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Bridges: Structures and Materials, Ancient and Modern

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Abstract

Every nation needs the infrastructure to perform all kind of activities related to the improvement and service of the society. Transportation system became part of the infrastructure due its connection between two destinations, using maritime, land, or aerial methods, creating a link for social and economic activity. Bridges are widely used to cross rivers, valleys, and roads, providing a passage with other parts of the land since ancient times to modernity. Each structure has different requirements to cover, such span clearance, traffic flow, geometry and characteristics of the place to build; therefore, a great variety of bridges can be developed. Common materials used on construction are structural steel, reinforced concrete, pre-stressed concrete, or post-tensioned concrete; depending on the structural behavior of each type of bridge, there will be a maximum clear span to cover, which depends directly on the project's budget. There are a variety of loads and environmental conditions that the new and existing structure needs to support effectively, including dead load, traffic, rain, wind, flood, and seismic events, using effective structural design process and techniques; on the other hand, there are long-term deterioration process, such as corrosion, wear, and fatigue, which should be considered on the maintenance process, avoiding additional costs, several damages, and catastrophic failures. Prevention and control of degradation process is achieved by effective maintenance methods applying protection technology such as paints, coating and cathodic protection. The purpose of this chapter is to show a brief review of ancient and modern bridges, including the process of design, material selection, construction, and maintenance.

Keywords: infrastructure, bridges, maintenance, deterioration, construction

1. Introduction

If a society wants all its function working efficiently, it requires many elements that meet its needs. Basic functions such as food, water, electricity and transportation require all types of structures to fulfill its purpose. Infrastructure embraces all the buildings that support the goods and services of the community, with an integral and optimal functioning.

All the services of the society require some type of support to be carried out. An engineer, architect or lawyer needs a space to develop their businesses and support its clients; a merchant needs a highway to transport their products to their final

destination; supplying water to any destination requires pipes, pipelines and tanks. There are many examples where each service requires some type of infrastructure.

As a general example, consider the construction of an international airport. The main purpose is the aerial communication of the city, which can be used for traveling, tourism and transportation of goods. Listing all the needs of any airplane, there will be at least the following requirements to fulfill:

- a. Landing strip to perform effectively the air traveling.
- b. Control tower for monitoring the air traffic flow.
- c. Airport building to perform all administrative activities.
- d. Hangar for airplane maintenance and storage purposes.
- e. Water supply, storage, pipelines and sewage for the entire place.
- f. Fuel supply and storage for the airplanes.
- g. Land highways and bridges to connect the city with the airport.
- h. Electricity towers and electrical station to supply energy.

According the previous example, there are many construction elements and buildings that enhance the aerial communication. The combinations of these structures contribute with the airport to operate efficiently. This type of infrastructure can contribute enabling tourism, transportation, productivity and employment opportunities, increasing the economic activity. Therefore, the infrastructure has a wide variety of structures which can be part of a specific sector and fulfill a simple function.

If any infrastructure element of the airport fails, there will be issues with its functionality; for example, if any bridge is closed due any malfunction or maintenance, the transport of the passengers, goods and services will be affected.

Bridges have a special place in transportation infrastructure due its direct relationship with other places. These structures have the purpose to carry on the traffic loads of the highway, crossing any obstacle and perform an effective communication between two destinations. Since there are many variables to consider in the performance of the bridges, such geometry, span clearance, traffic flow and available materials, there are many options of bridges to choose.

Planning, design and construction process for any bridge looks logical and necessary steps, looking for the good behavior of the structure during any traffic load or resisting flood or seismic events. However, maintenance process guarantee the life of the structure, which applied correctly, will avoid any closure of the bridge and traffic issues.

On this chapter, the main purpose is to focus on bridges as part of land transportation infrastructure, its behavior and the performance during the design, construction and maintenance process.

2. Infrastructure

Basically, all the buildings are part of the infrastructure and fulfill a specific function. According to the American Society of Civil Engineers (A.S.C.E.), there are

16 categories in the infrastructure: Aviation, bridges, dams, drinking, water, energy hazardous waste, inland waterways, levees, parks, ports, rail, roads, schools, solid waste, transit and wastewater [1]. Due to a wide variety structures, the infrastructure can be classified according to its use.

a. Transportation infrastructure

Related to all structures used by the people, products, goods or services to move forward its final destination. Depending on the type of transport, these can be divided into three categories:

- i. *Land*: City roads, highways, train rails and bridges.
- ii. *Maritime*: Structures used by ships or vessels, for example ports and channels.
- iii. *Aerial*: Airports and heliports.

b. Energy infrastructure

Related to all structures intended for the generation and distribution of any types of energy. Depending on the energy type, it can be divided into:

- i. *Electricity*: Electrical stations and supply networks.
- ii. *Oil and gas*: Refineries and pipelines.
- iii. *Alternative energy sources*: Wind towers, nuclear plants and geothermal plants.

c. Hydraulic infrastructure

Structures intended for water distribution and supply, divided into:

- i. *Water distribution network*: Related to water supply, distribution and irrigation. Examples include open channels, pipelines and aqueducts.
- ii. *Drainage networks*: Related to distribution and storage purposes, including gray water from industry and rain. Examples include sewer and drainage.
- iii. *Waste water treatment plants*: Related to structures with waste water cleaning purposes, including removing sediments to biological cleaning process.
- iv. *Water storage*: Related to structures to retain water. Examples include dams and storage tanks.

d. Telecommunication infrastructure

Related to all structures intended for telecommunication industry:

- i. *Cellphone network*: All structures supporting signal development for cellphone operations, including antennas and signal structures.
- ii. *Television, radio and internet network*: Related to antennas for signal distribution via cable wires and wireless signal.

e. Building infrastructure

Related to all structures intended for industry requirements, business community, energy operations and living places.

- i. *Industry and business*: Structures used for industry and business operation purposes. Examples include a single or multiple story structures and may be used as offices, machinery, equipment and industrial process.
- ii. *Living places*: Intended for population housing, including buildings of single or multiple story levels.
- iii. *Basic services*: Structures related to operation services as water distribution, electricity and general supplies.
- iv. *Primary services and recreational purposes*: Places designed for city assistance, including fire and police stations, hospitals, schools, theaters and stadiums.

Figure 1 shows a general view of Mexico City and the Vidalta cable-stayed bridge as transportation infrastructure, connecting via highways the whole series of multi-story buildings in the background.

According the previous infrastructure classification, all described structures do not work as isolated buildings. Instead, all elements must be connected looking for the harmony in a society, working effectively and should not affect any building performance.

As an example, there is a hospital that provides all types of medical treatment in an urban area. If the city's electrical stations stop working, the hospital will cease to be fully functional due to lack of electrical power, affecting medical equipment and lighting requirements. Now, if the same hospital has no enough roads for access, its capacity will be very limited, including medical staff and patients.



Figure 1.
View of Vidalta cable-stayed bridge, Mexico City [2].

