Investigating the Durability of Structures

by

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Bachelor of Engineering, McGill University, Montréal, 2011

Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

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Abstract

The durability of structures is one of primary concerns in the engineering industry. Poor durability in design may result in a structure losing its performance to the extent where structural integrity is no longer satisfied and human lives are at stake. Moreover, the associated costs of maintenance and repair due to inadequate design considerations are high. Thus, designing for durable structures not only helps sustain our infrastructure, it also reduces future costs.

This thesis identifies the key factors that define and impact durability, with particular attention paid to the effect of material choice on overall durability. This follows a study of the different deteriorating mechanisms that wood, steel and reinforced concrete undergo over time, and the different enhancement techniques used to reduce the adverse effects of these mechanisms. Finally, a comparison study is carried out comparing the different material properties of wood, steel and concrete and the effect of using alternative materials on cost and quantity of material used. This further enhances the understanding of the impact that the design choices make, during the early stages of the project, on the overall durability of the structure.

Keywords: Durability, material, deterioration, enhancement

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Dana Saba

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Chapter 1 Overview

1.1 Introduction

A good investment is one where the monetary value of a good is returned after a period of time with interest. It follows that durability enhances the investment value of goods. Over the years, the durability of structures has been of great concern to engineers and the demand for durable designs has been increasing. Lack of durability in designs may result in a structure losing its performance to the extent where structural integrity is no longer satisfied and human lives are at stake. To a less severe extent, lack of structural durability results in high long-term costs for repair and adjustments. One consequence may be shutting down the structure, which may cause inconvenience for the users and have additional costs for rerouting traffic in the case of a bridge, or displacing people from their homes in the case of a building.

It is necessary for engineers to provide appropriate means to ensure a safe design even under severe conditions and to reduce long-term costs. Design of durable structures requires a proper knowledge of the behavior of the materials used in the construction of any given structure. It is important for engineers to understand the composition of the materials used in the design, how they react to different environmental conditions, and how different materials interact with each another in the case of composite structures. Linking practical engineering to research in material science and to procedures to maintain and construct structures to develop more durable designs had not been tackled up until 1991 were a study was carried out by the International Council for Building Research, Studies and Documentation, CIB W94 "Design for Durability" (Soronis, 1992).

With time, any structure will deteriorate as it is used and worn out through different human and environmental activities. Therefore, the level of performance of a structure can be measured by the quantity of damage it experiences. There are two different categories of damage: structural and non-structural. It is primarily the structural damage that any engineer should keep in mind during the design process. Engineers have as their ultimate goal that the damage, whether structural or non-structural, caused to a structure ideally does not stop it from functioning safely. Public safety must be ensured at all times, whatever the state or the age of the structure.

The purpose of this thesis is to develop a better understanding of the concept of durability and its long-term implications. Durability is not a design requirement that is mandated by the codes or standards and therefore engineers and architects tend to disregard looking into it in depth (Soronis, 1992). Neglecting this aspect of structural design may result in severe consequences such as failure of a structure and/or unanticipated cost of repair. Therefore, it is of great importance to develop a solid understanding of durability and its long-term benefits to structural engineering.

Designing for a durable structure is a decision-making process that is carried out throughout the lifespan of the structure. It ranges from deciding on the type of materials used, to the way the construction sequence is carried out, to the type of maintenance procedures that will be implemented on the structure. Hence, a good starting point would be exploring the commonly used materials in this industry, their deterioration mechanisms and the different methods used to decrease the effect of these mechanisms.

Common structural materials used in the construction industry are steel, concrete and wood. Each material is affected by different sets of deteriorating mechanisms that would decrease design life.

Steel, an alloy made up of iron, carbon and various other elements, is highly affected by corrosion. It is the chemical reaction between the metal and the environment, namely, non-metallic elements such as oxygen, sulphur and chlorine, which lead to weakening of the metal. The incidence of corrosion dominates in wet environments where water acts as a medium for an electrochemical reaction to take place. The result of corrosion is weakening of the structural material due to loss of cross-sectional area and loss of its properties due to hydrogen embrittlement, or the penetration of hydrogen that results in brittle failure. One would question why use steel if it is susceptible to corrosion? It is the availability, cost and material properties that make this material valuable and hence widely used in the construction industry. Therefore, determining appropriate measures and using suitable technologies to counteract the effect and rate of corrosion is fundamental in the use of steel in design and construction.

Another construction material heavily used in the construction industry is concrete. There are different mechanisms that result in the deterioration of concrete: chemical reactions in concrete due to acids, salts and alkali-silica reactions, freeze and thaw cycles, and biological and chemical attacks. Therefore, monitoring the performance of structures to further study the effects of these deteriorating mechanisms on bridges and buildings is critical to determining means that will improve the durability of the structure.

In comparison with steel and concrete, wood is a natural material where the environmental conditions greatly influence design. Examples of the outcomes caused by different deterioration mechanisms on the three different structural materials steel, reinforced concrete and wood is illustrated in Figure 1.1.

Ultimately, it may be necessary to consider enhancement techniques to aid in the overall performance of the materials used in design of the structures.

The survival of any industry highly depends on the use of innovative methods and techniques for its advance and improvement. Technology plays an important role in solving existing problems and achieving long-term goals. Integrating technology into the preliminary design processes helps in the survival and growth of any industry; therefore, it is important to explore new methods and techniques to help improve the durability of the construction industry. As previously stated, the construction industry is one of the oldest industries, where steel, concrete and wood have been extensively used as construction materials. The rate of deterioration of these materials depends on several factors. Consequently, it is important to explore and study the different factors that influence our surrounding structures and make use of technology to further enhance their serviceability and durability.

Durability of structures is an ongoing concern in the engineering industry. However, the question "what is durability?" is yet to be answered. In order to design or evaluate a structure with respect to durability, it is essential to come up with criteria that would aid in quantifying this characteristic. To further enhance the understanding of the impact that the design choices made during the early stages of the project have on the overall durability of a structure, identifying the key factors that affect different materials and comparing their properties with respect to durability is necessary.

