Optimization of the Elevated Railway Structure of the Tren Urbano Project

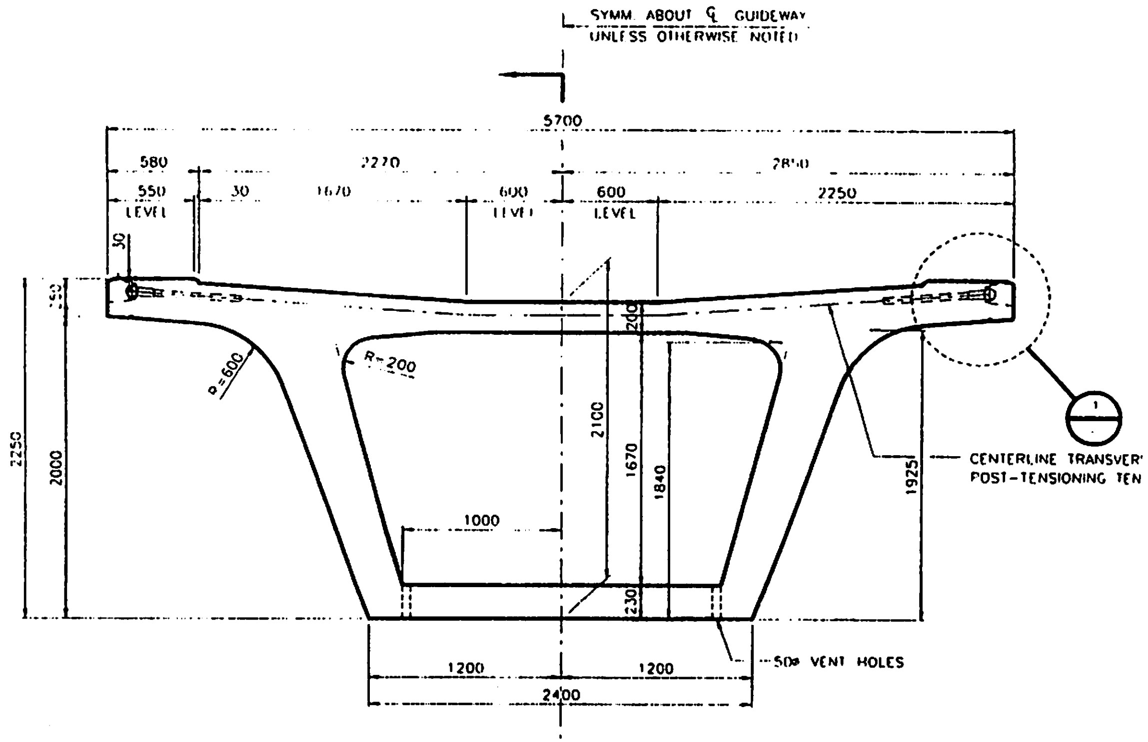
by Héctor J. Cruzado

Objectives

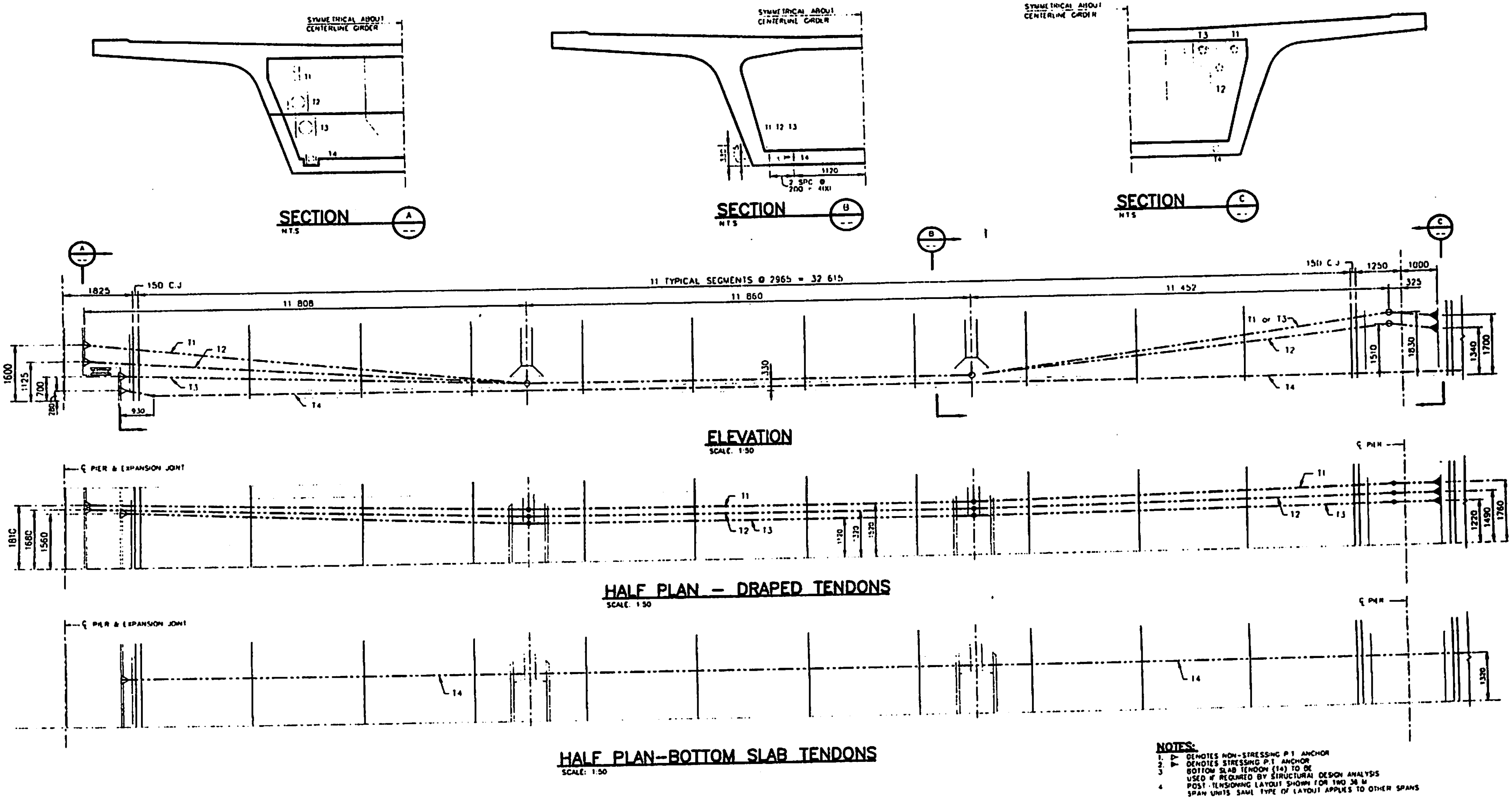
- Optimize the Bayamón phase design of the Tren Urbano Project in terms of four parameters:
  - 1. Structural Behavior
  - 2. Serviceability
  - 3. Economy
  - 4. Aesthetics
- Give recommendations to Tren Urbano to improve future phases of the project.

Tren Urbano