3. Bridges, a general overview

We recognize that all structures are part of the infrastructure and each one works together. The bridges take a special role, due its function to connect two different points, crossing valleys, rivers, lakes and cliffs.

Bridges are needed on land transportation infrastructure because they connect different points that usually can be inaccessible. If we analyze a single bridge crossing a river, it can have many views, depending on each person's perspective [3]:

- a. A person who lives in the city can visualize the bridge as a simple access to schools, parks and theaters, or a simple way to visit a family member.
- b. An engineer or architect visualizes the bridge as a way to connect the road with two points of the city, such as hospitals or fire stations.
- c. From the business community, the bridge can be viewed as access to different areas for trade, distribution of goods and services.

Depending on the needs of the society to have a bridge, it would be its importance. A bridge that serves as a quick link to recreational parks with a low traffic flow will have less impact than a bridge crossing a large river and connecting two points of the city with high traffic flow.

Taking into account the sentence above, we can realize that bridges are not built arbitrarily; a whole planning should be performed including design, construction, operation and maintenance of the structures. Therefore, for the transportation system, the bridge is a key element [3] according to the following reasons:

- a. Capacity control

- i. Bridges must comply with traffic flow needs during its life period.

If a bridge has a small number of lanes, narrow sizes or poor spaces, the structure cannot maintain a continuous vehicular flow.

- ii. Bridges must comply with required loads during its life period.

This means that the analysis and structural design must take into account all the loads that the bridge must support. For example, if the structure is located on an interstate highway and was not designed to support heavy truck loads, it will have limited vehicle traffic and those trucks will not be able to use the bridge; therefore, these trucks will have to plan an alternate route.

- b. High cost for the entire road system

- i. Bridges represent a high percentage of road's budget.

If we analyze the construction process of a road and measure the cost per unit distance, the bridges are very expensive compared to the highway.

- ii. High cost variability for different bridge geometries.

Depending on the number of lanes required, types of vehicles to be supported, distances and/or clear span to cover, materials and available labor, the cost of the bridges are variable. Proper planning is required to meet the needs and comply with the budget.

- c. The bridge as part of the system

- i. If the bridge has a failure, the road system fails.

If we analyze the entire road and at specific place, one of the bridges does not work, the vehicular flow will be affected, increasing traffic flow, delays, time lost and the need of alternative route.

- ii. If the bridge is not operating, alternate routes will be affected.

When a bridge does not work, people who used the affected road will have the need to use an alternative route, which probably is not designed for a sudden increase of vehicular flow, causing wasted time, greater distances and additional fuel required.

For a successful transportation system, a balance should exist between vehicle volume, supported loads and proper budget. **Figure 2** shows a section of Mexico City's transportation system, showing balance between the number of lanes, signs, bridges and several road accesses.

3.1 Types of bridges: ancient and modern

We can think that all existing bridges with the variety of materials, geometries, loads and designs have always existed. However, the evolution of bridges has occurred within the changing needs of the society since the 19th century, with the improvement of materials, optimization techniques, architectural and structural designs [3].

3.1.1 Ancient bridges

In the beginning, bridges were built with a simple geometry and had very limited uses, because they only covered very short span, such as small rivers. These bridges used basic materials such as wood, ropes and stone.

3.1.1.1 Stone arch bridges

The first bridges that were built based on mathematics methods were the stone arch. The exact construction date is not known, but there are structures built by civilizations such as the Greeks or the Romans, where they used this type of bridges as aqueducts, roads for people walking and carriages.

The stone arch bridges, as shown in **Figure 3**, take advantage of the compressive capacity of the rock due its geometry, supporting its own weight and live loads. These structures are usually robust and each of the arches supports the upper deck. Some examples of this bridge's type are the Segovia Aqueduct, located in Spain and the Pont Du Gard Aqueduct, located in France, both built between the 1st and 2nd centuries.



Figure 2.
View of Mexico City road system [4].

3.1.1.2 Wooden and steel truss bridges

By the beginning of the 19th century, the structures used wood as common material and truss bridges began to emerge (**Figure 4**). These wooden trusses took advantage of the axial stress capacity of the bar elements, creating bridges with longer spans, low weight and enough stiffness to withstand higher loads. Due the large number of geometries that can be created with trusses, there are possible arrangements which the bar elements can have taking advantage of the tension and compression stress capacities. Some examples can be mentioned:

- a. Trusses with straight bars
 - i. Geometries as Pratt, Warren and Baltimore types.
 - ii. Geometries using cables for tension elements.
- b. Combination between trusses and arch
 - i. Geometries as Wernwag and Burr types.

3.1.2 Modern bridges

In the mid-19th century, with the development industry sector, vehicles and trains entering into circulation using the current transportation system. Therefore, a greater number of roads, railroad and bridges were built to serve the increase of transportation demands.



Figure 3.
Stone arch bridge crossing a small river.

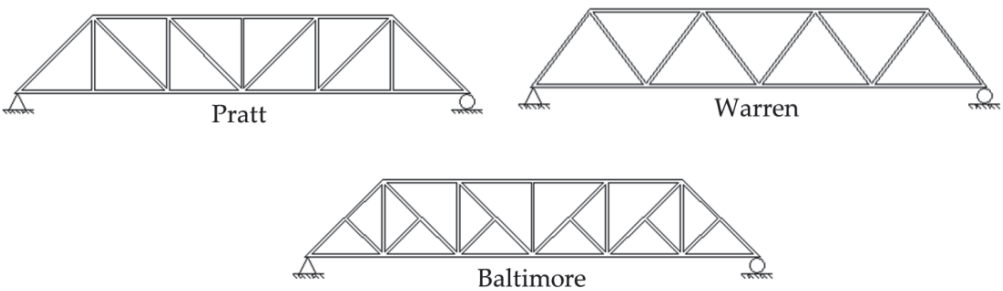


Figure 4.
Geometry types of trusses.

3.1.2.1 Steel truss bridges

Since the increase of traffic flow and weight of vehicles started, the wooden bridges were already insufficient to support these vehicle loads and the structures began to use steel materials. With the structural steel available on construction market, these bridges had a significant improvement, including the increase of spans length covered and supporting higher loads. Steel trusses bridges replaced wooden trusses and began to build bigger structures. **Figure 5** shows an example of this bridge's type.

3.1.2.2 Suspension bridges

The introduction of suspended bridges was an important innovation, due the very large spans length that they can cover. These structures have very large geometries with visual impact on the users, using them as a symbol for the city. Examples of such structures are the Brooklyn Bridge, located in New York and the Golden Gate Bridge, located in California. The overview of the Golden Gate Bridge is shown in **Figure 6**.

The geometry of the suspended bridges consists of two central support towers, the main cables supported between the towers, the secondary cables supported on the main cables, the main deck and supporting girders. As a structure, all cables work as tension elements and support the main deck where the traffic flows.