Figure 1.1: Effect of deterioration mechanisms on the three structural materials wood, reinforced concrete, and steel.

1.2 Thesis Outline

To begin, Chapter 2 of this thesis will define durability and study the codes and standards used to guide the design of durable structures. Subsequently chapter 3 will study the three most commonly used structural materials in construction: wood, steel and concrete, their deterioration mechanisms and the techniques used to help improve the materials performance either by chemical or physical enhancement. Finally, Chapter 4 will tie things together through a case study on a historic structure, covered wooden bridges, by investigating and comparing the advantages associated with designing the bridge using alternative materials. This study will emphasize the importance of incorporating durability in the design of structures and the long-term advantages associated with it.

Chapter 2 Durability

Durability is the measure of a structure's performance with respect to a specified time period. Therefore, to ensure adequate performance of the structure over its design life, durability should be understood and considered (Nireki, 1996). Durable design and construction are necessary to meet users' new demand for structures. Hence, by defining and identifying the factors, the decision-makers, and the guides and standards used, durable design can be enabled. This greatly relies on the knowledge and level of experience of designers and their ability to make the right decisions.

This chapter will include:

- A definition of durability
- Outlining durability through a design problem
- Identifying the factors affecting durability
- Studying the guides and standards currently used to develop durable designs

2.1 Definition

Ancient builders have shown their concern for durability of their structures, as many of them still stand today. In the past, the scales of the structures constructed compared to those of modern days were much larger. Durability is one of the factors that led to the construction of structures of such measure. Due to the large quantity of materials used, which added up to the dead weight of the structure, the structures were less vulnerable to deterioration. This is reflected in the design of many historical structures, a few examples of which are the pyramids in Egypt, the Coloseum in Rome, and the Great Wall of China. The design of these structures illustrated the concern of the designers at the time, to deterioration and degradation of the materials used. Hence, using a large quantity of material weight resulted in a robust structure, which helped increase the resistance of the structure to the aggressive environment and its implication on the structure's performance. However, nowadays, the demand is for long, slender, lightweight designs. In contrast to most historical structures, the weight of such structures needs to be minimal. Despite the fact the materials used today have gotten more durable, lightweight designs increases the structure's susceptibility to deterioration. Moreover, every design consideration is crucial in the design of such structures since minor errors may result in severe consequences (Soronis, 1992).

Designing for a durable structure is a challenge. The definition of durability varies from one person to another. What is the design life of a structure? What type of loads does it resist? Do engineers design a structure or a product to last forever? These are a few questions that the term durability raises. By definition, the term durability refers to the ability to withstand damage, decay and deterioration over a period of time (Nireki, 1996). The more durable the structure is, the longer its lifespan. However, many factors come into play when designing for a durable structure, most of which depend on client and design requirements. Some of these factors are, the type of structure being built, the types of materials used, the environmental conditions the structure will be interacting with and its required performance. Therefore, it is important to identify the purpose and the conditions surrounding the structure. These factors will help in directing the design path of the structure and aid in the decision-making process of material and geometry used, construction sequence, and maintenance procedures that will be carried out.

The performance of all structures gradually declines over time due to the interaction between the materials and the surrounding environmental conditions, such as biological degradation of timber structure due to microorganism attack, corrosion of steel in steel structures, and steel reinforcement in reinforced concrete structures. The different means of deterioration shows as years goes by, the performance of a structure will deteriorate. Thus, any structure is engineered to perform over a specific design life through which the structure is expected to behave in a certain manner under specific loadings and maintain its structural integrity throughout. The relation between the performance of a structure over a period of time is illustrated in Figure 2.1 (Blok et al., 2003).

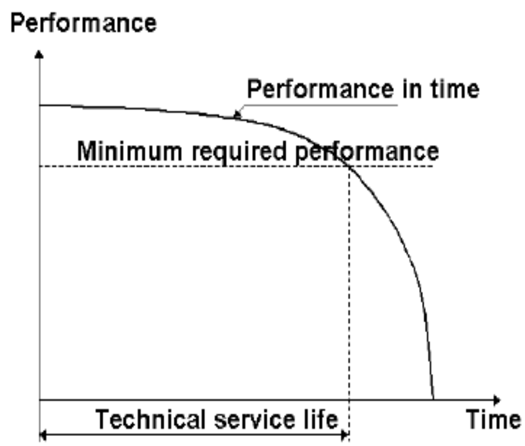

Figure 2.1: Non-linear relationship between performance of a structure over time (Blok et al., 2003).

The ultimate goal of any structural engineer is to ensure the public safety under any circumstance; this is the minimum design requirement for a structure. Consider a highly seismic region, based on the design codes the structure must be designed to ensure occupant's safety. However, it would be practical to design beyond the code requirements such that the structure maintains its form and performance after an earthquake instead of having it undergo major re-construction. Although the up-front cost of the project would be high, long-term cost of rehabilitation and maintenance of the structure is diminished, which consequently improves the structure's durability.

It is important to define not only durability but also specific terms associated with a durable design. According to Blok et al. (2003), durability is broken down into two categories: technical durability and functional durability. This is derived from three terms associated with the lifespan of the structure: design working life, technical service life and functional working life. The interrelatedness of these terms is depicted in Figure 2.2. As mentioned earlier, a structure is designed to serve its purpose for a specified lifespan, which in this case is referred to the “design working life”. As for the “technical service life”, it refers to the time period the structure’s performance meets the design requirements for its intended use taking into account foreseen maintenance procedures. Finally, the “functional working life” refers to the time period in which the structure meets its users’ new requirements.

