DEPARTMENT OF CIVIL ENGINEERING

Synthesis Project

Development and Study of the Zaghouan Interchange – Tunis–Jelma Highway

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Acknowledgements

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Abstract

This project presents the design and analysis of the Zaghouan interchange. The layout and detailed design were created using AutoCAD, while the bridge behavior was analyzed with SAP2000 to assess structural performance under various loads. The road study, including lane number determination, was carried out using Excel. The overall modeling and analysis of the interchange were performed with ALIZE. This project integrates design, structural analysis, and traffic considerations to ensure safety, functionality, and efficiency.

Keywords: Interchange design, Bridge analysis, AutoCAD, SAP2000, Traffic study

Résumé

Ce projet présente la conception et l'analyse de l'échangeur de Zaghouan. La mise en plan et la conception détaillée ont été réalisées avec AutoCAD, tandis que le comportement du pont a été analysé à l'aide de SAP2000 pour évaluer ses performances structurelles sous différentes charges. L'étude de la route, incluant la détermination du nombre de voies, a été réalisée avec Excel. La modélisation et l'analyse globale de l'échangeur ont été effectuées avec ALIZE. Ce projet intègre la conception, l'analyse structurelle et les considérations de trafic afin d'assurer sécurité, fonctionnalité et efficacité.

Mots-clés : Conception d'échangeur, Analyse de pont, AutoCAD, SAP2000, Étude de trafic

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General introduction

Transportation infrastructure plays a vital role in the development of any region by facilitating mobility, reducing travel time, and improving safety. Among these infrastructures, road interchanges are essential for ensuring smooth traffic flow at the intersections of major roads, highways, or urban networks.

This synthesis project is part of the study of a section of the Tunis-Jelma highway, with the aim of designing the Zaghouan interchange (C133). The main objective is to ensure smooth and safe traffic flow while respecting the geometric, environmental, and economic constraints of the site.

The Zaghouan interchange project aims to design a functional and safe structure that meets both traffic and structural requirements. This project involves several stages, including the conceptual design using AutoCAD, structural analysis of the bridge with SAP2000, traffic study and determination of the number of lanes using Excel, and overall modeling and evaluation with ALIZE.

The main objective of this work is to integrate engineering design, structural assessment, and traffic considerations to propose an efficient and safe interchange that can serve the growing transportation needs of the region.

Chapter 1: Design of the Zaghouan Interchange

1.1. Introduction

The design of an interchange requires careful planning to ensure safety, efficiency, and smooth traffic flow. This section introduces the main principles and objectives of the Zaghouan interchange design, including the arrangement of main roads, ramps, and bridge structures. The design process takes into account traffic demands, geometric constraints, and structural requirements.

1.2. Project Presentation

The project, titled "Planning and Study of the Zaghouan Interchange – Tunis–Jelma Highway," is part of a national initiative to enhance Tunisia's road infrastructure and regional connectivity.

It focuses on designing the Zaghouan Interchange, which will connect the city of Zaghouan and its surroundings to the Tunis–Jelma Highway, a key north–south transport axis. (see figure 1)
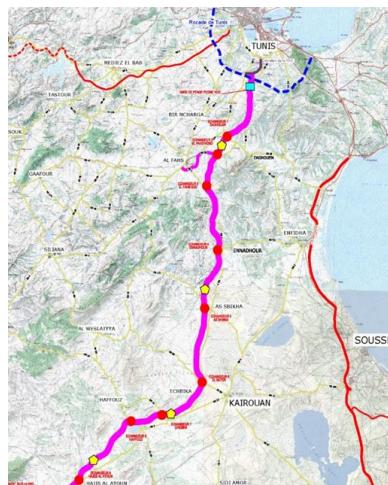
Figure 1 :Presentation of the Tunis–Jelma Segment

This section covers a total length of **188 km**, divided as follows:

- **Tunis – Fahs:** 32 km
- **Fahs – Kairouan:** 83 km
- **Kairouan – Jelma:** 72 km

1.3. Traffic Study and Lane Layout of the Interchange

A detailed traffic study is essential to determine the appropriate number of lanes and the level of service for each road within the Zaghouan interchange. This study involves analyzing traffic volumes, peak hour flows, and vehicle types to ensure that the interchange can accommodate current and future demand efficiently.

Excel was used to calculate and organize traffic data, determine the number of lanes required for each road and ramp, and assess the level of service according to standard traffic engineering criteria. The results of this analysis guide the geometric design, lane distribution, and overall layout of the interchange, ensuring safety, smooth traffic flow, and compliance with relevant regulations.

1.3.1. Traffic Projection

Traffic projection is essential to properly determine the number of lanes for the interchange. For the Zaghouan interchange project, the service start year is 2028, and the infrastructure is expected to have a lifespan of 20 years (until 2048).

Future traffic was estimated using the following formula:

$$Tn=Tm\times(1+\tau)^{n-m}$$

- Tn : projected traffic for year n

- Tm : base traffic in year m

- τ : annual traffic growth rate (here 2 %)

- n −m : number of years between the base year and the projected year

Calculations were performed using Excel, allowing the estimation of projected traffic between 2028 and 2048 and different sections of the interchange. This projection is then used to determine the required number of lanes for each section, preventing future congestion and ensuring safety and smooth traffic flow.

1.3.2. Traffic Projection Data :

- **Annual growth rate (i):** 2%
- **Year of commissioning:** 2028
- **Design life:** 20 years

Calculations were performed using Excel, allowing the estimation of projected traffic between 2028 and 2048 and different sections of the interchange. This projection is then used to determine the required number of lanes for each section, preventing future congestion and ensuring safety and smooth traffic flow.

1.3.3. Origin-Destination (O/D) Matrix

The Origin-Destination (O/D) matrix is a key tool in traffic analysis, representing the number of trips between different entry and exit points of the interchange. It helps to identify

traffic patterns, peak flows, and critical links, which are essential for determining lane requirements and ramp capacities.

Matrice O/D :

Zaghouan

680

210

660

960

Tunis

Jelma

190

1020

1VL=1uvp
1PL=2uvp

Trafic à l'HP en uvp (2012)
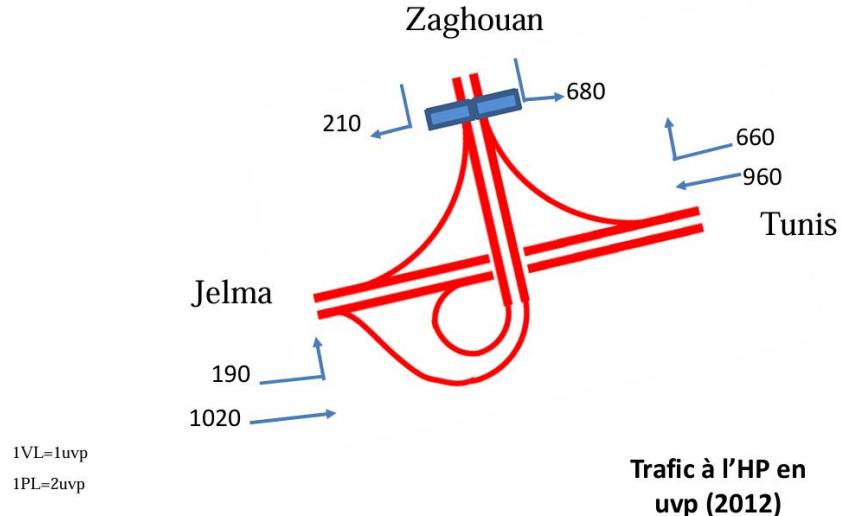
Figure 2: Traffic movements at the interchange

Figure 3 shows the main traffic movements at the Tunis–Zaghouan–Jelma interchange. The traffic study aims to analyze vehicle flow distribution to optimize lane configuration and ensure safe, efficient circulation. The Origin–Destination (O/D) matrix, developed from traffic counts and projected flows, provides estimated hourly traffic volumes between key directions and supports the design of ramps and lanes for smooth interchange operation.

For the Zaghouan interchange, the traffic data were projected using a growth rate of **2 % per year**, taking into account future increases in vehicle volumes. Each cell of the matrix indicates the number of vehicles traveling from a specific origin to a specific destination, adjusted according to this growth rate.