Due the tension cables, suspended bridges can take advantage of the ability to obtain very large spans without intermediate supports. They are widely used to cross very large rivers where conventional bridges are unable. However, one of the



Figure 5.
Forth bridge, Edinburgh, Scotland [5].



Figure 6.
Golden Gate suspended bridge, San Francisco, U.S.A. [6].

disadvantages of this type of structures is the aerodynamic stability, product of the slenderness relationship between main slab, span clearance and the action of thrust forces produced by the wind loads.

3.1.2.3 Reinforced, pre-stressed and post-tensioned concrete bridges

With the introduction of Portland cement on the market and the development of concrete construction techniques, design theories for reinforced concrete were developed for structures on the early 20th century.

For long span bridges, reinforced concrete bridges based on arch below main deck are used. It basically consists of an arch in the lower section and piers to support the main deck. All the elements of the bridge are working under compression, with the exception of the main deck that works at flexure. These types of bridge take advantage of the material capacity on compression and avoid tension elements.



Figure 7.
Bridge of pre-stressed concrete Girders el Zacatal, México [7].

Most of the existing bridges cover small and medium spans, which are very useful for roads and highways connecting cities. Girder-based structures with simple or continuous supports are widely used for these cases.

Girder-based bridges can be inefficient due the bending behavior of the girder if we compare it with trusses. However, the girders are relatively easy to build and the relationship between cost and benefit makes these types of structures economically competitive. **Figure 7** shows El Zacatal Bridge, located on Mexico and based on pre-stressed concrete girders.

3.2 Structures and functions

Depending on the span to be covered, the traffic flow, the availability of materials and labor, the designer will define the geometry of the bridge. Most of the bridges have short spans and use girders of reinforced concrete, pre-stressed concrete or structural steel. Bridges with intermediate spans use trusses and arches. For very large spans, suspended bridges are the best option.

All types of bridges must have the following qualities:

- a. Cover the vehicular flow demand, with enough lanes and/or spaces.
- b. Support dead, live and accidental loads.
- c. The structure is economically viable.

3.2.1 Structural analysis and design

To comply with the previous qualities, the general statement to ensure safety on the structural design of any bridge should follow the next equation:

$$\text{Resistance} \geq \text{Effects of the loads} \quad (1)$$

The structural design process includes two general ways to comply with Eq. (1) and develop safety structures [1]:

a. Allowable Strength Design (ASD)

- i. This procedure uses the linear behavior of the materials with a defined yield strength which is located below the ultimate strength.
- ii. Safety is obtained specifying the effects of the loads should produce stresses as a fraction of yielding stress.

b. Load and Resistance Factor Design (LRFD)

- i. This procedure reduces the resistance multiplying a resistance factor ϕ , usually less than 1; and the load is multiplied by a load factor γ , usually greater than 1.
- ii. Since each load has different levels of recurrence, these factors will vary depending on the load type.

The general way to obtain the stresses depends directly on the applied force, the internal force and the geometry of the structural element [8]. The behavior of each load applied can be listed as follows:

3.2.1.1 Axial stress

Applied to elements with tension or compression forces.

$$\sigma = \frac{P}{A} \quad (2)$$

Where:

σ : Axial stress. Units: lb./in² (N/mm²)

P: Internal axial force. Units: lb. (N)

A: Cross-sectional area. Units: in² (mm²)

3.2.1.2 Direct shear stress

A to elements with direct shear forces.

$$\tau = \frac{V}{A} \quad (3)$$

Where:

τ : Direct shear stress. Units: lb./in² (N/mm²)

V: Internal shear force. Units: lb. (N)

A: Cross-sectional area. Units: in² (mm²)

3.2.1.3 Torsion stress

Applied to elements with torsional moments.

$$\tau = \frac{Tr}{J} \quad (4)$$

Where:

τ : Torsional stress. Units: lb./in² (N/mm²)
 T: Torsional moment. Units: lb-in (N-mm)
 A: Cross-sectional area. Units: in² (mm²)

3.2.1.4 Bending stress

Applied to elements with bending moments.

$$\sigma_b = \frac{Mc}{I} \quad (5)$$

Where:

σ_b : Bending stress. Units: lb./in² (N/mm²)
 c: Distance between neutral axis and external fiber. Units: in (mm)
 I: Moment of inertia of the cross-sectional area. Units: in⁴ (mm⁴)

3.2.1.5 Shear stress due bending

Applied to elements with bending moments.

$$\tau_b = \frac{VQ}{Ib} \quad (6)$$

Where:

τ_b : Shear stress due bending. Units: lb./in² (N/mm²)
 Q: Moment of area. Units: in³ (mm³)
 I: Moment of inertia of the cross-sectional area. Units: in⁴ (mm⁴)
 b: Width of the cross-sectional area. Units: in (mm)

For structures with combination of forces applied at the same times, all stresses are present and interact in the same time. Therefore, the stress combination can be represented with maximum and minimum principal stresses, as shown below:

$$\sigma_{1,2} = \left(\frac{\sigma_x + \sigma_y}{2} \right) \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2} \right)^2 - \tau_{xy}^2} \quad (7)$$

Where:

σ_1, σ_2 : Maximum and minimum principal stress.
 σ_x, σ_y : Normal stress on x or y direction due axial or bending forces.
 τ_{xy} : Shear stress due direct shear forces, torsion or bending forces.

Units for all stresses: lb./in² (N/mm²)

According to Eq. (7), we should note that on maximum and minimum principal stress, the shear stress is always zero. Now, the maximum shear can be found following the next equation:

$$\tau_{max} = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2} \right)^2 - \tau_{xy}^2} \quad (8)$$

In the case of the maximum shear stress, the normal stress is not zero and can be found as follows:

$$\sigma_{prom} = \left(\frac{\sigma_x + \sigma_y}{2} \right) \quad (9)$$

3.2.2 Bridge categories according the location of the main deck

The bridges can be classified according to its size, geometry, main function and structure type. As a general way, the bridges can be divided into three categories:

Category 1: The structure is located below the main deck.

- a. Straight trusses.
- b. Trusses with arch geometry.
- c. Arches with stone or masonry material.
- d. Rigid frames.

The geometry of this type of structures allows the user to have a clean view of the road. In addition, most of the structural elements of the geometry have to work under compression stress.

Category 2: The structure is located above the main deck.

- a. Trusses.
- b. Suspension bridges.
- c. Cable-stayed bridges.

For these types of structures, the geometry is fully visible and for large bridges, such as suspended or cable-stayed, the user can appreciate the architecture. Most of the structural elements have to work under axial loads, mainly tension.

Category 3: The structure coincides with the main deck.

- a. Girder-based bridges.
 - i. Lightened and solid slabs.
 - ii. Girders with varieties of cross sections.

These types of structures work mainly under bending and shear stresses. Bridges of this type are the most used for short span.

3.3 Special bridges: Mexicali, Tacoma, Coatzacoalcos, Calatrava Jerusalem

Due to the great imagination of design and construction process, there are a large number of bridges in operation with a wide variety of geometries. Therefore, below are a few examples to show.