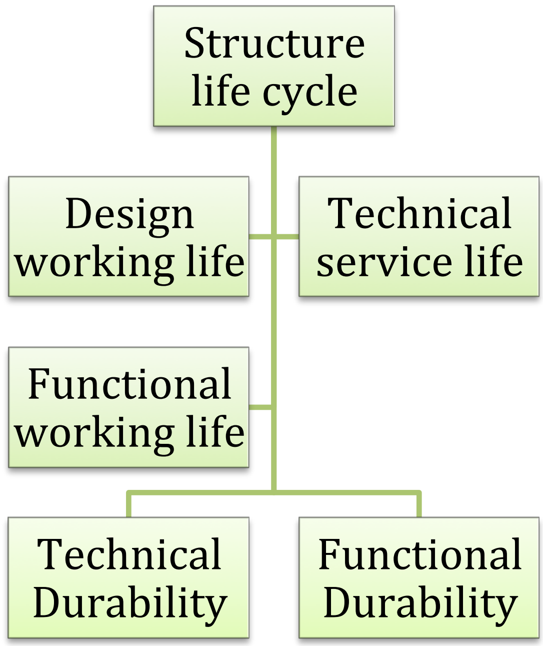

Figure 2.2: Terminology used in assessing the life cycle of a structure (derived from Blok et al. 2003)

Furthermore, Blok et al. show the coupling relationship between technical service life and functional working life, as illustrated in Figure 2.3. According to their research, the most beneficial structure is one for which a linear relationship exists between the two time periods. This indicates it is best to design a structure that is adaptable to possible future changes, due to high cost associated with changes, and one that is well designed and maintained to withstand deterioration over its design life. A structure that falls above the curve would require being adapted to attract new users, while one falling below the curve would require repairing the structure to meet new demands. As for the definition of durability, technical durability refers to the ability of the structure to meet its design requirements over its technical service life, while functional durability is the ability of the structure to adapt to changes to meet user requirements and therefore lengthening the functional working life of the structure (Blok et al., 2003).

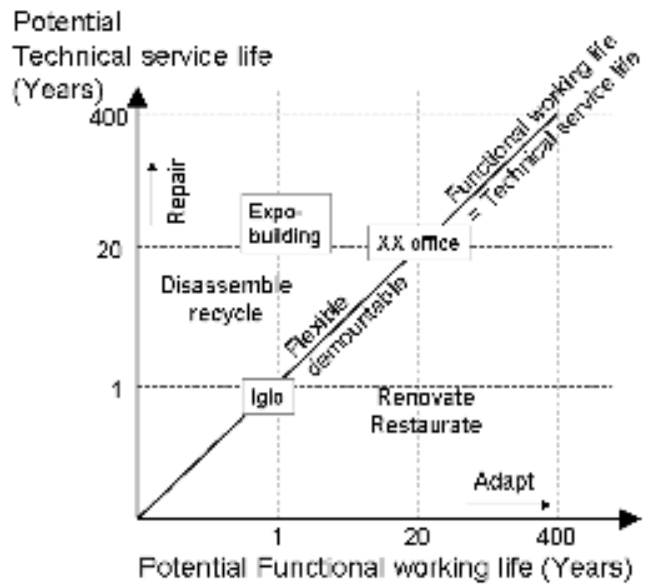

Figure 2.3: A favorable structure is one were the relation between technical service life and functional working life is linear (Blok et al., 2003).

2.2 Outlining durability in a design problem

The subject of durability is outlined in the process of analysis and synthesis of a project (Soronis, 1992). To further clarify this, let us consider as an example the design problem to be engineering and constructing a residential building. The analysis of the problem refers to addressing the different parts of the project while synthesis is looking at how the different facets come together. This would require coordination between different departments and acquiring proper knowledge to be able to make suitable choices to achieve a durable structure. For instance, coordination between material scientists, geotechnical engineers and structural engineers and having a good understanding of the structure's performance is important on the decision-making process of the type of foundation used that would best fit this structure. Another example of coordination that would take place is between the structural engineers and construction workers to be able to construct the final product. Durability is involved in both processes. The decisions made in the process of analysis and synthesis to develop a design and to achieve the final goal is crucial in producing a durable structure. A summary of the two processes is shown in Figure 2.4 (Soronis, 1992).

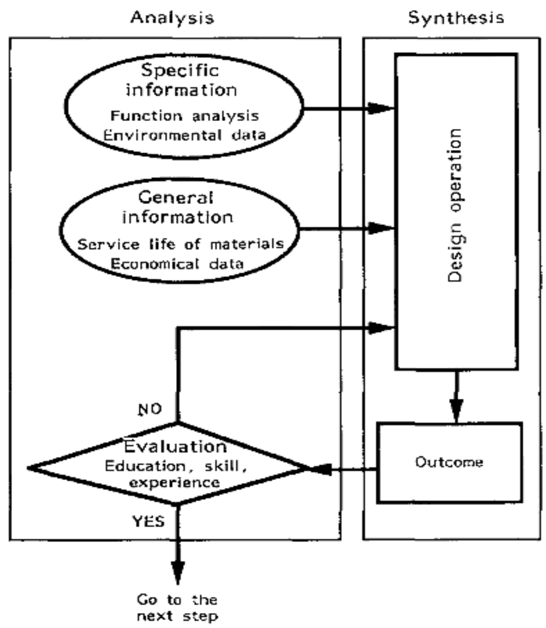

Figure 2.4: Achieving a durable design is a process that is involved in both parts that categorize a design problem: analysis and synthesis (Soronis, 1992).

To be able to tackle the matter of durability effectively, it is important to identify the key players involved in the decision-making process and in each stage of the project's life cycle. Moreover, identifying the factors that affect the decisions made by the individuals involved throughout the process is of equal importance to achieving a durable design.

2.3 Factors affecting the durability of structures

Design for durability is a process that needs to be carried out throughout the design life of the structure, as illustrated in Figure 2.5 (National Research Council Canada, 2005). It starts with the design and decision process carried out by the engineer and client, and ranges from the construction sequence carried out by builders, to the type of maintenance procedures implemented throughout the structure's design life (Nireki, 1996).