Matrice O/D 2012			
O/D	Tunis	Zaghouan	Jelma
Tunis		660	960
Zaghouan	660		210
Jelma	1020	190	

Figure 3 : O/D Matrix 2012

The arrows highlight the predominant traffic flows, distinguishing between major and secondary turning movements. This allows the identification of priority lanes and the required number of dedicated turning lanes for each branch of the interchange.

This O/D analysis is essential for determining the adequate lane layout, improving traffic safety, minimizing congestion, and facilitating smooth movement between the three connecting cities.

Matrice O/D 2028				Matrice O/D 2048			
O/D	Tunis	Zaghouan	Jelma	O/D	Tunis	Zaghouan	Jelma
Tunis		906	1318	Tunis		1346	1958
Zaghouan	906		288	Zaghouan	1346		428
Jelma	1400	261		Jelma	2081	388	

Figure 4 : Traffic projection between 2028-2048

Based on these results, it is concluded that a 2x2 lane carriageway is required for the Tunis–Jelma motorway, whereas for the three other slip roads with a UVP below 2000, a single lane is sufficient. (see figure 4)

1.4. Interchange Design Using AutoCAD

The interchange design using AutoCAD involved three main steps. First, the type of interchange was selected based on traffic patterns, land constraints, and safety requirements. Next, the operation of the interchange was analyzed to ensure smooth vehicle circulation and efficient connections between Tunis, Zaghouan, and Jelma. Finally, two AutoCAD design variants were developed and compared to identify the most effective and functional configuration.

1.4.1. Justification for Choosing a Trumpet Interchange

The trumpet interchange was selected for the Zaghouan project due to several advantages:

1. **Efficient Land Use:** The trumpet design requires less land compared to other interchange types, making it suitable for areas with limited space.
2. **Smooth Traffic Flow:** It allows free-flowing traffic movements with minimal conflict points, reducing congestion and improving safety.
3. **Simple Geometry:** The trumpet interchange has a straightforward geometric layout with a single loop ramp, which simplifies construction and maintenance.
4. **Cost-Effectiveness:** Its compact design reduces construction costs while maintaining efficiency for all traffic movements.
5. **Adaptability:** This type of interchange is particularly suitable for connections between a major highway and a secondary road, as in the Zaghouan site.

Based on these considerations, the trumpet interchange provides an optimal balance between functionality, safety, land use, and cost, making it the most appropriate choice for this project.

1.4.2. Functioning of the Interchange

The trumpet interchange allows smooth and safe traffic movements between a major highway and a secondary road. Its design consists of a main directional ramp and a single loop ramp that facilitates turning movements with minimal conflict points.

Traffic entering the interchange from the secondary road merges onto the main highway via the loop ramp, while vehicles exiting the highway follow the directional ramp to reach the secondary road. This configuration ensures continuous traffic flow, reduces congestion, and enhances safety by minimizing the number of intersections and sharp turns.

The compact layout of the trumpet interchange also allows efficient use of land while accommodating all expected traffic volumes. Overall, this type of interchange provides a reliable and effective solution for managing traffic at the Zaghouan site.(figure 5)


Figure 5 : Trumpet Interchange

1.4.3. Interchange Design Using AutoCAD

The geometric design of the Zaghouan interchange was carried out using **AutoCAD**, providing precise and detailed plans of the entire infrastructure. This stage includes the layout of main roads, ramps, loops, and the associated bridge.

Two design variants were developed:

➢ **Variant 1: Amani BARHOUMI**

The supports are aligned along the bridge axis and represented by **magenta rectangles** in the drawing. The **main road axis shown in yellow**. This layout allows continuous traffic flow on both the overpass and the underlying road. (See figure 6)
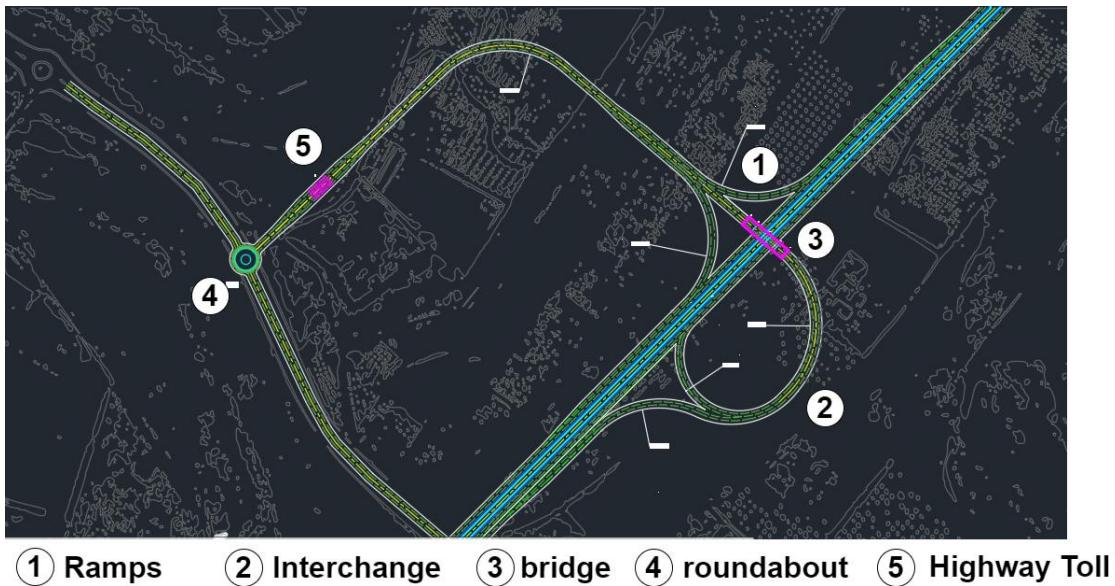
Figure 6 : Detailed plan view of Variant 1

Traffic lanes are marked in green, indicating directions of movement and lane limits. The bridge is an integral part of the trumpet-type interchange, ensuring smooth traffic flow between the highway and the secondary road while minimizing land occupation.

The main bridge of the Zaghouan interchange is designed to ensure the crossing between the two main traffic axes.
The bridge, located above the motorway, is a slab bridge with a total length of 68 m and a width of 12 m. It is composed of the following structural elements:

- **C1 and C5:** Abutments positioned at both ends of the bridge, providing support and anchorage for the structure. The first and fourth spans each measure 14 m.
- **P2, P3, and P4**: Intermediate piers evenly distributed along the bridge, designed to transfer vertical loads and ensure the longitudinal stability of the deck. The second and third spans each measure 20 m.
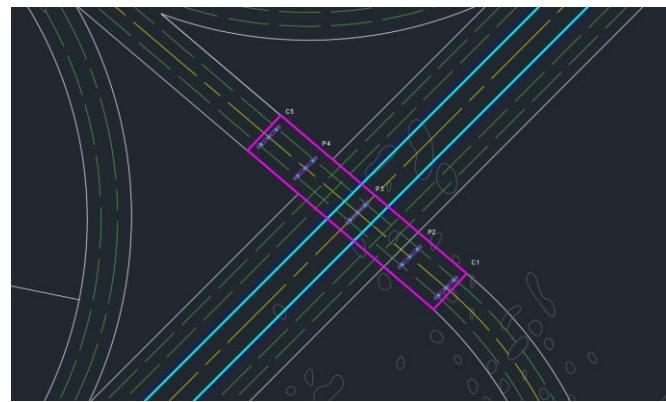
Figure 7 : Bridge layout on AutoCAD
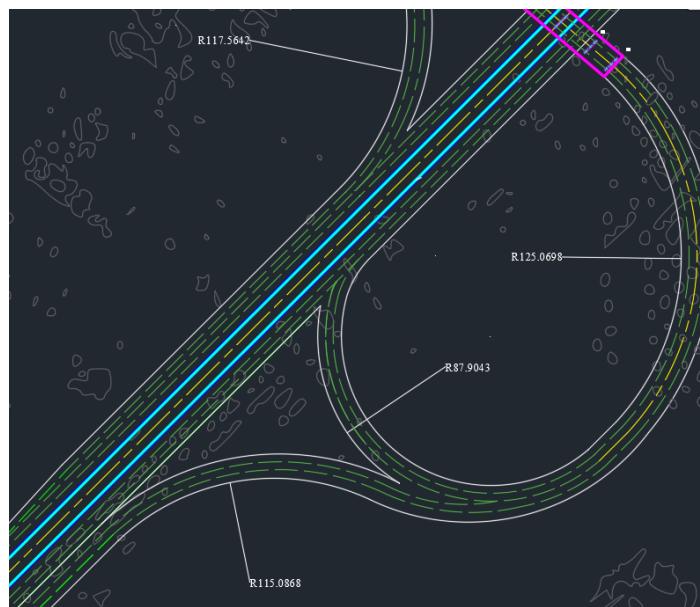
Figure 8 : Geometric Design of Interchange Curves

The interchange ramps and connectors have been designed using horizontal curves that satisfy the geometric standards for safe and comfortable vehicle circulation. Each curve radius selected is greater than **80 meters**, which aligns with the design criteria for interchange slip roads operating at moderate to high speeds.