3.3.1 Mexicali bridges: solution of the road distributor

The Mexicali road distributor consists of a series of bridges connecting the main roads with the purpose of traffic flow continuity. Basically consists of two reinforced concrete bridges as underpass section and two structural steel bridges as overpass section. This structure is shown in **Figure 8**.

The underpass bridge section, both for vehicular and a railway line, consists of a reinforced concrete slab supported at the ends by retaining walls and circular columns of reinforced concrete supporting the center of the span. The main structure of this bridge section works as continuous girder. The spans are relatively short and the structural slab depth is enough to fulfill the flexure stresses requirements.

The structure also has two structural steel decks as an overpass bridges, consisting of continuous girder and supported by steel columns. The length of the spans is small since they do not exceed 165 feet (50 m). A particular feature of this particular structure is the energy dissipation device located below the girder supports. Mexicali has high seismic activity and the structure needs to withstand the seismic loads with good lateral displacement performance.

3.3.2 Tacoma narrows bridge: a lesson learned

The suspension bridge located at Tacoma Narrows consists of two main structural steel towers supporting a main cable and the main deck is stiffened by two steel girders. A total length of 5905 feet (1800 m) and a span of 2930 feet (893 m) were covered. It was inaugurated in 1940 and became one of the largest bridges in the world.

The main feature of this bridge was the dramatically collapse of the main deck after a few months of inauguration, due to the oscillating movement with the action of the wind flow. These forces were considered for structural design; however, with a much slower wind velocity, the vibration movement increased with enough speed to make the structure collapse. Looking into **Figure 9**, the oscillating movements of the bridge can be observed.

Under research, the main reason for the collapse of the bridge was the concept of resonance, which means, a range of coincidence between the natural frequency of the structure and the frequency of wind thrust loads. The concept of vibration and resonance is not visible easily and many factors influenced on the event:



Figure 8.
Mexicali bridges, road distributor [9].

- a. Very high slenderness ratio of the bridge.
- b. Use of girders instead of truss as deck stiffener.
- c. Obstruction of air flow due the girder itself, causing whirlwind.

After this event, studies on aerodynamics and aero-elasticity topics in the structures increased significantly, developing procedures to simulate these events on structures, including bridges of very large spans.

3.3.3 Coatzacoalcos bridge: Mexico infrastructure

The cable-stayed bridge located in Veracruz, Mexico consists of two main reinforced concrete towers that support the main deck with cable tensors and the slab stiffened by two reinforced concrete girders. The structure has a total length of 3838 feet (1170 m) and a span length of 944 feet (288 m). **Figure 10** shows an overview of the structure.



Figure 9.
Tacoma narrows suspension bridge, under aerodynamic vibrations [10].



Figure 10.
Coatzacoalcos II cable-stayed bridge overview [11].



Figure 11.
Jerusalem cable-stayed bridge [12].

The bridge consists of 15 supports, 14 sections and the main structure. The towers and secondary columns are made of reinforced concrete; the main girder is shaped like a drawer with reinforced concrete and the cable tensors supporting the main deck are made of structural steel. It was inaugurated in 1984 and considered one of the largest structures in Mexico.

3.3.4 Jerusalem bridge: architecture and modernity

This cable-stayed bridge is located in the city of Jerusalem and has a total span of 1181 feet (360 m). The bridge aims to help the city light rail system and the structure consists of a main tower connecting the structural steel slab using 70 steel cables and reinforced concrete supports.

The main feature of this bridge belongs to the architecture and geometry. It was designed by Santiago Calatrava, a world-renowned architect and engineer, and the user can recognize the structure as an unconventional bridge. As shown in **Figure 11**, we can see the special geometry of the main tower and each of the cable tensors, showing a harp shape. In addition, the main deck has a curved form.

The structure was inaugurated in 2008 marking a symbol in the city of Jerusalem. Due to the great height of the main tower and its harp-shaped geometry, the bridge can be appreciated from any place of the city.

4. Bridges construction and materials

Due the large number of variables on the conceptual design of a structure, there is no special formula for determining the best option of a bridge. Many variables come into play, from the experience of the engineers and architects, to the specific needs of the place, such as topography, soil characteristics and materials availability.

There are several models to describe the general process of design, built, operation and maintenance of a bridge in a general way. One of the most compact flowcharts was proposed by Addis [13], shown in **Figure 12**.

The process for any bridge design consists of input data, regulations, design process and results, explained as follows:

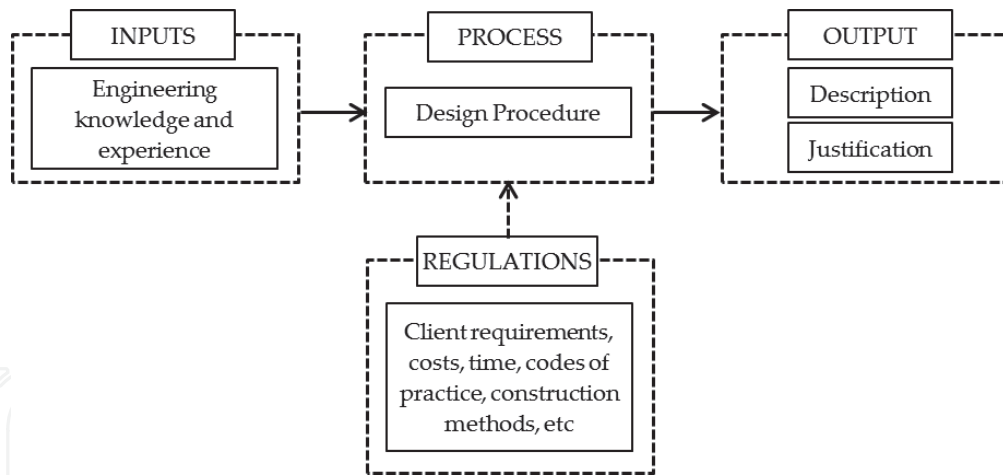


Figure 12.
Model of the bridge design process [13].

4.1 Inputs

All the information required to start the design process of any bridges is placed in this category and can be classified as public and personal. Public information refers to all existing bibliography like books, magazines, publications and software available in the industry. These references should include all topics related to bridges such as material properties, construction process, architectural design and structural design. Personal information refers to the experience acquired by engineers, architects and companies dedicated to the construction industry.

4.2 Regulations

All the rules, restrictions and limitations imposed on the process of creating and design fall into this category. Details such as the budget, the client's guidelines, construction regulation and allowed materials are some of the established rules.

4.3 Output

All the information processed to be able to build any bridge is placed in this category and can be divided into the description and justification of the results. The description refers to all drawings, including architecture, structural, facilities and roads. The justification refers to all technical information that supports the drawings, from structural engineering to budgets.