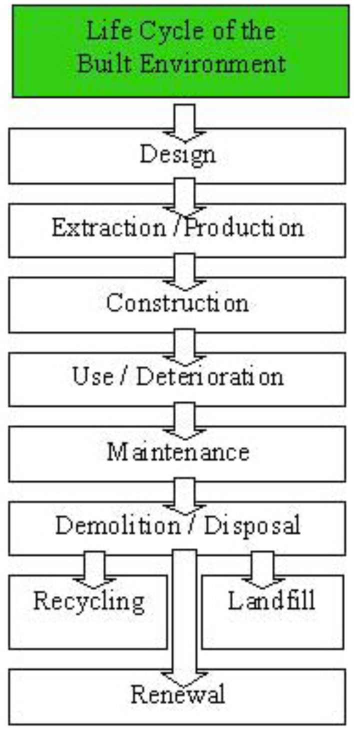

Figure 2.5: The different stages of a project's life cycle through which durability need to be accounted for to achieve a durable design (National Research Council Canada, 2005).

For any structure there is a set of factors that need to be defined and that all individuals involved in the decision-making, engineering, constructing and maintaining processes must be aware of. Some of these factors are:

- Type of structure
  - Exposed versus unexposed
    - Example: a building would require different design considerations compared to a sculpture in a museum or a bridge
  - Temporary versus permanent
- Type of material used in design and construction
- Type of surrounding environment
  - Dry versus wet climate
  - Probability of an re-occurring natural disaster in the region
    - Example: seismically active regions
- Restrictions given by the client
  - Timeline given for the project
  - Allocated budget for the project
- Future adjustments to original scope
  - Possible expansion of the project in the future
  - Possible relocation of structure

        - Example: design the structure to be easily dismantled would require specific design and construction attention
    - Use of structure for additional services
        - Example: addition of a bike path to a highway bridge

The factors listed above play an important role in directing the design toward a specific path and in achieving durability and maintaining our infrastructure. For instance, budget and schedule limitations restrain designers from investing in materials that may be more durable due to the high cost associated with it, while schedule limits the designer from looking further into different design alternatives that may enhance the durability of structures. Consequently, it is important to identify the key players in each stage of the project and their influence on the final outcome.

The initiation of a project begins with the client's willingness to invest in it. It is the client that decides on the purpose of the structure, the type of structure to be designed and constructed, the location of the structure, and the time and budgetary restraints. Therefore, having a clear scope of work that is identified by the client is essential. From there, a team of architects and engineers, varying from civil to electrical, depending on the scope of work, are brought on board with a project management team. Through collaboration of the different disciplines in the analysis and synthesis processes of the project, durable designs are achieved. In parallel, the project management team would work on tying the components of the project together to achieve the client's ultimate goal.

To achieve durability, the design life of the structure, its intended use and location are the first few factors that need to be identified in the early stages of the project. These depend on the client's requirements. Hence, identifying whether the structure is temporary or permanent and the importance of the structure's safety, for example a hospital versus a warehouse, narrows down the designer's vision. Given the design life of the structure, through recommendations made in conjunction with other conditions mentioned based on knowledge and experience of engineers, enables designers to develop a durable design. The type of material used and geometry of the structure are the type of decisions made based on the given constraints that in turn greatly influence the structure's durability. Furthermore, the type of construction sequence and maintenance procedures implemented greatly depends on the latter, which subsequently impacts the cost and the anticipated time required to complete the project. Throughout this process the project management team works in parallel with the designers to develop a schedule and a cost breakdown that best satisfy the client's requirements. It is through collaborative work between the different teams and the client that results in a durable/high-quality structural.

Reducing the overall cost of the project is one of many objectives a project manager would want to achieve. Meeting structural safety and serviceability requirements during a structure's design life would cut down on the overall cost of the project (Soronis, 1996). Depending on the extent of innovation and type of materials used for the design, the cost of the project may vary. From an economic stand point, it's the overall cost of the project that defines durability (Soronis, 1992).

Cost of construction and the anticipated cost of maintenance greatly depend on the intended use of the structure and the materials properties used in design. According to research carried out by Soronis (1992), the cost of durability depends on the initial cost of the materials used in the structure, operation costs and maintenance cost, which includes repairing and/or replacing parts of the structure. A graph illustrating the relation between the different costs to the material's durability is shown in Figure 2.6. This graph illustrates that as the desired level of durability increases, the cost of materials used to achieve this level is high while the associated maintenance cost is low. As the cost of materials is much greater than the cost of maintenance, the total present value will be high as it is dominated by the materials' initial costs and vice versa. Referring to the graph, "L" indicates the optimal level of durability achieved for the lowermost cost of the project's life cycle. Hence, if the client is willing to invest in more durable materials, which increase the initial material cost, and consequently the present life cycle cost, a higher level of durability is achievable.

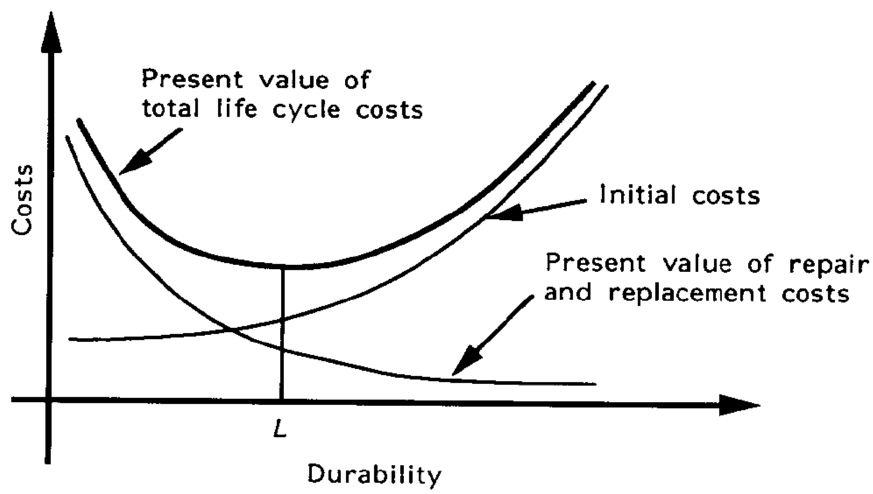

Figure 2.6: This graph shows the relation between durability of a material to its initial, maintenance cost, and total present value of the life cycle costs (Soronis, 1992).