The main radii used in the alignment design are as follows: **R = 125.07 m**, **R = 117.56 m**, and **R = 87.90 m**.

These radii ensure:

- Adequate visibility distance for drivers.
- Reduced lateral acceleration and improved comfort.
- Safe maneuvering for heavy and light vehicles.
- Compliance with roadway geometric design norms.

Larger radii on the gently curving sections enhance speed continuity between the main carriageway and the ramps. The minimum radius adopted (R ≈ 87.90 m) remains above the threshold value of 80 m, which avoids sharp turning effects and supports a smooth traffic flow throughout the interchange.

> **Variant 2: Ferdaws BEN SLAMA**

In this variant, the supports are also aligned along the bridge axis but have been repositioned to optimize the overall geometry of the interchange. The bridge deck, shown in blue, crosses the main road axis (in blue) with a smoother curvature and improved alignment to enhance traffic safety and comfort.

Traffic lanes, indicated in green, are designed with adjusted widths and gentler connection curves to facilitate vehicle movement and reduce conflict zones.

The green rectangles represent the bridge supports, strategically placed to ensure structural stability while minimizing interference with the underlying traffic.

Figure 9 : Detailed plan view of Variant 2
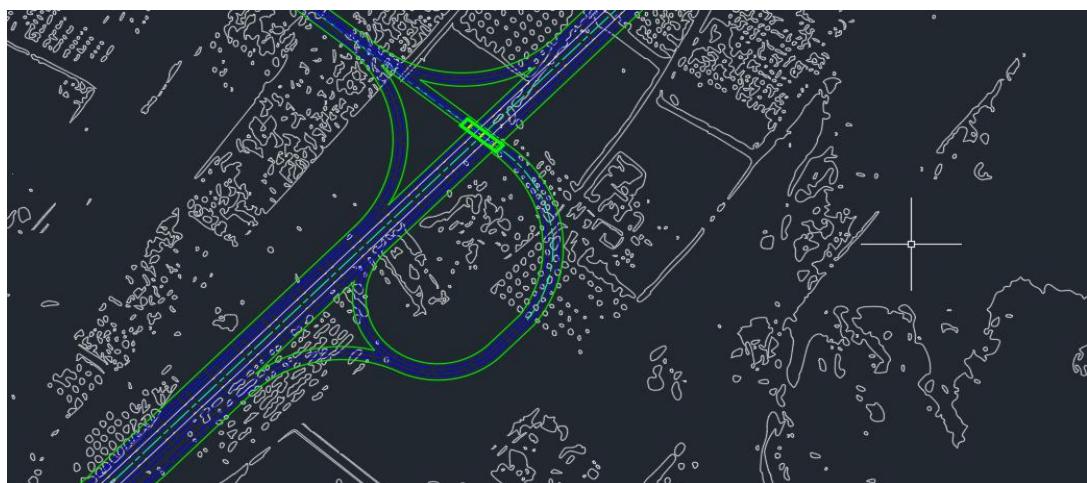
Figure 10 : Layout of Variant 2 and its ramps in AutoCAD

Figure 11 : : Geometric Design of Interchange Curves

Figure 11 illustrates the geometric layout of the interchange curves for Variant 2. The specified radii ensure smooth transitions in compliance with road design standards, while promoting traffic continuity and safety at intersections.

1.5. Conclusion

In this chapter, the design of the Zaghouan interchange was presented, including the geometric layout, lane distribution, and detailed drafting using AutoCAD. The traffic study allowed for the determination of the appropriate number of lanes and ensured a smooth traffic flow with a high level of service.

The use of AutoCAD provided accurate and detailed plans, which serve as a foundation for the structural analysis and further modeling of the interchange. Overall, this chapter establishes a comprehensive and precise design framework, ensuring both functionality and safety of the interchange.

Chapter 2: Bridge Study Using SAP2000

2.1. Introduction

This chapter focuses on the structural analysis of the interchange bridge using SAP2000. The study began with the modeling of the bridge, followed by a dynamic analysis of the natural vibration modes to evaluate its global behavior. Subsequently, the bridge was analyzed under the MC120 load model for each of the two studied sections. The obtained results allowed the assessment and comparison of the structural performance of both configurations.

2.2. Modeling on SAP2000

As shown in Figure 7, a 2D model was created in the XY plane, with a total length of 68 m and a width of 12 m, representing the bridge deck. The first step involves defining the deck geometry, material properties, and section characteristics. The second step consists of introducing the supports at the abutments and intermediate piers to accurately reproduce the boundary conditions and ensure realistic structural behavior under applied loads. In addition, a 1 m × 1 m mesh was adopted to provide a precise and uniform discretization of the deck surface, ensuring accurate numerical results.
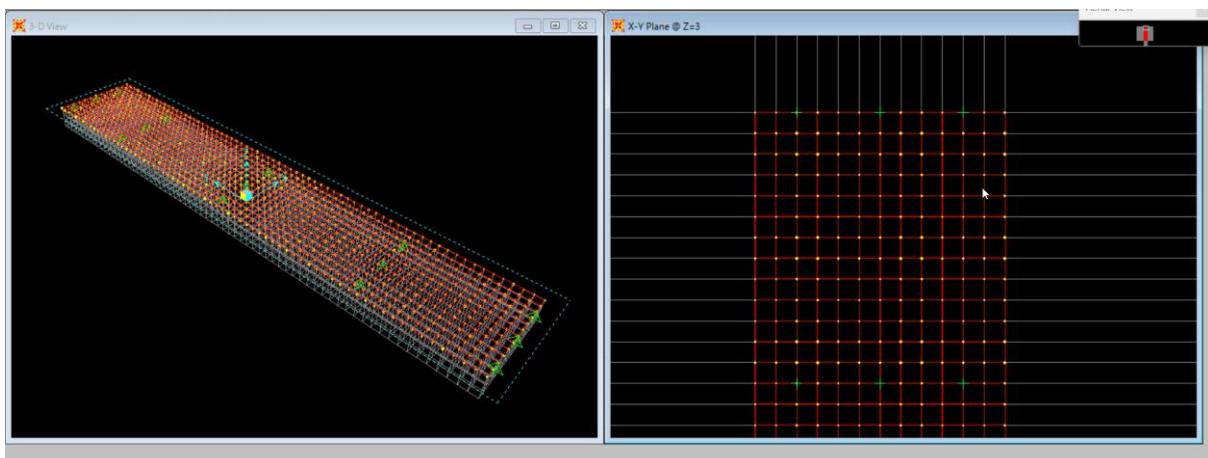
Figure 12 : Modeling of the bridge deck in SAP2000

2.3. Dynamic analysis

A modal analysis was carried out to identify the natural vibration characteristics of the structure. The first five mode shapes were extracted and visualized to understand the dynamic behaviour and the most significant deformation patterns under dynamic loading. The modal results provide the natural frequencies and associated mode shapes, as well as the modal mass participation factors that indicate how much of the structural mass contributes to each mode.

2.3.1. Modes

As shown in Figure 13, the first four natural modes are characterized by bending behavior of the bridge deck.