4.4 Design procedure

In the central part of the flowchart is located the bridge design process, where the input data, regulations and results are interacting together. The design of a bridge implies the imagination of engineers and architects to solve the problem statement, use of the previous knowledge to select the best geometry option and justify the solution with the required calculations.

The flowchart process applies to any type of bridge and can be simple or complicated as required. If we want a successful development of any bridge, there must be a balance between the variables described in **Figure 12**.

Another point regarding the design process of bridge is the selection of the appropriate material and geometry. According to **Table 1**, a recommended bridge's type is shown using geometry, material and span range selection variables [3].

Bridge type	Material	Span range
Slab	Concrete	0–40 ft. (0–12 m)
Girder	Concrete	40–1000 ft. (12–300 m)
Girder	Steel	100–1000 ft. (30–300 m)
Cable-Stayed	Steel	300–3500 ft. (90–1100 m)
Truss	Steel	300–1800 ft. (90–550 m)
Arch	Concrete	300–1380 ft. (90–420 m)
Arch	Steel	800–1800 ft. (240–550 m)
Suspension	Steel	1000–6600 ft. (300–2000 m)

Table 1.
Span lengths for various bridge types [3].

The recommended span range is related directly with budget challenges of each project. As an example, consider the construction of 100 m span length structure which can be developed using a concrete slab and concrete girder, according to the recommendations of **Table 1**.

Performing a structural and design of the proposed bridge, we can find the minimum size for the concrete slab and the concrete girders; considering concrete slab, the thickness to support 100 m of span will require a great depth in slab and therefore, a large amount of concrete material will be required; therefore, if we use girders, the amount of material will be less in comparison.

Depending the span range and geometry of the project, the best economical option of bridge selection will be the efficient use of each material mechanical properties, stress-strain relationship and the characteristics of the site.

4.5 Steel bridges

Bridges with steel material can enter into any of each three categories described on Section 3.2.2. Depending on the type of steel to be used, yielding allowable stress of the structural steel can vary between 36 ksi (249 MPa) and 70 ksi (483 MPa). According to the American Institute of Steel Construction [14], common steel alloys are A36, A992 and A572 Grade 50.

Within the steel bridges, the most common geometries are:

- a. Straight truss, variable geometry truss or arc-shaped trusses.
- b. Cable-stayed bridges.
- c. Suspended bridges.
- d. Bridges supported by girders.

A steel truss bridge is shown in **Figure 13**, with straight truss at the center of the span and variable height near the column supports. The incremental height on the truss near the columns occurs due an increment axial stress in each truss member. The foundation, anchorage and check slab are made of reinforcement concrete; piers can be made of steel or reinforced concrete, depending the site characteristics.

Steel cable-stayed bridge and suspension bridge with general geometry are shown in **Figures 14** and **15**. Both structures have a main tower supporting the main

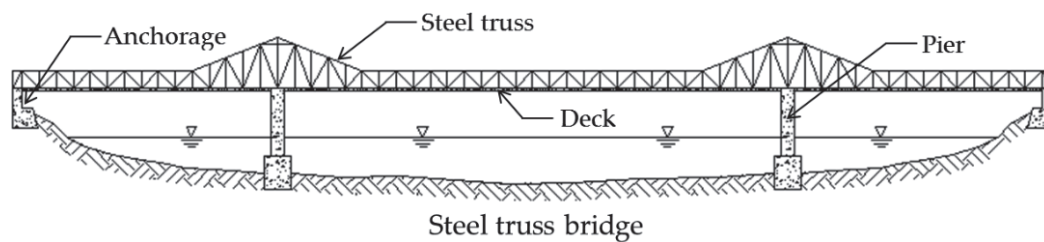


Figure 13.
Steel truss bridges for long span lengths.

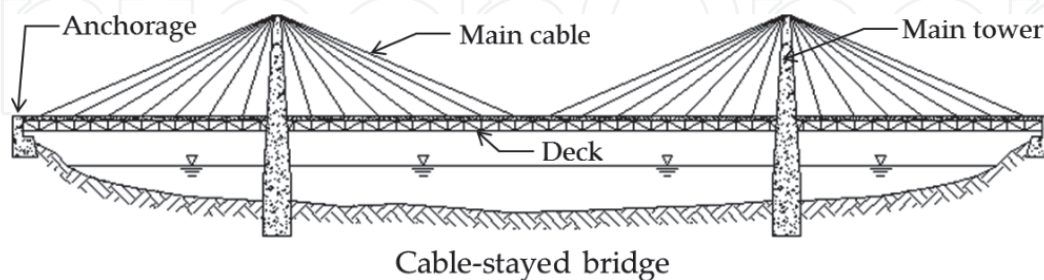


Figure 14.
Steel cable-stayed bridges for long span lengths.

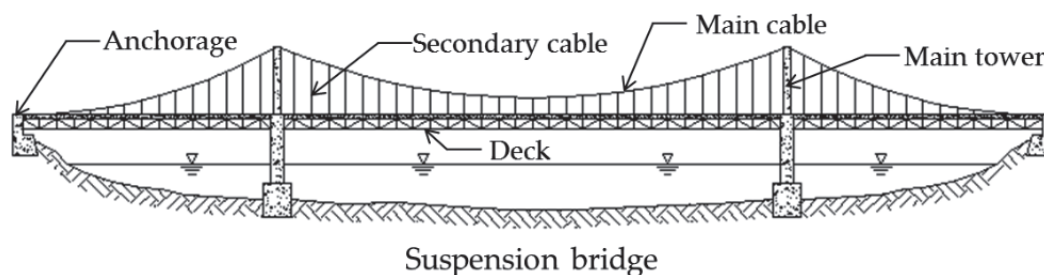


Figure 15.
Suspension bridges for long span lengths.

cables; the difference between these two bridges is the arrangement of the cables. Cable-stayed bridges use a series of cables to support the deck connected directly with the main tower; when the suspension bridges use a main cable supported between the towers and a series of secondary cables supporting the main deck.

For both cable-stayed and suspension bridges, the main deck has a high slender ratio due the long span covered and need additional structural elements to increase the stiffness. Trusses are commonly used to stiff the main deck and allow the wind to flow through these structural elements.

Tension stress is developed by the cables, which are the optimal geometry giving a capacity to increase the span length. Looking into **Table 1**, for span lengths higher than 3500 ft. (1100 m), the suspension bridge is the only economical option to choose.

Bridges supported by steel girders are shown in **Figure 16**. The main deck is the combination of the concrete slab, a wide variety of structural steel beam, piers and anchorage geometries. The steel girders can be simply or continuous beams using hot rolled sections or developed by steel plates.

Steel girders are working with bending stresses, which usually requires more material if it is compared with truss elements. However, according to **Table 1**, these types of bridges can be economical competitive for short and medium span lengths due its easy construction procedures and less time-consuming during installation of the girders. Also, these girders have a great stiffness compared with truss bridges, reducing vibration responses produced by traffic and wind flow.