- Precast Segmental Prestressed Concrete



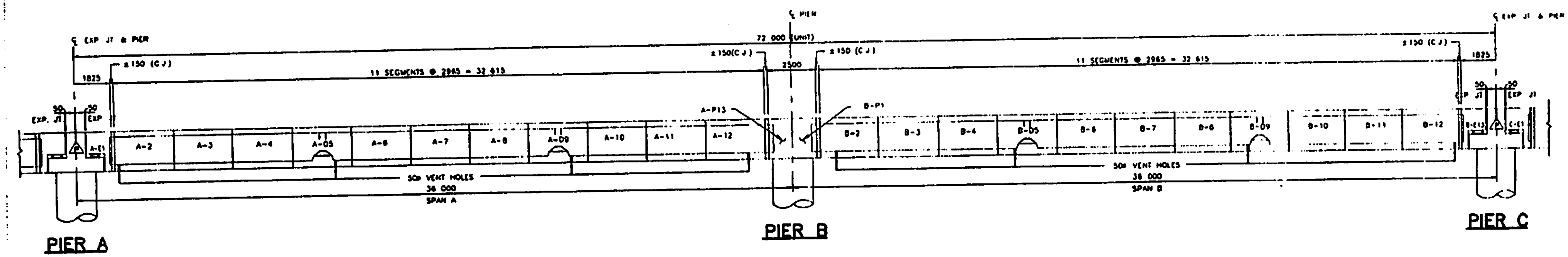
Tren Urbano



SYMMETRICAL ABOUT CENTERLINE GIRDER
SECTION A
SECTION B
SECTION C
11 TYPICAL SEGMENTS @ 2965 = 32 615
ELEVATION
SCALE: 1:50
HALF PLAN – DRAPED TENDONS
SCALE: 1:50
HALF PLAN–BOTTOM SLAB TENDONS
SCALE: 1:50
NOTES:

Tren Urbano

- Two Span Continuous Units are being designed for the Bayamón Phase.



- Multi-span symmetrical continuous units are permitted, simple are being considered.

