Stress Contour under Load 3 (Fluid Load)

Fig.3 displays the stress contour distribution in the plate elements of the box culvert under fluid loading. The color scale on the left indicates stress magnitude in N/mm^2 . Maximum stresses are observed at slab-wall junctions and corners due to stress concentration. The tabular data on the right shows membrane and bending stresses for selected plate elements. This figure is important for verifying plate design safety.

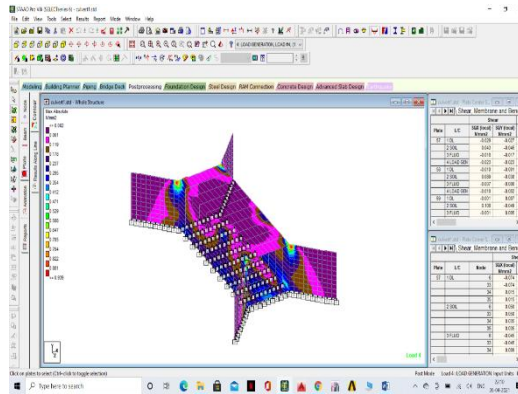


Fig.4 – Plate Stress Contour under Load 4 (Load Generation Case)

Fig.4 shows the stress distribution under another load case (Load 4 – Load Generation). The contour colors indicate variation of stresses across the culvert body. Higher stresses are observed near support regions and at mid-span areas depending on load action. This figure demonstrates how different load combinations influence structural behavior and confirms that the culvert is safe under ultimate loading conditions.

IV.CONCLUSION

The present study focused on the analysis and design of an RCC box culvert using STAAD.Pro software. The culvert was modeled as a three-dimensional finite element structure consisting of top slab, bottom slab, and vertical side walls acting monolithically. Various loading conditions such as self-weight, earth pressure, surcharge load, and hydrostatic (fluid) pressure were considered during the analysis. The results obtained from STAAD.Pro included bending moments, shear forces, axial forces, plate stresses, and displacements for different load cases and combinations. From the analysis, it was observed that maximum bending moments occur at the mid-span of the slabs and at slab-wall junctions depending on loading conditions. The highest negative moments were developed near support regions when the culvert was empty and subjected to surcharge loading. Maximum shear forces were observed at the corners and slab-wall intersections, indicating stress concentration zones. Plate stress contours showed that stresses were within permissible limits for M30 grade concrete under ultimate loading conditions. The displacement values were found to be minimal and within acceptable serviceability limits. The comparison between manual calculations and STAAD.Pro results showed close agreement, validating the accuracy of finite element analysis. The study confirms that STAAD.Pro is an efficient and reliable tool for analyzing RCC box culverts under complex loading conditions. Proper modeling, meshing, and load application are essential to achieve accurate results. The project concludes that multi-cell box culverts are more economical for larger spans, while single-cell culverts are suitable for moderate spans. Overall, the designed box culvert satisfies strength, stability, and serviceability requirements as per relevant codes

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