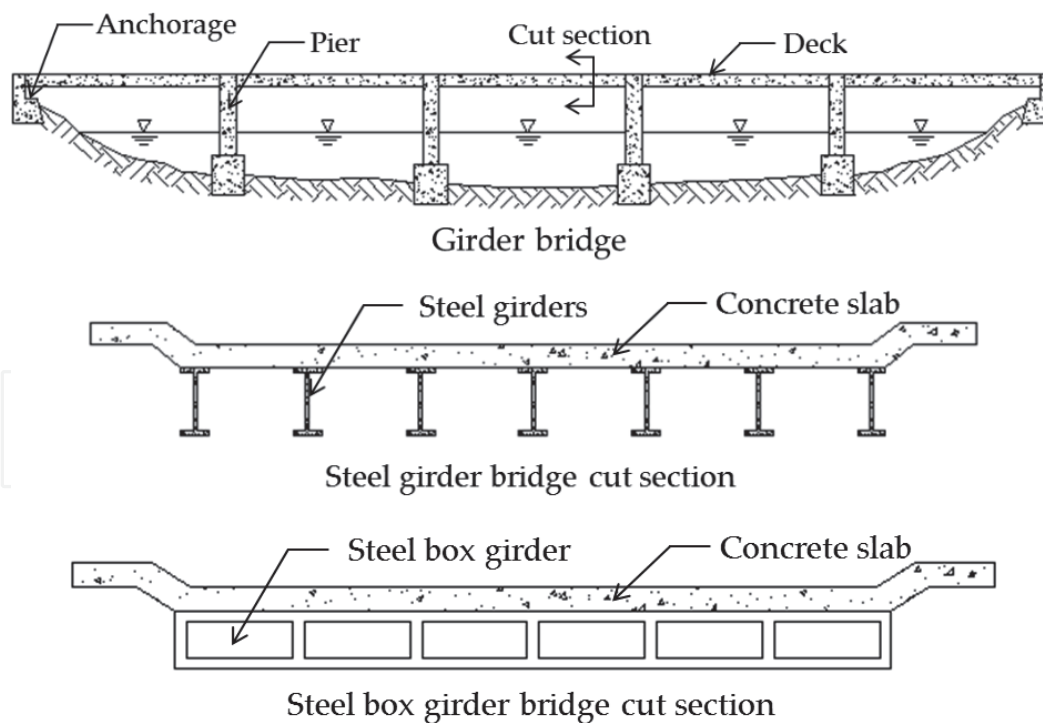


Figure 16.
 Steel bridges for short and medium span lengths.

4.6 Concrete bridges

Concrete bridges can be categorized as below or directly on the main structure, as described on Section 3.2.2. According to the American Concrete Institute (A.C.I.), the compression strength of concrete can vary from f'_c of 3 ksi (20 MPa) to 7 ksi (48 MPa), depending on cement, water, natural gravel and sand ratios used [15].

There are many advantages of concrete material compared with structural steel, including its capacity to support compression stresses and the availability on construction industry. Tension stresses are carried out by the reinforcement, making a composite structural material.

Within the reinforced, pre-stressed and post-stressed concrete bridges, we can find the following geometries:

- a. Arc-shaped concrete below the main deck.
- b. Cable-stayed bridges, where the entire structure used concrete except for tensors.
- c. Bridges supported by girders.

Arc-shaped concrete bridge is shown in **Figure 17**, which consists of an arc shaped element below all the structure, supporting the piers and the main deck. The concrete arch-shaped element is working mainly by compression stress due its curvature, taking advantage of the material capacity. Piers are working as flexure-compression stress and the main deck is working as shear and bending stress. According to **Table 1**, the recommended span length for structural and economical purposes is 300–1380 ft. (90–420 m).

The principal feature of pre-stressed concrete girders against simply reinforced concrete girders is the increase of the span length without the need of increases the

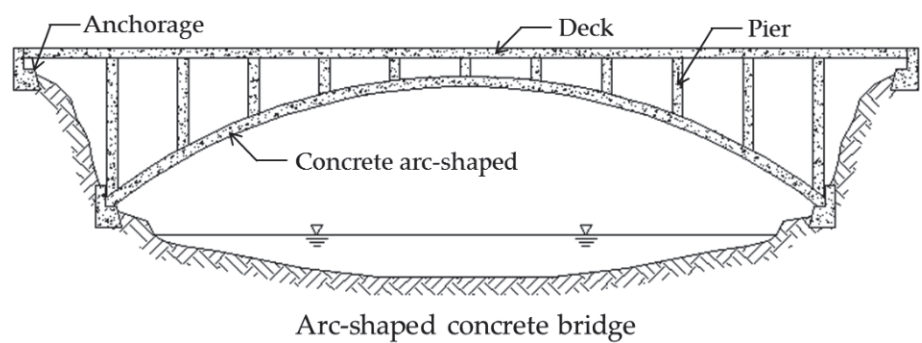


Figure 17.
Concrete bridges for medium span lengths.

beam height, taking advantage of the effective inertia and providing greater stiffness to the bridge. This geometry type is widely used to build bridges across the cities, highways or interstate roads.

According to **Table 2**, there are a wide variety of recommended girders, considering precast pre-stressed or cast-in-place post-stressed concrete with different cross-sectional geometries, taking account the clear span to cover and the material mechanical properties [16].

Each construction procedure have its own benefits; for example, precast pre-stressed girders have the advantage of less time installation consuming and minimum frameworks to use compared with cast-in-place post-stressed girders or cast-in-place slabs, but only can be performed a simple cross-sectional area; by the other hand, cast-in place girders can have any desired cross-sectional geometry, which is adaptable and commonly required on any project.

A concrete girder bridge is shown in **Figure 18**, considering few types of construction procedures and geometries, using the same piers and anchorage.

Cast-in-place reinforced concrete slab or T-beams can be used for small span lengths, as recommended in **Table 1**, and precast pre-stressed I-beams are used for spans lower than 150 ft. (45 m) according **Table 2**. All these types of girders works for bending stress, which limits the span range; however, due its easy construction procedures, are widely used for most common bridges.

4.7 Other materials

Most bridges use structural steel and concrete as main materials. However, there are other materials that can help to complement the structure, depending on some features:

Bridge type	Span range
Precast pre-stressed I-beam	0–150 ft. (0–45 m)
Cast-in-place post-stressed box girder	100–300 ft. (30–90 m)
Precast balanced cantilever, constant depth	100–300 ft. (30–90 m)
Precast balanced cantilever, variable depth	200–600 ft. (60–180 m)
Cast-in-place cantilever segmental	200–1000 ft. (60–300 m)
Cable-stayed with balanced cantilever segmental	800–1500 ft. (240–450 m)

Table 2.
Span lengths for various concrete bridge types [16].