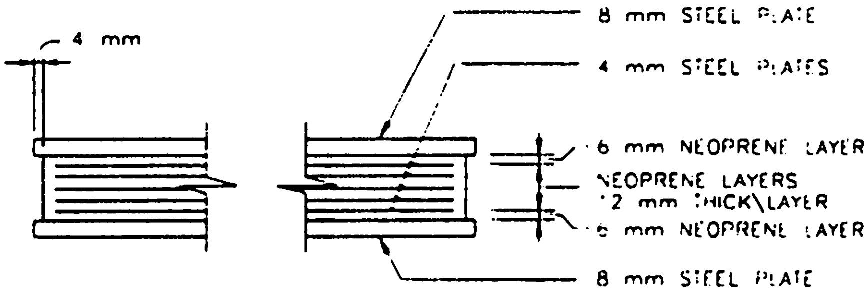
Tren Urbano

- Load combinations that include Earthquake loads control most of the design.

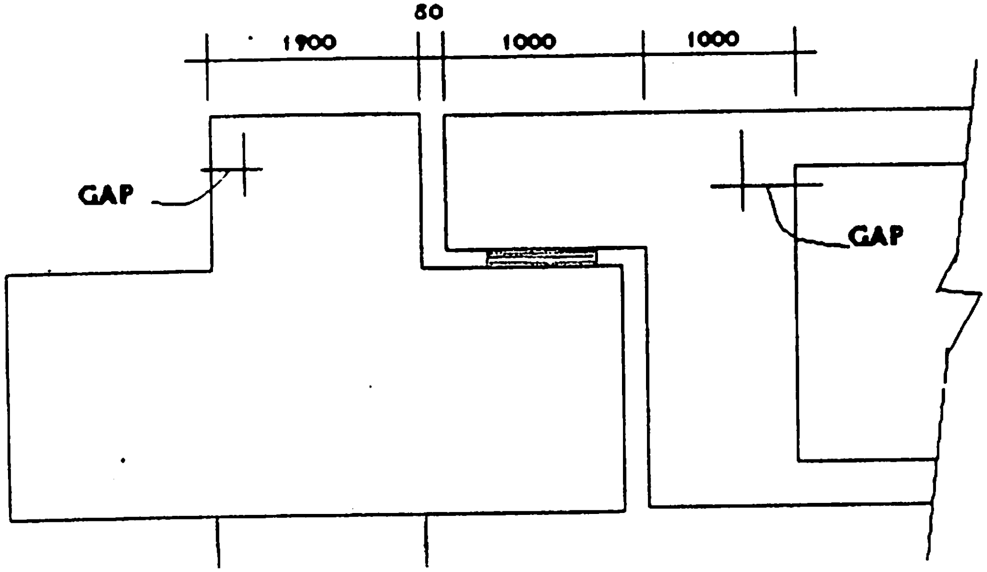
- The environmental conditions in Puerto Rico play a big role in design considerations.

Tren Urbano

- Elastomeric Bearings are going to be used in Expansion Pier Segments.