2.4 National Standards and Guides

Due to time constraints, and constant upcoming deadlines that designers and engineers are required to meet, they do not have the privilege to further look into alternatives that may better their design. Therefore, the use of other resources to assist engineers in this matter is important. Some of these resources include consultation with material scientists on material properties and behavior, and the use of standards and guidelines that lay out procedures to further direct engineers during the design process. As mentioned earlier, the first to address this matter was CIB W94 document in 1991 (Soronis, 1992). Two common standards are:

- The British Standards, BS7543

- The Canadian Standards, S478

2.4.1 British Standard, BS7543

The British Standards, BS7543 “Guide to durability of buildings and building elements, products and components” (first published in1992), provide guidance to engineers when determining the required and predicted service life, and design life of a structure. In addition, it discusses the different type of deterioration mechanisms and their causes, and examples of premature deterioration. The scope of the BS7543 is aimed at new construction mainly related to buildings. It does not account for scope changes over the life cycle of the structure like, changes in the intended use of the structure to meet user’s new requirements.

It is the client who defines the type of structure to be engineered. With this information the service life of the structure can be predicted accordingly. The service life of a structure is a specified period of time where the structure is expected to perform adequately taking into account maintenance procedures that include activities such as repair or replacement of parts of the structure. Having knowledge and data based on other structures placed in similar surrounding conditions and used for similar purposes greatly help in predicting the service life of a structure. With respect to the design life of the structure, the client, the designers and engineers will specify a recommended period of time that satisfies the owner’s requirements. The design life of the structure impacts the choices made in attaining a durable design. To achieve durable designs, the structure’s performance needs to be maintained throughout its design life. Recommendations for the design life period for buildings specified in the standard are summarized in Table 2.1.

The level of maintenance that the standard outlines is shown in Table 2.2. This ranges from performing scheduled maintenance procedures on the structure to replacement of elements of the structure due to failure. Additional factors such as surroundings conditions, level of performance and the time period over which the durability of the structure is evaluated need to be defined. The level of performance refers to the limit where the functionality of the structure’s element is no longer acceptable. Moreover, the level of experience of each individual involved in the project has great influence on the decisions made that will eventually affect the level of durability a structure may exhibit.

Category	Description	Building Life	Examples
1	Temporary	Up to 10 yrs	Site huts; temporary exhibition buildings
2	Short life	Min. 10 yrs	Temporary classrooms; warehouses
3	Medium Life	Min. 30 yrs	Industrial buildings; housing refurbishment
4	Normal life	Min. 60 yrs	Health, housing and educational buildings
5	Long life	Min. 120 yrs	Civic and high quality buildings

Table 2.1: Category of a building’s design life outlined in British Standard Institution, BS 7543:2003

Level	Description	Scope	Examples
1	Repair only	Maintenance restricted to restoring items to their original function after failure	Replacement of jammed valves; reglazing of broken windows
2	Scheduled maintenance plus repair	Maintenance work carried out to a predetermined interval of time, number of operations, regular cycles etc.	Five yearly external joinery painting cycle. Five yearly recoating of roof membrane with solar reflective paint
3	Condition based maintenance plus repair	Maintenance carried out as a result of knowledge of an item's condition. [The condition having been reported through a systematic inspection (procedure)]	Five yearly inspection of historic churches etc leading to planned maintenance

Table 2.2: Different maintenance level outlined in British Standard Institution, BS 7543:2003

Further, the standard discusses the different means of deterioration that effect building components and materials. This includes biological agents such as insects and micro-organisms, weathering agents due to environmental conditions, stress agents, chemical and physical agents, and agents due to users' interaction with the structure. The latter includes activities as simple as replacing a broken glass window to lack of regular inspection checks carried out on the structure that results in the acceleration of the deterioration mechanisms. Additionally, the standard outlines a few examples of structures that experience premature deterioration, where the service life of a component of a structure or a material is less than the design life.

One of the shortcomings of the British Standard is lack of sufficient guidance on structure's adaptation to new requirements. It is important for designers to address issues that may either involve incorporating new design requirements or adapting an existing structure to new design requirements. Careful reassessment of the structure's performance will need to be carried out to ensure the durability of the structure.

2.4.2 Canadian Standards, S478

Similar to the British Standards, BS7543, a Canadian Standard, S478: "Guideline on durability in Buildings" was first published in 1995. It outlines the different factors associated with durability, ways of assessing deterioration, and methods to predict the service life of a structure. Moreover, it provides guidance for incorporating durability-enhancing techniques into design, construction sequence and maintenance procedures to prolong the structure's design life.

The standard defines durability in terms of service life, predicted service life and design service life. Service life is the period for which the structure does not experience any unanticipated costs and repair activities. Predicted service life is based on data collected from previous structures, models and tests that have been carried out. Unlike the British Standards that uses the principal of Masters and Brandt to predict the service life of a structure (Soronis, 1996).The Canadian Standards uses three different methodologies to determine the predicted service life. Illustrating the performance that an identical assembly exhibits, or modeling a possible deterioration mechanism, which depends on the factors that define the project, or by testing new means that will be used towards accomplishing higher level of durability are methods used in predicting the service life of a structure. Lastly, the designer in agreement with the client's requirements defines the design service life. The design service life of a structure is categorized into four parts: temporary, medium life, long life and permanent. Table 2.3 shows the different time periods associated with each category.