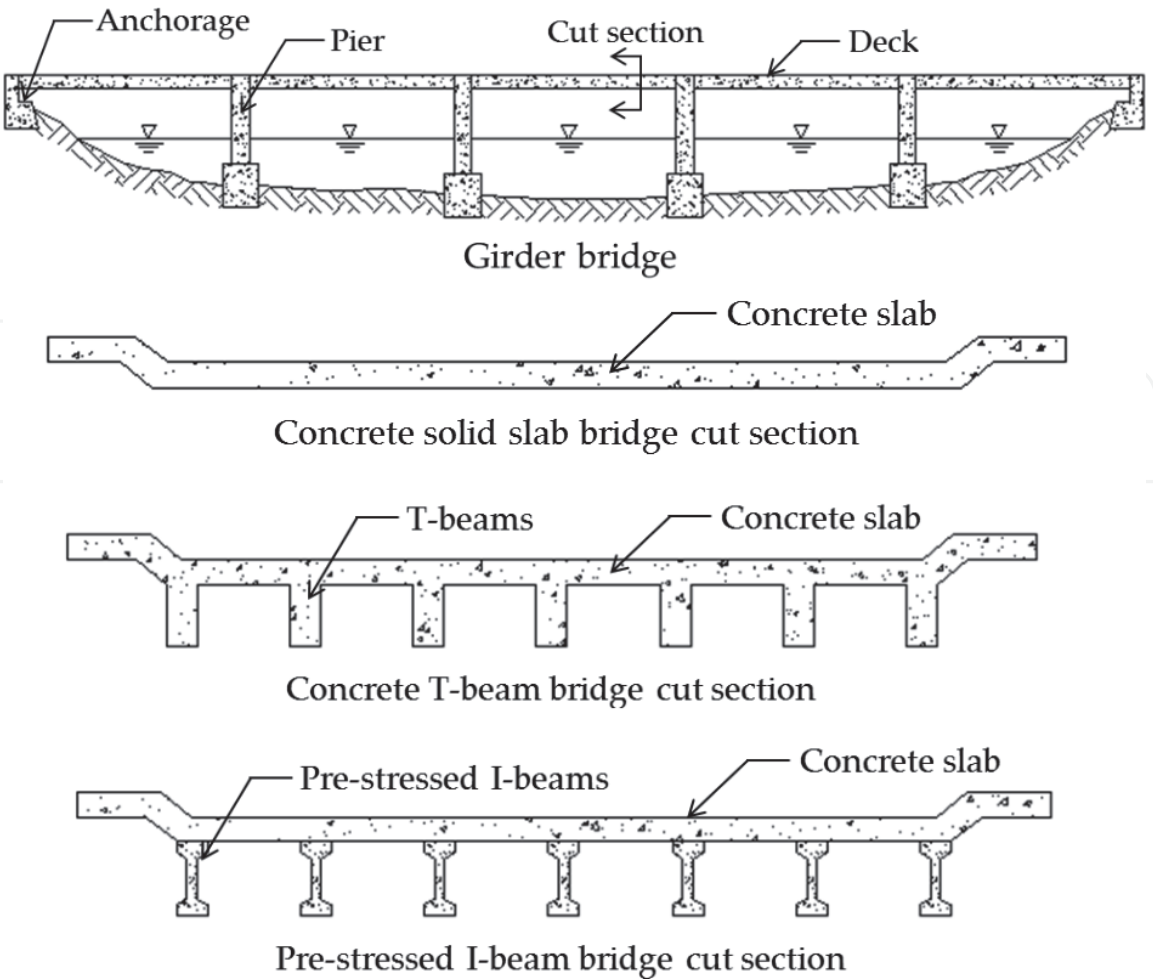


Figure 18.
Concrete bridges for short span lengths.

- a. Wooden bridges, used for small crosswalks or where span lengths are short and loads are low.
- b. Stainless steel, where it replaces carbon steel parts of the bridge, increasing resistance to humidity and environmental factors.
- c. Carbon fibers, used as rehabilitation process and perform capacity improvement of existing structural elements.

5. Maintenance avoids bridge deterioration

The general process for the development of any bridge are described in the flow chart showed in **Figure 12** and includes planning, design, operation and maintenance procedures. To ensure the useful life of the bridge, a maintenance plan must be established, depending on the physical and environmental factors.

According to AASHTO, there are a high variety of loads that the bridge must support and should be considered in the structural design process [17]. These loads are considered as physical factors and can described as follows:

- a. Dead loads

Refers to the own weight of the structure, including installations, finishes, bearing surface and all loads that will not have variability over time.

b. Live loads

This type of loads refers to a generalized use of the bridge, this means the traffic flow and people walking, including braking, impact, collision and their dynamic loads. This category includes environmental factors such as rain and snow.

c. Accidental loads

This type refers to an extraordinary event that the structure needs to support, commonly produced by wind and earthquake loads. In some cases, a collision by a ship or a flood event may be considered.

In addition to physical loads, there are other factors that can affect the useful life of the bridge, named environmental factors and described as follows:

a. Humidity

This environmental factor affects the chemical composition of iron and steel materials, which in direct contact creates corrosion process and develops a material degradation.

b. Abrasive factors

These factors can affect the material composition due the chemicals reactions by air, water and soil exposures. Each material could have a specific chemical reaction and depends for the levels of exposure.

Dead, live and accidental loads affect the mechanical properties of the structure itself, which results are stresses and deformations. If a load exceeds the capacity of the material, some type of damage will occur, from permanent deformation to crack growth, and the structural element will require a repair.

The environmental factors are associated with the material degradation process, which can results in reduction of the effective inertia. All cases imply the reduction of material resistance and element sizes, developing a stress and strain increase, and therefore, a possible failure.

Proper maintenance avoids possible damages on the structural elements due any physical or environmental factors, and therefore, an increase of the structure expected life.

6. Degradation process: corrosion, wear and fatigue

Since the physical and environmental factors are present in each structure, all materials may be subjected to alterations in their chemical composition, modifying the mechanical and physical properties, shortening the useful life of the structure and requesting any kind of repairmen. These factors with the alteration are listed in this section.

6.1 Degradation due environmental factors: corrosion

Structural steel and concrete reinforcing steel in presence of humidity will have the problem of corrosion, a chemical process involving an electrochemical reaction which occurs due the direct exposure to water, creating rusting and developing the material degradation process.

For reinforcing steel in concrete structures, the corrosion problem can be present when the rebar is exposed, oxidizing the area and develops structural problems.

Figure 19 shows a damaged pier due corrosion of the reinforcement steel, losing the coating and reducing the cross-sectional area, which means a reduction of the mechanical capacity of the element.

On the other hand, if the structural steel is fully exposed to the environment without any humidity protection, the level of oxidation will be present on the entire element and will develop a generalized rusting reaction. **Figure 20** shows a structural steel bridge with all elements damaged by corrosion.

6.2 Degradation due physical factors: wear and fatigue

Wear degradation during the life of a bridge occurs due its continuous use, where the friction is present by physical forces, including the pass of the vehicles over the main deck. These vehicles generate frictional forces when perform braking and accelerating, causing wear on the structure. For bridges where the piers are in contact with water flow, the friction causes degradation.