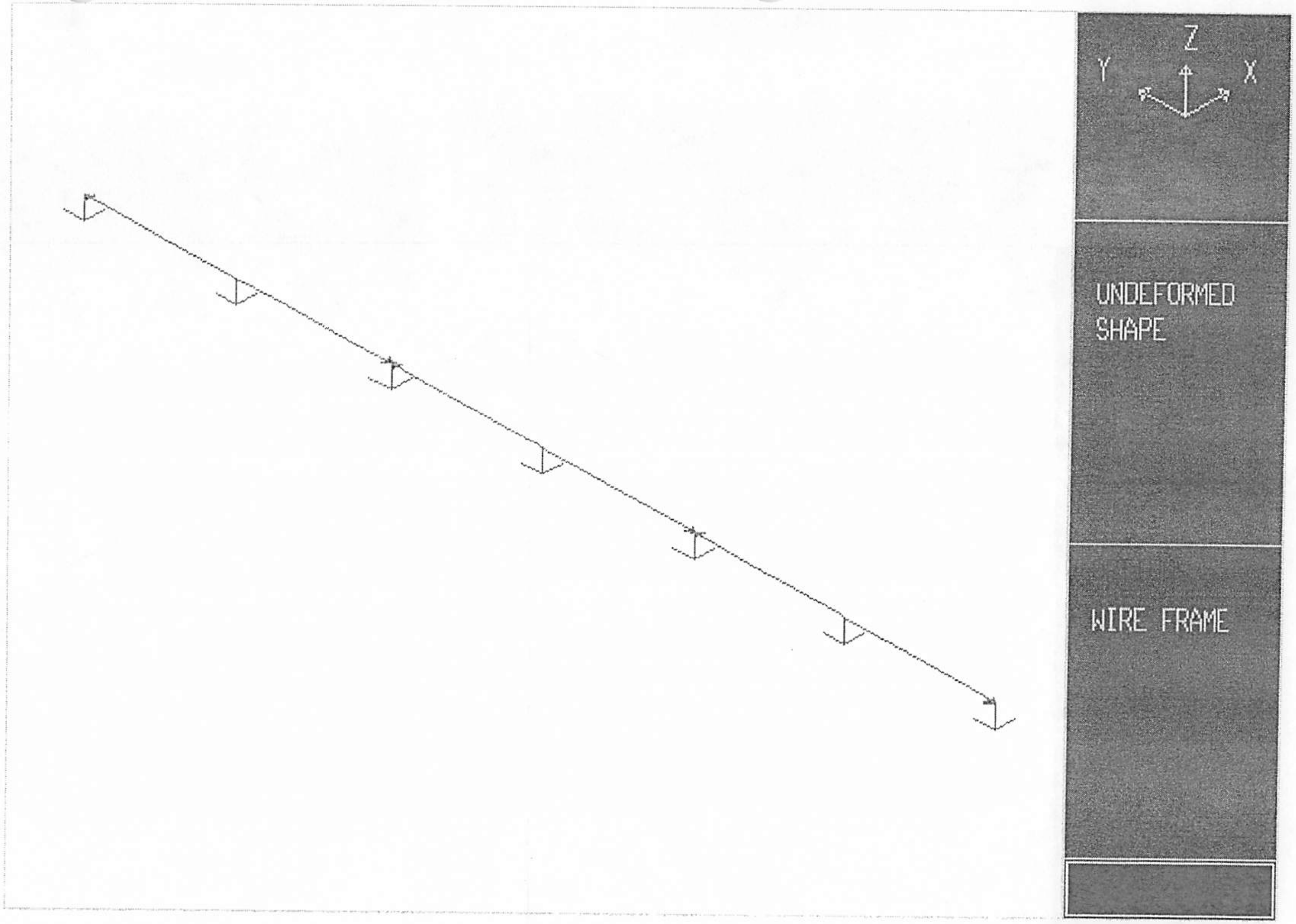
BEARING CROSS SECTION
EXPANSION JOINT SEGMENT
NOT TO SCALE

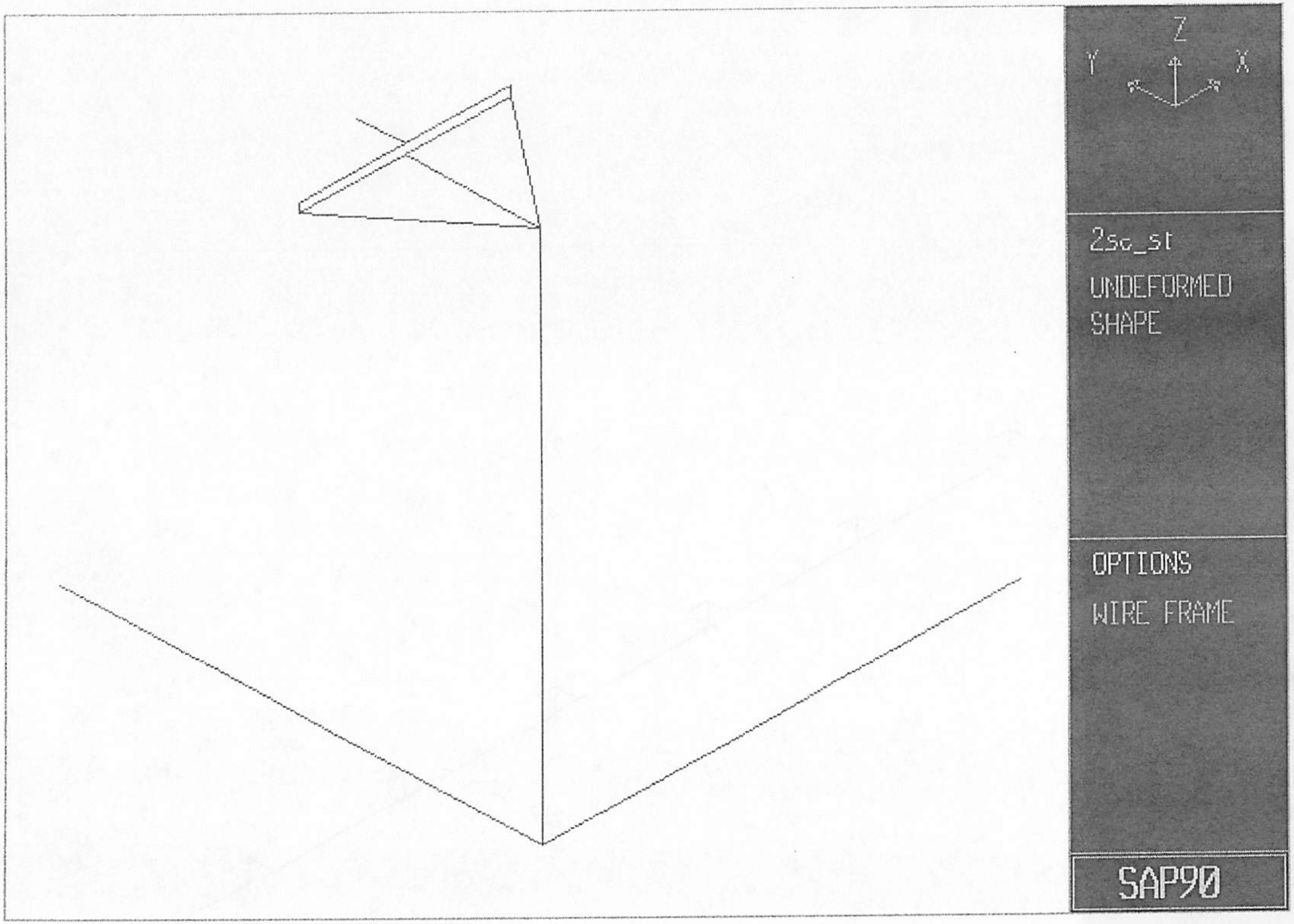


Research Approach

- Use a Structural Analysis Program to model 12 structures
  - simple-span
  - two-span continuous
  - three-span-continuous
  - four-span-continuous
  - five-span-continuous
  - six-span-continuous

  Each of the above is modeled for both single track and double track.