The fundamental durability requirement for a structure is to have a maintained level of performance through its defined design service life. According to the Canadian Standard, durability is achieved only if it is accounted for throughout the different stages of a project: conceptual design, detailed design, construction and maintenance. The extent of damage a structure may experience is categorized into eight different levels according to the consequence associated with each. It ranges from minor damages such as replacement of light fixtures to severe casualties such as endangering human lives. Table 2.4 outlines the different categories and the associated effect of failure.

Category	Design service life for building	Examples
Temporary	Up to ten years	• non-permanent construction buildings, sales offices, bunkhouses • temporary exhibition buildings
Medium life	25 to 49 years	• most industrial buildings • most parking structures*
Long life	50 to 99 years	• most residential, commercial, and office buildings • health and educational buildings • parking structures below buildings designed for long life category*
Permanent	Minimum period, 100 years	• monumental buildings (eg, national museums, art galleries, archives) • heritage† buildings

Table 2.3: Category of a building's design life Canadian Standard Association, S478-1995.

Category	Effects of failure†	Example
1	No exceptional problems	Replacement of light fittings
2	Security compromised	Broken door latch
3	Interruption of building use	*Repair* requires discontinuation of service or dislocation of occupants
4	Costly because repeated	Window hardware replacement
5	Costly *repair*	Requires extensive materials or component replacement or extensive use of scaffolding
6	Danger to health or the ecological system	Excessive dampness, mold, soil gases, asbestos, PCBs
7	Risk of injury	Loose handrail
8	Danger to life	Sudden collapse of structure

Table 2.4: Different categories of failure (Canadian Standard Association, S478-1995).

Showing the effect of durability from an economical aspect is not accounted for in both standards, S478 and BS7543. To achieve durable designs from an economic standpoint, the different engineering activities ranging from purchasing the different commodities to constructing and maintaining the structure need to be affordable. By further illustrating the effect of different choices made on the cost of durability will further aid designers in making suitable decisions.

2.5 Discussion

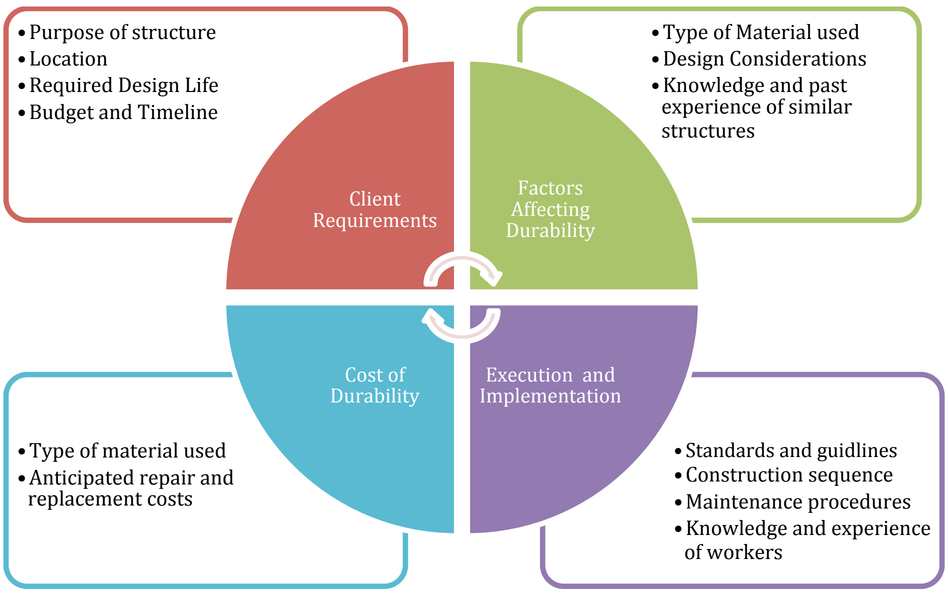

Figure 2.7: Flow chart summarizing the different elements that contributes to durability

Figure 2.7 above summarizes the different elements that contribute to durability. In order to achieve durable design, durability consideration needs to be accounted for throughout each level of the project. It begins with defining a clear scope of work including the intended purpose of the structure and its design life, and the environmental conditions of the site. These factors need to be clearly identified, as they are detrimental to the behavior of the structural components and material properties. Once identified, these factors influence the decisions taken by the individuals involved in each stage of the project. Hence, effective decision-making to best suit the structure's surroundings and satisfy the owner's requirements can be applied based on one's knowledge and experience. It is important to have a good background in material properties and behavior to further incorporate durability into a structure's design and execution. Ultimately, it is the overall cost over the structure's life cycle that is affected depending on the extent of attained durability that the owner is willing to invest in. Furthermore, the overall cost in maintaining a specified durability varies in turn depending on many project-specific factors like the type of materials used and type of maintenance procedures implemented. To aid designers in achieving durable designs, guides and standards are used as resources. While the S478 and BS7543 guidelines that were studied and compared earlier illustrate examples of different causes that lead to the failure of structural components, and provide guidance for predicting a structure's design life, they do not discuss the effects of using alternative materials with respect to the amount of material required for design, and its associated cost on durability. The type of materials used has a great impact on the durability of a structure and on the cost of producing durable designs. To further illustrate the importance of the choice of material made in the design process, a comparative study of the different materials used in the construction industry and their effect on a structure's durability is discussed in the following chapter.

Chapter 3 Materials and Technology

Durability involves implementing different engineering and construction techniques in combination with proper material usage at lower costs. Making the right decisions and choosing appropriate solutions achieves the development of durable designs (Soronis, 1992). This requires engineers and designers to extend their knowledge beyond the technical application of engineering that is analysis and design. It is the interaction between the materials used in a structure and its surrounding environment that limits durability. As illustrated in Figure 2.1, the performance of a structure deteriorates over time, resulting in a non-linear relationship. However, this is in the context of the type of material used and the materials interaction with the environment.