Mode 1

Mode 2

Mode 3

Mode 4
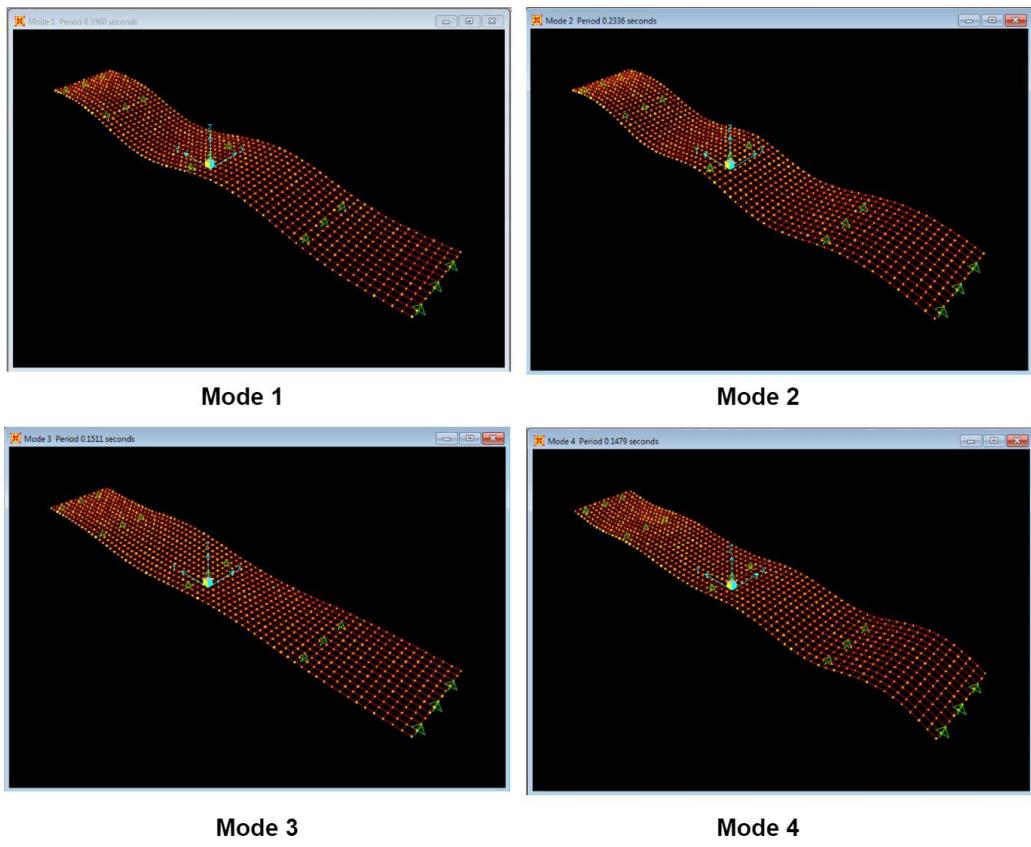
Figure 13 : Vertical bending modes

- **Mode 5 (Torsional mode) :**
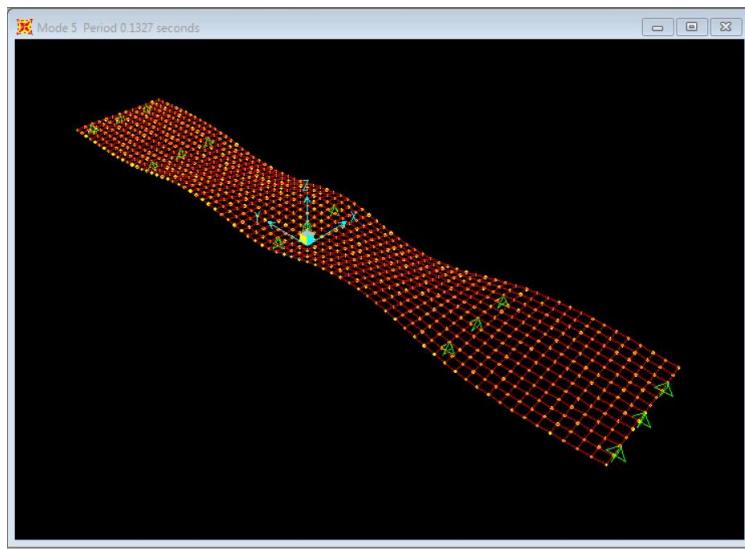
*Figure 14 : Torsional mode*

As shown in Figure 14, Mode 5 represents a torsional vibration of the bridge deck.

Table 1 : Summary table of periods and frequencies

Mode	Period (T)	Frequency (Hz)
1	0.336	2.9761
2	0.2336	4.2808
3	0.1511	6.6181
4	0.1479	6.7613
5	0.1327	7.5357

For the bridge, the first mode exhibits the largest period, reflecting the global flexibility of the structure in vertical bending. As the mode number increases, the periods decrease and the frequencies rise, representing higher-order, stiffer vibration modes. These modes have a smaller influence on the overall dynamic response but are important for local effects and structural safety verification.

The seismic excitation frequency range (2–5 Hz) coincides with the first two natural frequencies of the bridge (2.98 Hz and 4.28 Hz), indicating a potential risk of resonance. A bridge enters resonance when an external excitation frequency caused by wind, moving vehicles, or earthquakes matches or is very close to one of the bridge's natural frequencies obtained from modal analysis. When this occurs, the vibration amplitudes can increase significantly, potentially leading to excessive vibrations, structural damage, or dynamic instability, similar to the historic collapse of the Tacoma Narrows Bridge (1940).

To mitigate resonance risks, the following measures are recommended:

- Modify structural stiffness, for example by adjusting deck sections, support conditions, or materials, to shift natural frequencies.
- Increase damping using viscous dampers, tuned mass absorbers, or suitable bearings.
- Control excitation sources, such as limiting vehicle speeds or adjusting axle spacing for heavy convoys (e.g., military loads).

These measures help reduce vibration amplitudes, improve energy dissipation, and ensure the dynamic stability of the bridge under seismic or other dynamic loads.

2.3.2.   Bridge Study under the MC120 Load

In this section, the bridge was analyzed using the MC120 load model to assess its performance under realistic traffic loads. Each studied section was subjected to this load according to current standards, allowing the determination of internal forces, bending moments, and deflections.

The analysis enabled:

- Identification of critical areas of the bridge where stresses and deformations are highest.
- Comparison of the responses of the two studied sections to evaluate their structural efficiency.
- Verification of the bridge's compliance with safety and serviceability criteria under the MC120 load.

The results provide a solid basis for decisions regarding the bridge's design optimization and future maintenance.

- **Section 1 (Military load case 1)**

In the first case, the MC120 load is applied at the center of the first span, as shown in Figure 15.
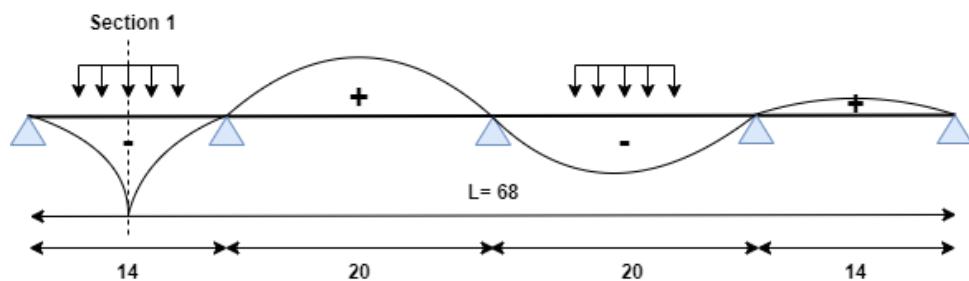
Figure 15 : Influence Line – Section 1 (Military Load Case 1)

According to this diagram, the military load can be applied at the midspan of the first span. Since the minimum distance between two military loads is 30 m, the second load is applied at the midspan of the third span.