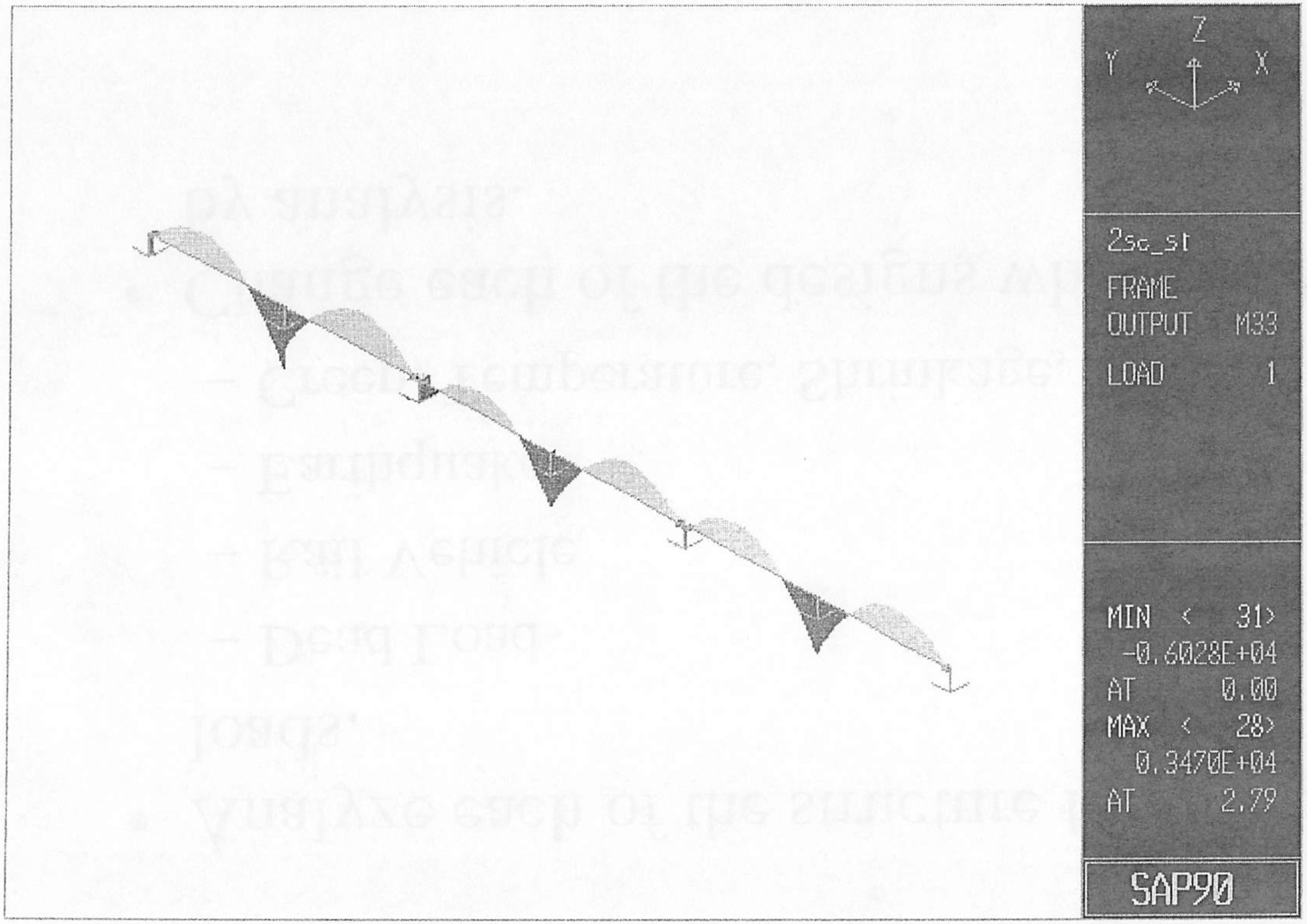

Z
Y
X
UNDEFORMED
SHAPE
WIRE FRAME



Z
Y
X
2sc_st
UNDEFORMED
SHAPE
OPTIONS
WIRE FRAME
SAP90

Research Approach

- Analyze each of the structure for critical loads.
  - Dead Load
  - Rail Vehicle
  - Earthquake
  - Creep, Temperature, Shrinkage, Settlements
- Change each of the designs when required by analysis.


Z
Y
X
2sc_st
FRAME
OUTPUT M33
LOAD 1
MIN < 31>
-0.6028E+04
AT 0.00
MAX < 28>
0.3470E+04
AT 2.79
SAP90

Research Approach

- Perform an Analysis for each of the designs giving value to:
  - Structural Behavior
  - Serviceability
  - Economy
  - Aesthetics

Research Approach

- Structural Behavior
  – Compare the structural behavior of each structure under design loads.
    - strength
    - deflections and vibrations

Research Approach

Life-Cycle Cost Analysis

- Serviceability
  - Ride comfort.
  - Maintenance and operation.
  - Demolition and/or replacement.
- Economy
  - Labor.
  - Materials.
  - Maintenance and operation.
  - Demolition and/or replacement

Research Approach

- Aesthetics
  - Only aesthetic difference: expansion joints.
    - Research on expansion joints topics:
      - Installation
      - Corrosion
      - Insulation
      - Nesting
      - Expansion joints in Puerto Rico

Work Schedule

1. Model each of the 12 structures.
2. Analyze for critical loads.
   - Dead Load, Live Load, Earthquake
   - Temperature, Shrinkage, Creep, Prestressed, Settlements, Interaction of the rail with the beam
3. Change designs when required by analysis.
4. Comparison of structures.
   a Structural Behavior: Using results of Structural Analysis.
   b Serviceability and Economics: Life-Cycle Cost.
   c Aesthetics: Research on Expansion Joints.
5. Recommendations.

Tren Urbano Research Proposal

A Study in Operations, Maintenance, and Inspection Policy

Massachusetts Institute of Technology
Department of Civil and Environmental Engineering

Daniel A. Zarrilli

Goals and Objectives:

The purpose of this research is to investigate the inspection and maintenance strategies necessary for the successful long-term operation of Tren Urbano and to identify options for a long-range inspection program. Through the study of similar rail transit systems and interaction with government leaders, contractors, and inspectors, I will develop a strategy for the inspection and maintenance of Tren Urbano.

Background:

Contract Book II of the Systems & Test Track Turnkey Contract – Operations and Maintenance explicitly states:

2.7 – System Maintenance:

> "The Contractor shall maintain the Service Property in accordance with…all…applicable provisions of the Contract Documents. Maintenance Services shall include furnishing all labor and utilities and furnishing and replacing all materials, supplies, parts, components and tools and equipment necessary to accomplish the proper inspection; cleaning; adjustment; preventive and corrective maintenance; lubrication;

repair; testing; replacement of parts and equipment; supplying of spare equipment, consumables and expendables; and repair of spare equipment of all parts of the Service Property and the Project."

Therefore, the Owner is requiring the Contractor to be responsible for performing all of the proper inspection and maintenance on Tren Urbano. This, as agreed upon, seems fair. However, one can easily see the problems in the terminology of the above. What are "proper" inspection and maintenance procedures? For both the Contractor and Owner to agree upon an answer, a more detailed specification is needed.

Subsequently, the contractor is required to submit, as outlined in **Section 17020** of the **Technical Provisions – O&M**, no later than 360 days prior to commencement of revenue service, a **Facilities Maintenance Policy and Procedures Manual**. This manual will outline the scope of maintenance and inspection procedures for the entire project, including tracks, mainline structures, stations, rights-of-way, and other buildings and grounds of the project. In order to fully evaluate the services proposed in this manual, the owner needs some way to gauge the completeness and appropriateness of the proposed services.

A major focus of this research will be to develop a set of guidelines that would be utilized by the Owner to assess the proposed services. What should be expected of the Contractor? What procedures need to be followed? At what frequency should inspections be performed? Why are inspections important at all? Since the contractor is solely responsible for the proper inspection and maintenance of the entire project, it is the Owner's responsibility at this point in time, and definitely prior to 360 days before the start of revenue service, to establish the scope of required inspection procedures. Failure to establish guidelines at this juncture could mean the blind acceptance of inefficient, improper, or corner-cutting procedures, which would jeopardize the long-term serviceability of the project, or even the safety of it's users.