Usually traffic flow perform low wear degradation over the deck, however, if the road have any defect, will create bumps and wear will be increased rapidly, creating damages. Bridges using simply supported girders will require construction joints between supports; these joints are examples of places were bumps are easily created



Figure 19.
Concrete piers of reinforced steel with corrosion problems [18].



Figure 20.
Bridge of structural steel with corrosion problems [19].

due poor construction procedures. **Figure 21** shows a typical bump problem, which can be avoided using any joint procedure and materials offered in the industry.

Another physical factor that affects the structure is fatigue, caused by the loading and unloading forces due the traffic flow, affecting the stressed elements of the bridge. Fatigue causes degradation on material mechanical properties with each load cycle; this means each vehicle passing over the deck. If each cyclic load produces a stress equal or higher to yielding stress of the material, therefore a large amount of cycles will cause a decrease on the material allowable, allowing brittle failure of the element. **Figure 22** shows a crack developed due fatigue stress loads; notice there are no yielded zones on the beam, only a sudden crack.

6.3 Prevention and protection

Since material degradation process is inevitable for both physical and environmental factors, a few actions must be considered on the design process to control



Figure 21.
Bridge concrete construction joint damaged [20].



Figure 22.
Steel beam with fatigue crack failure [21].

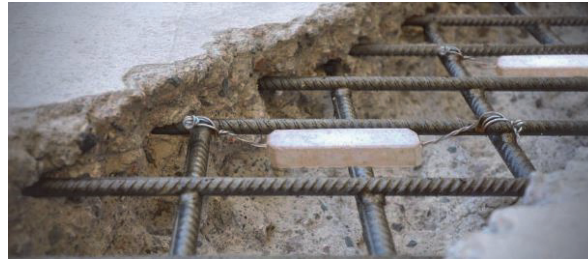


Figure 23.
Steel beam with fatigue crack failure [23].

corrosion, wear and fatigue. Prevention and protection procedures are required, including maintenance process to avoid possible damage.

Corrosion prevention is the best economic way to preserve the structural elements of any bridge and the result is a positive benefit in the useful life of the materials [22]. Acidic corrosive emissions and hydrocarbons, in combination with high humidity accelerate the process of corrosion and degradation. The designer should analyze the type of electrochemical attack that would occur during the life of the structure.

For structural steel, epoxy paints are used to insulate direct contact of water or moisture. For the reinforcement of concrete, should take care of the coating to avoid exposure to moisture. As shown in **Figure 23**, the possibility of install a cathodic protection system should be considered.

Wear degradation process is unavoidable for any surface subjected to friction; therefore, the damage depends of the applied load and affected zone. If a flexible roadway is used, wear degradation is higher and requires additional maintenance compared with reinforced concrete roadway. By the other hand, reinforced concrete piers may have contact with the water flow of the river; frictional forces would be present and wear factor became an issue, requiring additional coating to protect the reinforcing bars.

For fatigue degradation process, the designer must consider the weight of all vehicle types, cyclic loads, loading scenarios and fatigue material properties as a way to prevent brittle failure. All elements should have enough stiffness to avoid high stresses under typical cyclic load cases, therefore the fatigue allowable stress should be greater than the applied loads. Fatigue procedures as Modified Goodman Diagram or Miner's Rule are used [24].

7. Testing and monitoring

To ensure the success of all methods implemented to avoid bridge degradation, a testing and monitoring plan must be established as part of the maintenance procedure. The cost of maintenance plan should be incorporated on the bridge's budget [25].

As a first step, visual review of the bridge structural elements should be performed in a scheduled given time. The girders, piers, connections, cables, deck and materials used must show no damage, such as cracks, corrosion, visible deformations or any variable that indicates a problem. Monitoring techniques are used as a way to measures the loading cycles, cracks or corrosion and prevent any damage on the bridge.

For corrosion mitigation and prevention, the maintenance process must have a plan taking into account the next features:

- a. Expected useful life of the bridge.
- b. Environmental exposure.

- c. Classification of the bridge.
- d. Details of corrosion mitigation and prevention methods.
- e. Maintenance programs.

If there is no budget on review and monitoring procedures, maintenance will not be a preventive action and becomes corrective, which means higher repair costs and partial or total closure of the bridge.

8. Conclusion and recommendations

The definition of infrastructure includes wide variety of structures, each one with a specific purpose and its function serves the development of the society. All elements of the infrastructure are connected and any issue of an individual part will affect the entire system, slowing down the economic growth.

Transportation infrastructure has the purpose to connect two places using aerial, land and maritime methods, developing a wide variety of structures to comply with its objective. Bridges are part of land infrastructure and are used as link between two places with difficult access using single roads or highways. These types of structures have higher construction costs per mile if they are compared with single roads; therefore, there must be a complete plan to develop the project, which should include the number of lines required to meet traffic flow, vehicle load, site, geometric and budget requirements.

Large bridges exist since hundreds of year ago, where its use was restricted to aqueducts, carriages and road connectors for travelers, using as construction material stone and wood. The introduction of train and vehicles on the industry with the development of structural steel and Portland cement, modern bridges began, increasing load capacity and span length to cover.

There is no specific formula to choose the best option of bridges, due large amount of factors that depends on the structure, as geometry of the bridge, the experience of the construction companies, materials, loads to be carried out, labor available, budget and local site restrictions. A whole process that involves planning, design, construction and maintenance of the structure must be established.

The best economical option for a bridge is the combination of the efficient interaction of geometry and material, taking advantage of tension elements as the main structure. As we can see in **Table 2**, cable-stayed and suspension bridge are the best economical option for span lengths higher than 1800 ft. (550 m), due tension capacity of the steel cables. The span recommendations of **Tables 1** and **2** are a combination of efficient stress capacity due proposed geometry, in alignment of low deformations and material savings, making lower costs and improving budgets.

While planning, design and construction stages of the bridge are carefully studied to ensure its functionality; maintenance is given less importance thinking that the structure will have its useful life without any problems, when reality implies a degradation process, due its use and environmental factors. Maintenance plan is needed to avoid over costs during the life of the bridge.

Wear and fatigue degradation can be carefully studied and analyzed during the design procedure process, which will be present on all structures. However, corrosion degradation depends of the local site environment, mainly humidity and water contact, considered automatically as maintenance plan. Some cases, this

maintenance plan is not developed during the design process, and therefore, is not implemented by the time required.

Maintenance plan is always required for a long term useful life of any structure, because degradation process is present all the time. There are issues to be solved if damage due environmental factor is present and maintenance plan was not developed during design process, including budget, repairmen high cost of damaged elements and closure of the bridge. As a conclusion, these issues can be avoided if proper maintenance plan is developed during the design process.


For a successful bridge development, a complete plan should be considered in the entire design process, including the bridge's proposal, design process, construction methods and maintenance program. All variables together will result as a long-term useful life for any structure.

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