-The first step is to define the dead weight and the military load (-110 Global direction Z).
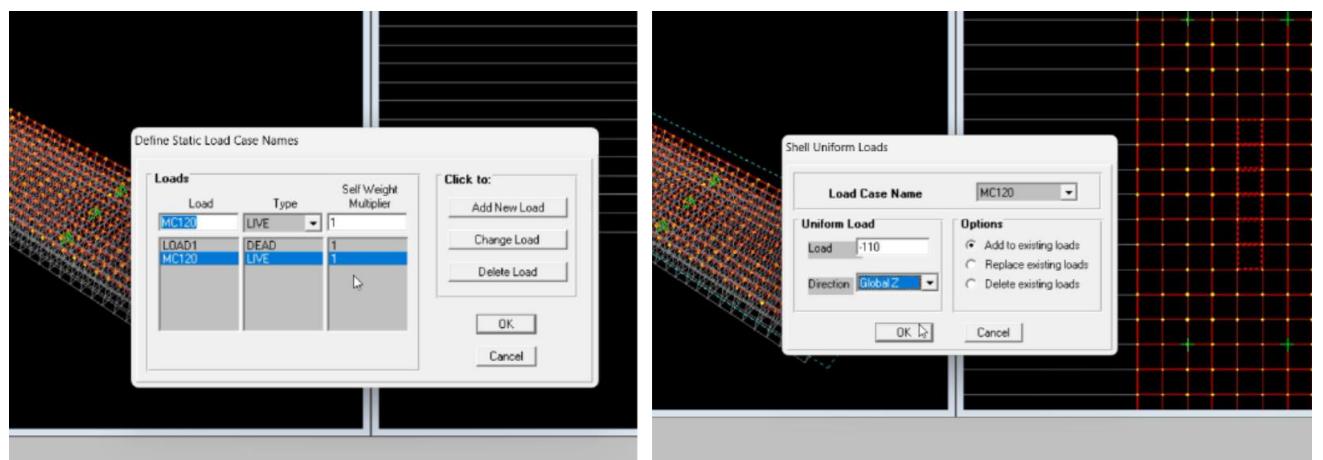
Figure 16 : Load case definition

-The second step involves applying the load combinations for the Ultimate Limit State (ULS) and Serviceability Limit State (SLS).(figure 17)
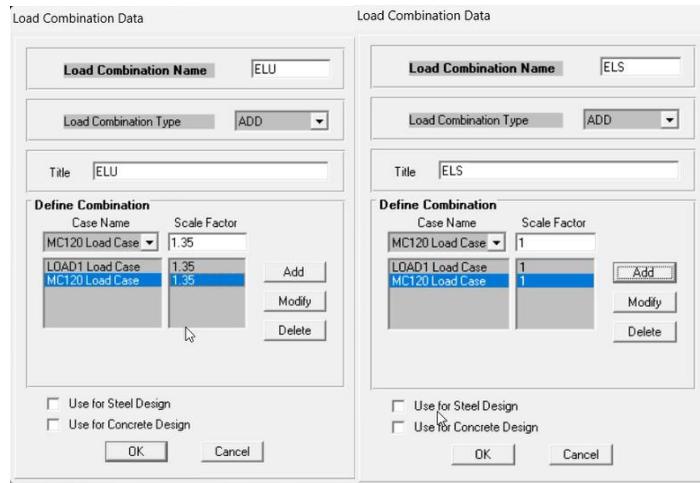
Figure 17 : Definition of load combination (ULS - SLS)

-The results :

This section focuses on the visualization and interpretation of the obtained results.
It aims to analyze the structural response under the applied loading conditions, highlighting key deformation and stress patterns.
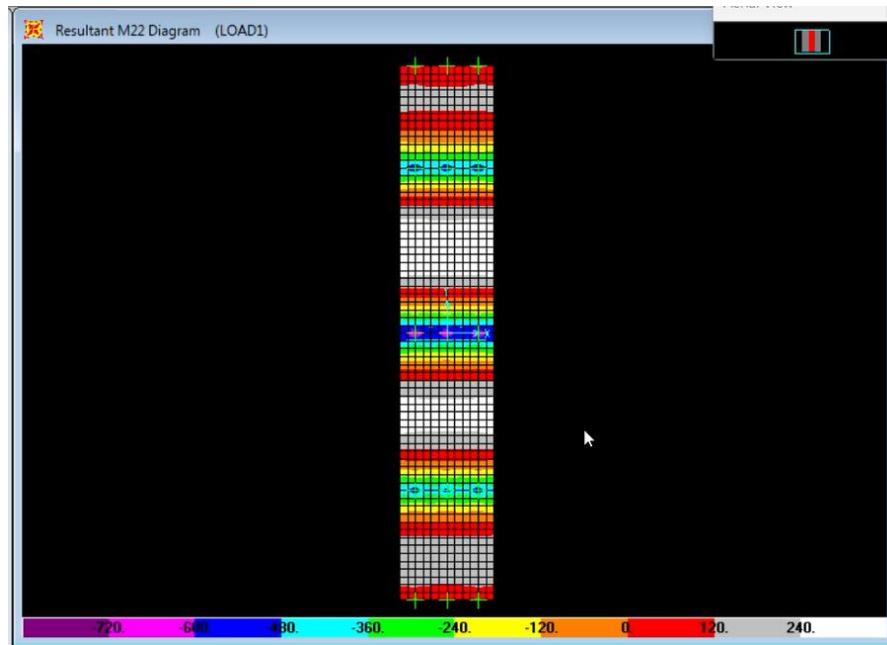

Figure 18 : The results of M22 -LOAD1 (case 1)

Figure 18 illustrates the M22 moment distribution for load case LOAD1 (Case 1). The diagram shows the variation of bending moments across the bridge deck, highlighting the critical zones subjected to maximum positive and negative stresses.
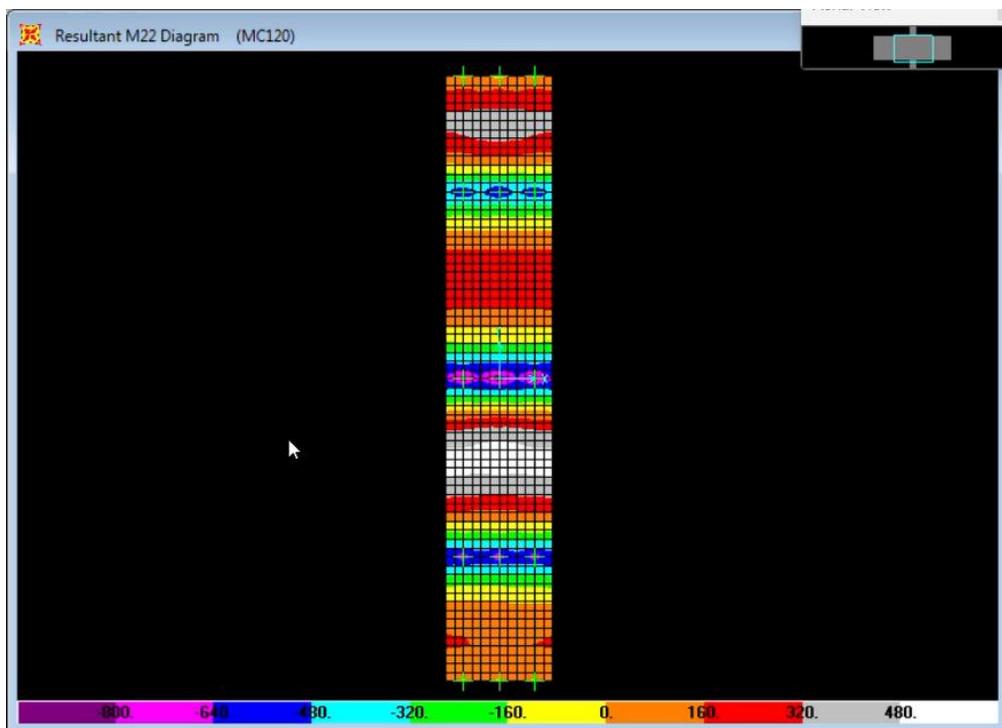
Figure 19 : The results of M22-MC120 (case 1)