Scope:

In the first year of this research, several duties will be performed. First, a literature search will be undertaken to evaluate various information including, but not limited to:

- Previous research in the field of inspection policy.
- Studies evaluating inspection effectiveness.
- Studies outlining inspection policy and procedure for rail transit systems.

Second, investigations will be done to evaluate the inspection and maintenance procedures of rail transit systems in several East Coast and several Latin American cities. These studies of other rail transit systems will include a historical overview of past inspection practices and their subsequent results, along with a present-day evaluation of current procedures, methodologies, standardizations, and expected or obtained results.

Finally, a thorough analysis of this data will result in an array of options, which could be laid out and discussed with their relevance to the Tren Urbano Project. Care must be taken to ensure that the studies chosen represent scenarios similar to Tren Urbano in order to make effective comparison.

A second focus of this research, to be conducted in the second year of research, will be a review of likely issues within the current design. Through an analysis of the structural design of stations and track work, a proper inspection program can be developed conducive to the goals of Tren Urbano. Certain information, including as-built plans, initial strength data, and photo documentation will need to be developed and archived at the point of completion of construction. This data is extremely important to inspectors, and serves as a valuable starting point for maintenance operations.

Summary:

The results of this research project will be:

- An evaluation tool to evaluate the Contractor's proposed Facilities Maintenance Policy and Procedures Manual.
- A review of the structural design leading to specific recommendations for proper inspection criteria.
- A more general conclusion on inspection procedures and methodologies for rail transit systems in North and Latin America.

Massachusetts Institute of Technology

Research Proposal:
Optimization of the Elevated Railway Structure in the Tren Urbano Project

Submitted to
Tren Urbano Project

By
Héctor J. Cruzado

Background

Designing a bridge or an elevated railway is a very complex task. It has the fundamental objectives of safety, serviceability, economy, and elegance. The final design will depend on the weight that it is given to each of these objectives.

Progress in the field of structural analysis include innovations in computer analysis and a greater understanding of the behavior of structures. Therefore, there has been an increase in the demand for structures that require less maintenance, that make optimal use of space, and that behave better when subjected to lateral loads such as earthquake and wind loads.

A great number of decisions have to be made in order to make a design that fulfills all the desired objectives. One of these decisions is the selection of what kind of span should be used. Basically, it must be decided between using simple spans or a continuous system. Furthermore, if a continuous system is selected, then a continuous unit needs to be chosen (two span continuous, three span continuous, etc.). Selecting a continuous system over the use of simple spans will have an effect on a number of important aspects of the structure. Some of these effects are positive, and some are not.

When using prestressed concrete, selecting a continuous system can provide one or more of the following advantages:

1. Reduction of the size of the cross-section due to the reduction of the maximum moments and stresses at the midspan. Having a smaller cross-section means having a reduction in the cost of materials and, possibly, construction. Also, the structure would be lighter, which means that the columns and foundations can be lighter, which in turn means further reduction in the cost of materials and, possibly, construction.

2. If the same size of the cross-section that would be used for a simple span is kept, this would mean a stiffer member than the simply supported one. Therefore:
   - The continuous unit could resist heavier loads than the simply supported member.
   - The continuous units would have a smaller deflection than the simply supported member if they were both subjected to the same loading.

3. The over-all structural stability is improved through redundancy.

4. Greater resistance to longitudinal and lateral forces.

5. The number of anchorages needed to tensioned the steel at intermediate supports can be reduced when compared to the quantity used for simply supported members. This means further reduction in costs and labor.

6. The number of expansion joints and bearings used could be reduced. This means that the structure would require less maintenance, and therefore, there would be a reduction in cost. Other problems associated with expansion joints, such as leakage, corrosion and nesting, could be minimized. Also, by reducing the number of bearings, the width and thickness of the piers can be reduced. In turn, having slender piers makes the structure more aesthetically pleasing.

7. The structure provides more ride comfort when compared to a simply supported system.

It can be seen, that the use of a continuous span can bring an improvement in the four fundamental objectives of bridge design.

Like any type of construction, selecting continuous units when using prestressed concrete can have disadvantages. These could be:

1. Reduction in the prestressing force when continuous tendons are used. This is due to the greater friction between the prestressing steel and the duct through which the steel pass.

2. Concurrence of moment and shear at the support sections, which either, reduces the moment strength at this sections, or requires the use of more reinforcement.
3. Excessive lateral forces and moments are formed in the supporting columns, particularly if they are rigidly connected to the beams. These forces are caused by the elastic shortening of the long-span beam under prestress, and by horizontal loading that could come from earthquakes, acceleration and breaking of vehicles, and temperature changes.