The type of materials used for a structure is one of the first decisions made during the project's life cycle. It is done in the early phases of the project since once chosen, it dictates many future considerations. The material selected may depend on the client's specification, the architecture requirement or it may sometimes be based on the engineer's judgment. Knowing the type of material used for the project, decisions made on budget, timeline and construction sequence can be expected to follow. For example, in the case of the construction sequence for a concrete structure could either be pre-fabricated versus cast-in-place concrete; this would affect the cost and timeline of the project. Moreover, being able to choose the appropriate material for a specific structure type and surrounding environment is crucial. Hence, by understanding the materials' structures, the type of deterioration they are susceptible to and methods to reduce the negative impact of these factors, assists an engineer in coming to a decision with the client and/or architecture that would be most suitable for the structure.

Due to the broad range of the topic, this chapter will focus on a few deteriorating mechanisms and enhancement techniques associated with each material. The following will be studied:

- Common construction materials used in structural engineering:
    - Wood
    - Steel
    - Concrete
- The deterioration mechanism each may undergo
- Techniques used to diminish the effect of the deteriorating mechanism for each material

Understanding the different factors and mechanisms associated with each material is essential in achieving durable designs. Accounting for these factors, engineers can anticipate for necessary maintenance procedures and repair measures that a structure may need to undergo throughout its design life, thus enhancing the overall durability of the structure.

3.1 Wood

3.1.1 Wood as a structural material

Since the Paleolithic era, wood has been used in the manufacturing of many products. Examples of such products are weapons, furniture, machines, shoes and buckets, many of which were essential for survival. Wood further played an important role in making mechanical machine inventions possible; in fact, the first printing press was made out of wood. In 7000BC, the production of wooden sledges was developed among fishermen and hunters in Northern Europe. This eased the transportation of heavy goods by exerting a pulling force. Moreover, with the invention of wheels around 4000BC, carts were produced and were the main source of transportation in Europe (Youngs, 2009). One of the oldest wooden structures still standing today is located in Japan, Horyuji temple, which was built more than 1400 years ago (Ito, 2005). Having this temple in a seismic region shows that this wooden structure was able to survive many severe conditions over the years and, therefore, makes wood an interesting material to explore structurally. Nowadays, wood is still used as a main source of structural material in construction as well as formwork for concrete and other structural components such as roof and trusses. Therefore, the evolution of wood over the years and its versatility is what makes this material unique and desirable.

Wood was the primary structural material for many years. However, with the development of other stronger materials such as steel and concrete, the use of wood in the construction industry decreased gradually. Also its properties as a natural and renewable material are what makes wood distinct compared to other conventional construction materials that are heavily used nowadays. Besides the many ecological advantages wood has, it is known for its aesthetic appearance and variety in color and density compared to other structural materials, making it distinctive. As the consequence of deforestation becoming a serious concern, wood in construction has been discouraged. Nevertheless the development of sustainable harvesting techniques decreased the negative effect on the environment. Through the use of technology and advanced techniques, enhanced forms of wood can be produced to construct bridges and other structural components, making it a desirable material (Bijen, 2003).

There are a variety of wood species, all of which vary chemically and physically and in their level of durability. Hardwood, for example, is known to be more durable compared to other wood species, in the western climate (Bijen, 2003). Durability of wood highly depends on its surrounding environment: its performance is influenced by the effect of natural, biological and chemical deterioration mechanisms. Other factors will eventually compromise the performance of any structure: inadequate design detailing, incompetent construction sequence, change in primary usage of structure and inefficient maintenance procedures would all result in deterioration of the wood with time.

Wood was extensively used in Europe as a primary structural material between the 10^{th} and the 18^{th} century and is still used nowadays as a main construction material on certain projects

(Youngs, 2009). One of the tallest wooden buildings, the nine-storey high "Graphite Apartment", located in London, was constructed out of cross-laminated timber, which is a series of glued-together wood panels creating an alternating alignment, through proper engineering, material usage and detailing. Furthermore, this structure was designed to be able to resist fire. Figure 3.1 illustrates an image of the Graphite Apartment building, and an indoor view of the structure (Fountain, 2012). The church of Surdesti, a wooden structure built in 1724 located in a region called Maramures in Romania, is one of the tallest wooden buildings in Europe, and stands at 72m (Constantinescu, 2008; Muica and Turnock, 1999). In addition, architecture Michael Green has come up with design of a 20-storey skyscraper made primarily out of wood. The conceptual image, a rendering of what the building would look like if built, is shown in Figure 3.1.

Figure 3.1: Nine-storey Graphite Apartment building in London, constructed out of laminated wood, church of Surdesti in Maramures, Romania, 72m high known to be one of the tallest structures made out of wood, conceptual design of a 20-storey skyscraper wooden building by Michael Green.

In British Colombia, Canada, there has been a growing phenomenon of the loss of pine trees due to insect attack by beetles. This insect known to grow in the forests of Western North America poses a serious danger to trees. It restricts the flow of water and nutrients in the tree through the release of a "blue stain fungus" that results in killing trees. Due to the increasing number of dead trees and to avoid the increase in carbon emissions that would occur from burning the logs, the British Colombian parliament was forced to consider using wood as a main structural material over other man-made materials, releasing what is known as the "Wood First Act" in 2009. Moreover, a method was developed by researchers to make use of the beetle-killed pine trees, consisting of a hybrid material, *Beetlecrete*, where the wood is mixed with normal cement to form a waterproof and fire-resistant pourable material yet used like wood (M.H., 2012).