   Figure 19 illustrates the M22 moment distribution for load case MC120(Case 1). The diagram shows the variation of bending moments across the bridge deck, highlighting the critical zones subjected to maximum positive and negative stresses.
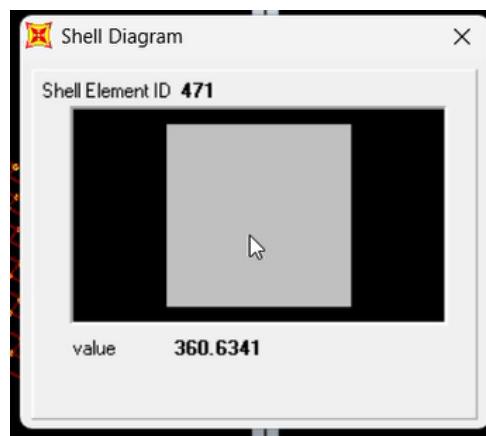
*Figure 20 : M22 (MC120) first span (case 1)*

Figure 20 presents the **M22 moment** at the **MC120** for the **first span** under **load case 1**. The maximum value obtained for the shell element **ID 471** is **360.63**, indicating the critical bending moment zone in this span.
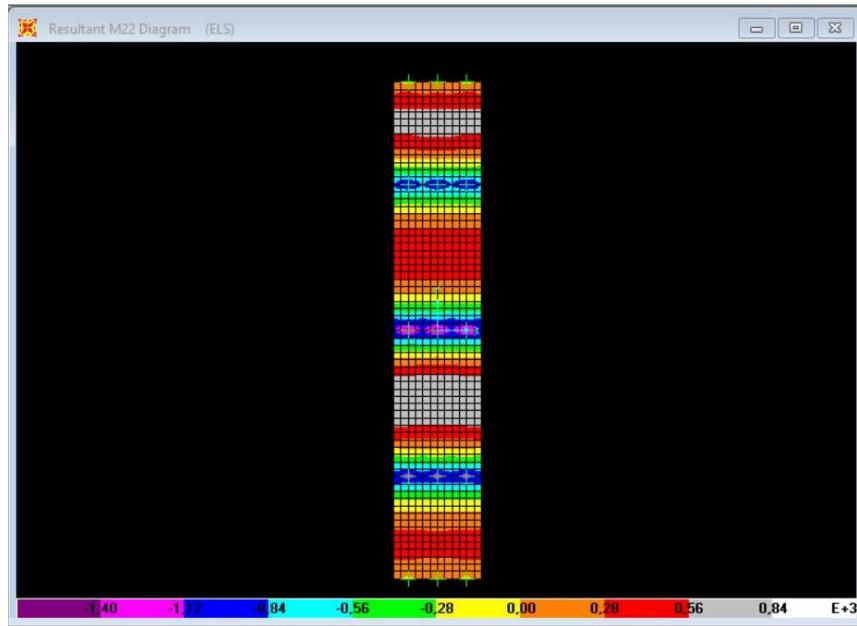
Figure 21 : The results of M22-SLS (case 1)

Figure 21 illustrates the M22 moment distribution for load case SLS (Case 1).

• Section 2 (Military load case 2)
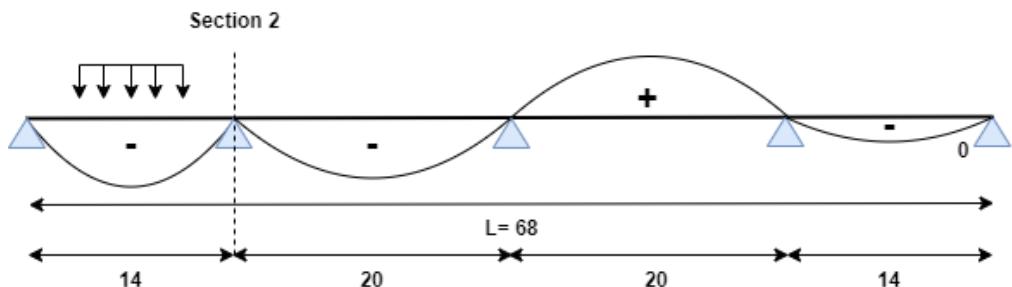
Figure 22: Influence Line – Section 2 (Military Load Case 2)

According to this diagram, the military load can be applied only at the midspan of the first span. Since the minimum distance between two military loads is 30 m and the value of the Influence Line of the fourth span is approximately equal to 0.
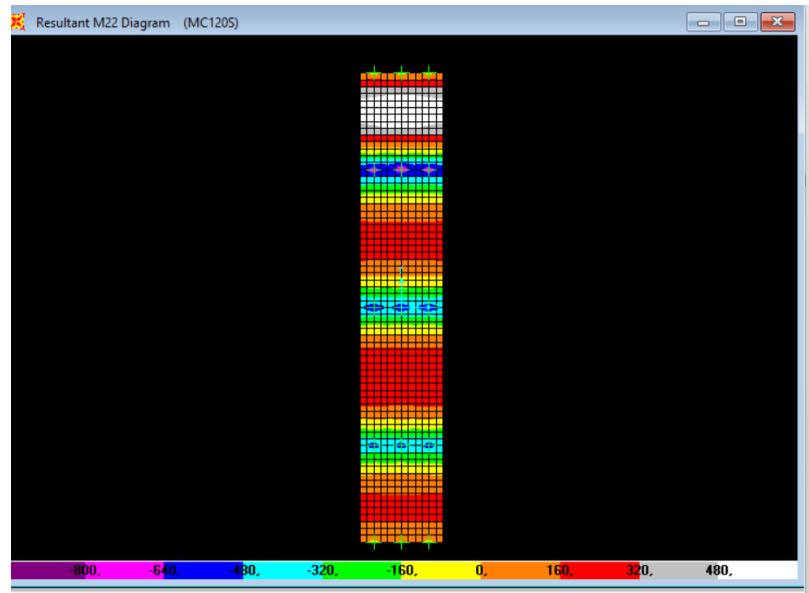
Figure 23 : The results of M22-MC120S (case 2)

Figure 23 illustrates the M22 moment distribution for load case MC120S (Case 2).
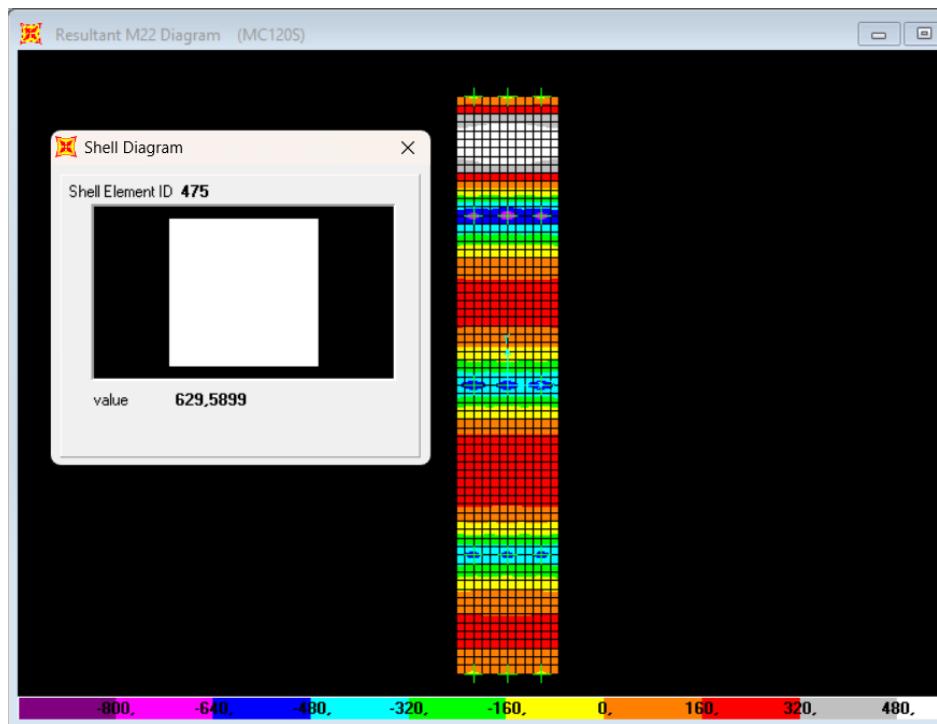
Figure 24 : M22 MC120S first span (case 2)

Figure 24 illustrates the M22 moment distribution for load case MC120S(Case 2) and presents the **M22 moment** at the **MC120S** for the **first span** under **load case 2**.