4. The secondary stresses, usually produced by shrinkage, creep, temperature variations, and settlement of the supports, are magnified when compared to a simply supported structure.
5. Greater elongations at the free-ends are caused by an increase in temperature.
6. If live loads are much heavier than dead loads, and if partial loadings on the spans are considered, the beam can be subjected to serious reversal of moments.
7. Continuous beams are more difficult to design than simply supported beams.

These disadvantages, depending on certain conditions, could outweigh the advantages. All of the mentioned disadvantages can be accounted for through appropriate design and construction.

Besides choosing between simple spans or continuous units, another important decision that has to be made when designing a bridge or an elevated railway is the selection of the bearings, expansion joints and supports to be used. The ones chosen must be fit to handle displacements of the structures such as those caused by the changes in temperature or seismic loads. In particular for bearings, a decision must be made between bearings of low cost that need a lot of maintenance and have a short life-span, or more expensive bearings that need less maintenance and a have a longer life.

The Tren Urbano Context

The current design of the elevated railway to be built for the Tren Urbano Project uses two-span-continuous units. These units are girders formed by precast box segments, seated in epoxy, and held together by partial prestressing (meaning that the girder section will have some tension stresses under loading).

At the beginning and at the end of each pair of spans there are expansion joints with elastomeric bearings that need to be replaced approximately every 25 years. It has been proven historically that this type of joints are affected substantially due to the environment in Puerto Rico and in other parts of the world. Lack of maintenance and replacement of these joints shortens the life of the bridges that use them. In addition, expansion joints are also known to be the source of other problems such as leaking, corrosion, and nesting.

Earthquake loads control the design of most of the elements that compose the elevated railway. Although there has not been an earthquake in Puerto Rico since 1918, the island is located in a zone highly predisposed for earthquakes. This, combined with recent events in California and Japan, make designing for earthquake loads an important aspect for the Tren Urbano Project. Design for earthquakes is a field that is increasing in awareness and sophistication.

Research Objectives

The objectives of this research are:

a) Improve upon the current design of the elevated railway structure of Phase I section of the Tren Urbano Project, in hope that these improvements are considered for adoption in future sections of the project.

This objective will be achieved by analyzing how the behavior of the structure would be affected by changes in span (simple span, two-span-continuous, three-span continuous, etc.), and trying different sets of bearings and supports with each of the changes in span. Alternative designs might have the following advantages over the current design:

1. Less vibrations.
2. Smaller deflections.
3. More stability.
4. Greater resistance and better behavior under lateral loads, particularly earthquakes.
5. Use of fewer expansion joints and bearings, which in turn would mean a structure that needs less maintenance.
6. Improved appearance.

b) Study the feasibility and economic impact of the alternative designs.

Once an optimal design is found, it needs to be determined what is needed to be done to make the changes and what are the costs associated with these changes. The cost-effectiveness of making the changes, as compared to keeping the current design, will be studied by performing a life-cycle cost analysis. This will determine the plausibility of making the improvements to the design.

Work Program

1. *Literature Review* (September 15 to October 15)
A literature review will cover the following subjects: prestressed concrete, segmental beams, continuity, joints and bearings, earthquake loads, and life-cycle costs.

2. *Research on Existing Structural Analysis Modeling* (October 15 to October 31)
Existing modeling techniques will be studied, including the use of both, commercial and academic computer programs. Special attention will be placed on the possible advantages and disadvantages of using these techniques for an analysis of the structure of the Tren Urbano Project.

3. *Model Refinement* (November 1 to November 20)
Based on information found on the modeling research and on the available tools to this researcher, an existing model will be adapted or modified so that it can be used to predict the structural behavior of the elevated railway of the design of the Phase I section of the Trèn Urbano Project. Also, it must be able to be modified so that it is possible to predict the changes in the structural behavior in the case of design changes.

4. *Structural Analysis* (November 20 to December 10)
Using the developed model, a comparison analysis between the structural behavior of units of different continuity and different bearing and support systems will be made. From the results obtained through the analysis, a design with an optimal structural behavior will be chosen.

5. *Publish Interim Report* (December 10 to December 31)
A report will be written presenting the progress made up to this point of the research.

6. *Life-Cycle Cost*
A life-cycle cost analysis will be performed to determine what is the cost-effectiveness of improving the elevated railway design.

7. *Refinement of Analysis and Design*
If necessary, the modeling of the structure will be improved. The Structural Analysis and the Life-Cycle Cost analysis will be combined to obtain the most optimal structure in terms of both, structural behavior and cost-effectiveness.

8. *Final Report*
A final report will be written, giving recommendations and presenting the conclusions reached in this study.