Figure 25 illustrates the M22 moment distribution for load case ELS2(Case 2) and presents the **M22 moment** at the **ELS2** for the **first span** under **load case 2**.
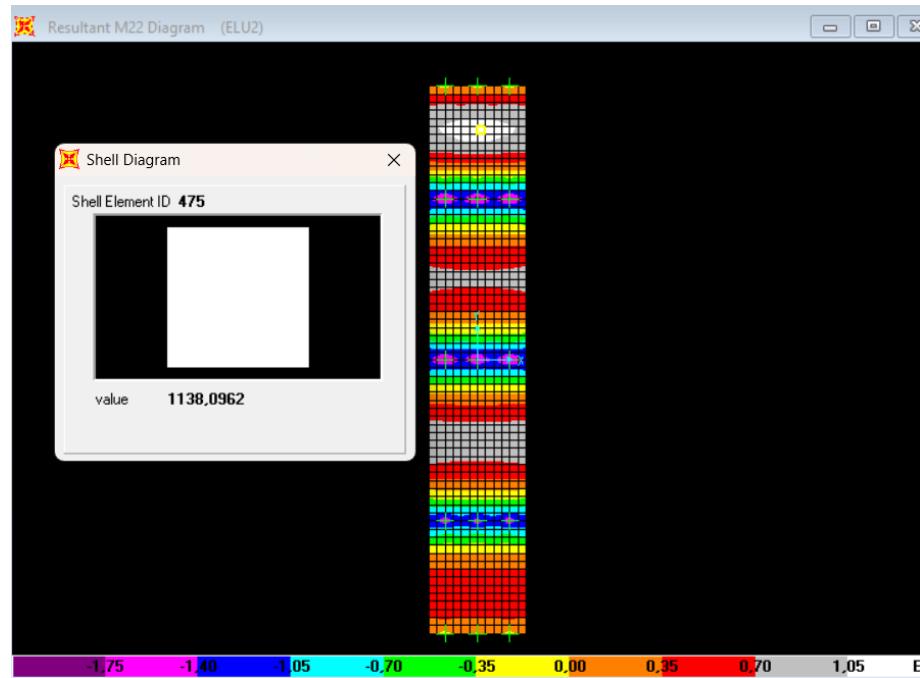
Figure 25 : The results of M22-ULS2 (case 2)

Figure 26 illustrates the M22 moment distribution for load case SLS2(Case 2) and presents the **M22 moment** at the **SLS2** for the **first span** under **load case 2**.
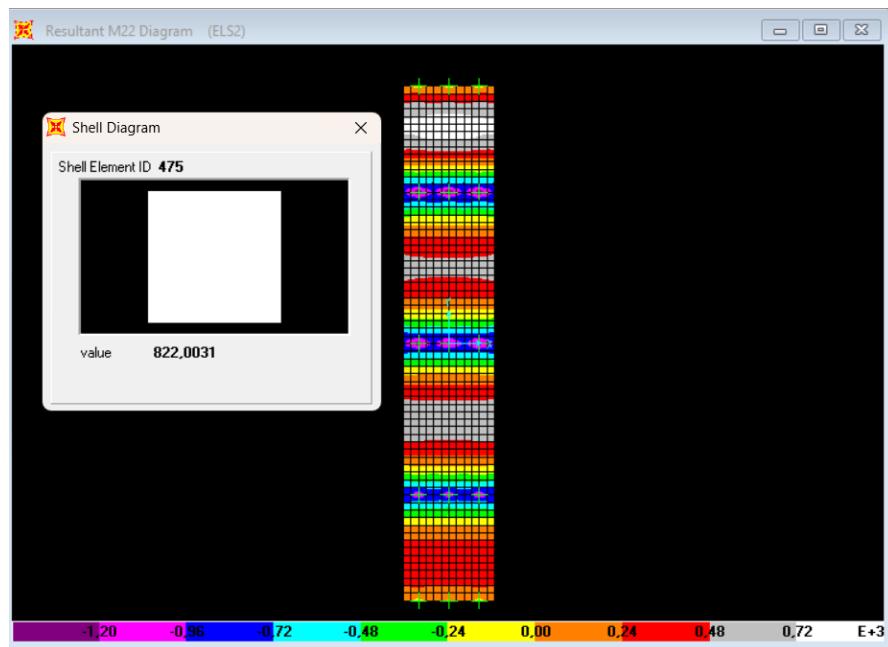
Figure 26 : The results of M22-SLS2 (case 2)

2.4. Conclusion

This chapter presented a detailed structural analysis of the interchange bridge using SAP2000. The study began with the modeling of the bridge, followed by a dynamic analysis of its natural vibration modes to evaluate overall structural behavior. The bridge was then subjected to the MC120 load model for each of the two examined sections. The results obtained enabled a clear assessment and comparison of the structural performance of both configurations, providing valuable insights into the bridge's response under dynamic and static loading conditions.

Chapter 3: Design of the pavement structure with Alizé

3.1. Introduction

This chapter focuses on the pavement design process. It begins with the analysis of traffic loading and the characterization of the subgrade soil, which are essential parameters for determining pavement performance. Based on these data, the pavement structure is then designed using the Alizé software to ensure durability and compliance with design standards.

3.2. Traffic calculation and subgrade characteristics

The evaluation of traffic and subgrade characteristics is a fundamental step in pavement design, as it directly influences the structural dimensioning and long-term performance of the roadway. The California Bearing Ratio CBR method was adopted to assess the bearing capacity of the subgrade soil. The CBR value was corrected according to climatic variations using the coefficients α and β, which represent the proportions of dry and humid months specific to each climatic region.

The corrected CBR was calculated using the following equation:

$$CBR = CBRi^{\alpha} \times CBRs^{\beta}$$

where CBR_i and CBR_s are the CBR values corresponding to dry and humid conditions, respectively.

According to the regional classification, Region B was selected, corresponding to β = 0.33 and α = 0.67.

Table 2 : Climatic Coefficients and Corrected CBR Values

Région climatique	Nombre de mois		Coefficient	
	Humide	Sec	β	α
A	6	6	0.5	0.5
B	4	8	0.33	0.67
C	2	10	0.17	0.83

The elastic modulus of the subgrade E was then estimated using the empirical relationship given by the following equation:

$$E = 5 \times CBR$$

yielding a value of E = 80 MPa.

This modulus was subsequently used as an input parameter in the Alizé software to ensure a realistic representation of the subgrade's mechanical behavior under traffic loading conditions.

Table 2 below presents the climatic coefficients used for the CBR correction and the derivation of the corresponding soil modulus.

3.3. Pavement design using Alizé

  The adopted pavement structure consists of four main layers, each ensuring the mechanical strength and durability of the roadway under traffic loads. The first layer is *bituminous concrete (BB)*, serving as the surface course and providing waterproofing and resistance to wear. The second layer is *bituminous gravel (GB)*, which distributes the stresses to the underlying layers. The third layer is a *treated granular base (GRH)*, contributing to the overall rigidity and structural stability of the pavement. Finally, the fourth layer corresponds to the *subgrade soil*, which provides the foundation support for the entire structure. Figure 3.1 below illustrates the pavement structure definition in the Alizé software, showing the different layers along with their mechanical properties and material types.

Figure 27 : Pavement Structure Definition in Alizé Software.

3.3.1. Calculation of Allowable Values

  These limits ensure that each layer can safely support traffic loads without excessive deformation or failure. The calculations also account for interactions between layers. The figure below illustrates the adopted allowable values.

➢ **Determination of cumulative traffic**

➢ **Data**

- %PL (percentage of heavy vehicles) = 12%
- i (annual growth rate) = 2%
- Service year = 2028
- Design life (p) = 15 years
- CAM (coefficient d'agressivité moyen) = 0.8

3.   Intermediate Definitions

1.   **Conversion of hourly peak traffic into daily traffic**

$$T_{uvp/j} = T_{uvp/HP} \times 8$$

2. **Daily traffic due to heavy vehicles**

$$T_{PL/j} = T_{uvp/HP} \times 8 \times \frac{\%PL}{1 + \%PL}$$

3. **Cumulative Traffic Calculation (Tc)**

The cumulative traffic over the design period is obtained using the geometric growth formula:

$$T_c = 365 \times T_{PL/j} \times \left[\frac{(1+i)^p - 1}{i}\right]$$

According to the traffic study:

$$T_{uvp\ 2012} = max \begin{cases} 680 + 210 = 890\ uvp/hp \\ 660 + 190 = 850\ uvp/hp \end{cases}$$

So T*uvp* 2012/*hp* = 890 *uvp/hp*

4. **Number of Axles**

After calculating Tc, the **number of axles (NE)** is determined as :

$$NE = T_c \times CAM$$

The table above presents the necessary values for the structural design**.**

Table 3: Summary of main Parameters of the Analysis

Data	Value
TPL	762.8571
TC	6765429.068
NE	5412343.254
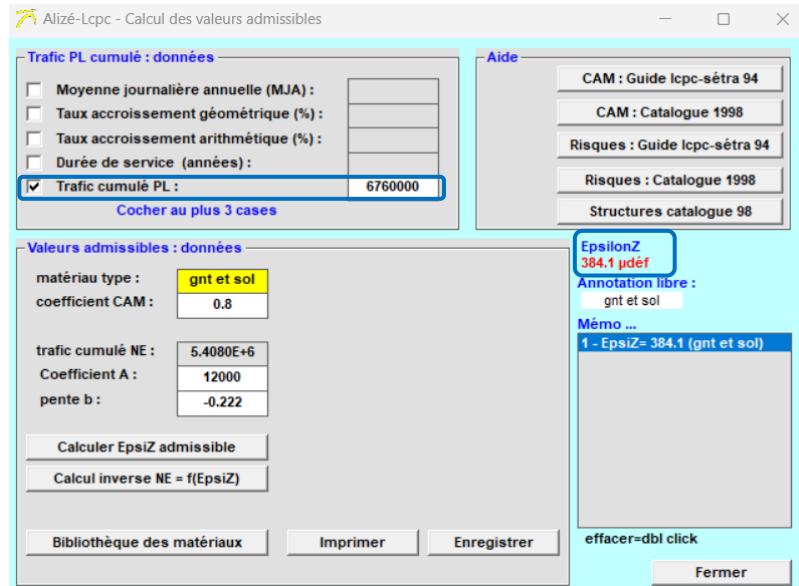
Figure 28 : Calculation of EpsZ using Alizé Software

The allowable stresses and strains were defined based on material properties and design criteria. For the pavement under study, the allowable horizontal strain is **ƐZ adm=384.1 µdef** and the allowable vertical strain is **ƐT adm=85 µdef**.

3.3.2. Comparison of the Calculated Result with the Allowable Value

The comparison between the calculated strains εZ and εT , and their respective allowable limits indicates that the pavement structure is under-designed. Both values exceed the permissible thresholds, highlighting the need to adjust the layer design. Consequently, the thickness of the pavement layers must be increased to meet the design requirements (see Figure 29).

Figure 29 : Results of calculated strains

Verification of Internal Forces
It is necessary to verify that the calculated strains satisfy the following conditions:

- Unbound materials (including subgrade): **Ɛz < Ɛz,adm**

- Bituminous materials: **Ɛt < Ɛt,adm**

This ensures that both compressive and tensile strains remain within the allowable limits for the pavement structure.

This figure presents the mechanical properties of the different layers in the pavement model, including thickness, modulus of elasticity, and Poisson's ratio. These parameters form the basis for the mechanical calculations in the Alizé-LCPC software. It can be observed that the material modulus varies depending on the layer type, directly influencing the overall stiffness of the pavement system.
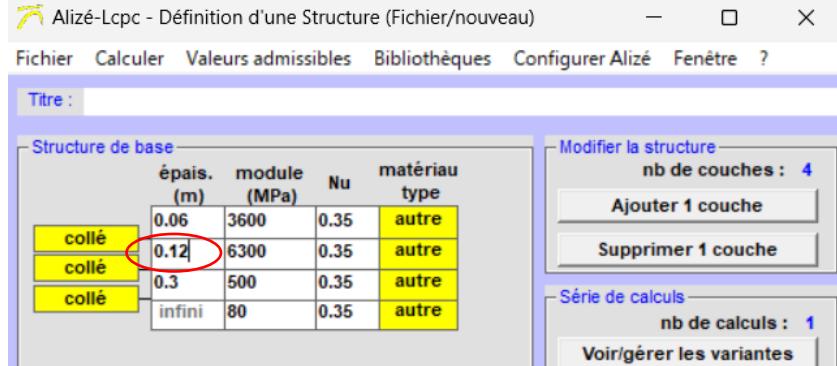
Figure 30 : Mechanical and Geometric Properties of Base Layers.

The results show relatively high deformations for this configuration, indicating insufficient stiffness of the upper layer. The stress and strain values exceed the allowable limits, showing that the structure is under-designed at this thickness.

Figure 31 : Variation of Results According to Layer Thickness (0.12 m to 0.18 m, Step of 2 cm).

With a thickness of 0.10 m, the deformations decrease slightly but still exceed the limits defined by fatigue and deflection criteria. This confirms that the mechanical resistance is not yet sufficient to ensure the pavement's durability.

Increasing the thickness to 0.14 m significantly improves the mechanical behavior. Stress and strain values tend toward the allowable limits, indicating a better distribution of forces within the structure. This configuration partially meets the design criteria.

At this thickness, tensile and compressive deformations are below the permissible limits. The structure meets safety and durability requirements, confirming that 0.18 m is an optimal thickness to ensure the pavement's performance.

The results presented in the table show the variation of tensile strain εT and compressive strain εZ according to the thickness of the bituminous gravel GB layer. For an initial thickness of 0.10 m, both $\varepsilon Z = 409.5\ \mu def$ and $\varepsilon T = 122\ \mu def$ exceed the allowable limits

$\varepsilon Z,adm = 384.4\ \mu def$ and $\varepsilon T,adm = 85\ \mu def$, indicating that the pavement is under-designed. As the thickness increases, both strain values decrease progressively.

At 0.18 m, $\varepsilon Z = 265.2\ \mu def$ and $\varepsilon T = 83.7\ \mu def$, which are both below the admissible limits. Therefore, a GB layer thickness of 18 cm satisfies the design criteria and ensures adequate structural performance of the pavement.

Table 4 : The values of strains depending on the thickness

Epaisseur (m)	0.1	0.12	0.14	0.16	0.18
εZ (μdef)	409.5	365.3	327.1	294	265.2
εZ.adm (μdef)	384.4	384.4	384.4	384.4	384.4
εT (μdef)	122	109.9	100.1	91.5	83.7
εT.adm (μdef)	85	85	85	85	85

3.4. Conclusion

This chapter presented the pavement design process carried out using the Alizé software. It included the analysis of traffic data, the characterization of the subgrade, and the structural design of the pavement layers. The iterative calculations allowed the optimization of the pavement thicknesses to ensure that the strain values remain below the allowable limits. The final design, with an 18 cm bituminous gravel layer, satisfies the performance and durability requirements, ensuring a safe and long-lasting pavement structure.

General conclusion

This project focused on the design and study of the Zaghouan interchange on the Tunis–Jelma highway, covering both the geometric and structural aspects. The work began with a detailed traffic analysis and the determination of subgrade characteristics, followed by the pavement design using Alizé software. Through successive iterations, the optimal layer configuration was defined to ensure that the stresses and strains remain within allowable limits.

AutoCAD was used to model the interchange geometry and visualize the different design variants, ensuring functionality, safety, and efficiency in vehicle circulation. The results of the analysis confirm that the final pavement structure meets the required performance criteria and provides durability over the design life.

This study highlights the importance of combining traffic studies, structural analysis, and geometric design to achieve a balanced, reliable, and cost-effective road infrastructure.