3.1.2 Deterioration Mechanisms

Wood is one of the oldest structural materials used in the construction industry. It is of great importance to preserve structures constructed out of wood especially ones of historic importance. Over time, the performance of wooden structures decreases due to age, chemical, biological and natural attacks as well as other factors such as inefficient design approaches. Depending on the extent of damage caused by one or more of these factors, certain repair measures will have to be accounted for to enhance the structure's performance. The severity of the damage and the expense of the repair will depend on the time after the damage started to occur that it was discovered. Regular maintenance procedures help in identifying early stages of deterioration; hence decreasing the intensity of the damage by taking necessary corrective measures. However, in many cases it may be difficult to detect initial signs of degradation, as they are not apparent until later stages. The most common sources of deterioration in wood are the following:

- Biological agents
  - Fungi
  - Insects→thermites, beetles and ants
  - Bacteria
- Environmental conditions
  - Weathering→ sunlight, precipitation and wind

One of the most significant biological agents that result in great structural damage to wood is fungus. Most damage to wooden structures in dry conditions is caused by fungi, the growth and survival of fungi depends on four factors: water, usually requires more than 22% by mass to be active, oxygen, wood as a source of nutrient and adequate temperature conditions ideally 25°C. Enzymes produced by the hyphae, second stage in the life cycle of a fungus (refer to Figure 3.2), attack the most crucial components of wood: the cellulose and lignin. A few common destructive fungi are white and brown rot fungi, soft rot and wood-disfiguring fungi. The effect of soft and brown rot are similar- they both result in decomposition of the cellulose- while white rot fungi decomposes the lignin component of wood. However, soft rot fungi require less oxygen compared to brown and white rot fungi to survive and usually affect wood structures exposed to damped conditions. Dark stains on wood are evidence of a brown rot fungi wood attack. On the other hand, wood-disfiguring fungi do not affect the wood structurally; however, they do result in affecting the physical appearance of the structure due to the growth of mould on the structure and blue stains. As the conditions required for fungus survival are not usually met in the building environment, they would not be of great threat for wooden structural elements (Bijen, 2003).

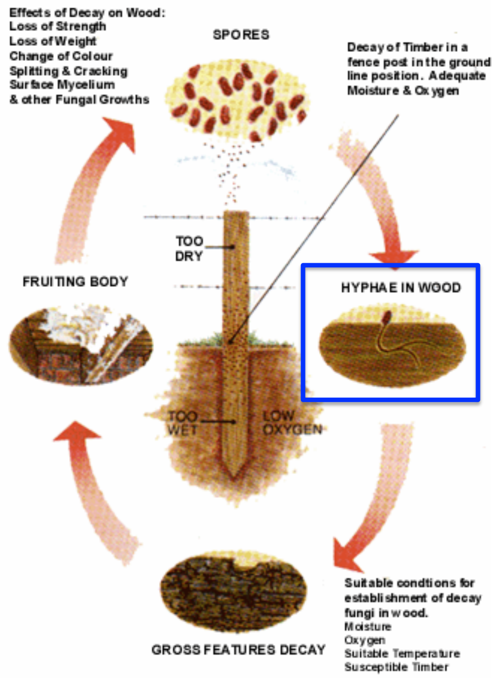

Figure 3.2: The second stage of the fungus's lifecycle, hyphae, produces enzymes that attack crucial wood components.

Other biological agents that affect the performance of wood are insects such as beetles, termites and ants. In the case of beetles, they are greatly destructive in British Colombia, as mentioned above. Since this type of insect is capable of flight, they tend to lay their eggs in wood pores where they later develop in to larvae, which eventually attack the wood. They result in significant damage structurally. The "Death Watch" beetles, the "Common Furniture" beetles and the "Powder Post" beetles are common species found in Europe that cause extensive damage by attacking the sapwood of certain wood species (see Figure 3.3 for a cross-section showing the different wood elements). Compared to other types of insects, termites tend to cause the largest amount of damage to wood, since they live in groups, and therefore spread much more quickly through a structure. Bacteria, on the other hand, affect wood regardless of the environmental conditions. In contrast to termites and other biological agents, their effect is apparent only after a long period of time. Due to their slow enzyme reaction, the damage caused by bacterial attack is relatively insignificant (Bijen, 2003).

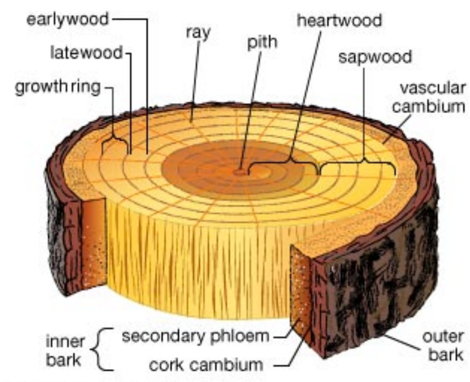

Figure 3.3: Cross-section showing the different wood elements including sapwood, which is most susceptible component to beetle attack

Another mechanism that results in the degradation of wooden structures is weathering. This mechanism results in surface degradation and occurs due to exposure to combined natural factors such as sunlight, precipitation and wind. Ultraviolet rays from the sun causes the initiation of this process that results in deterioration of the lignin, which eventually is washed away by water on rainy days. In contrast to other deterioration mechanisms, weathering occurs without the presence of water however, can assist in speeding up the deterioration mechanism. For instance, during rainy seasons the moisture gradient in wooden structures increases. This results in a desirable environment for biological agents to grow and reproduce which results in endangering the performance of wooden structures. Moreover, change in the level of moisture content of wood will cause it to vary in its dimension: tangentially, radially, and longitudinally. It is the tangential direction that is greatly influenced by the gain or loss of water in wood. The consequence of a change in the level of moisture content in wood influences the stability of wooden elements. If the moisture content of wood is greater than the fiber saturation point, it is stable. Below that point wood, is said to be an unstable and will either swell or shrink depending on the percentage gain of moisture (Sarkanen et al., 1999). This affects the performance level of wooden structures. On one hand, as the cross-sectional area of a wooden element decreases, due to shrinkage, the stress acting on the structure will increase and may exceed the capacity of the structure for a significant change in dimension. On the other hand, as the cross-sectional area of a wooden element increases, as it swells, this may lead to connection issues between different structural elements. In either case change in volume of a wooden element leads to compromising the structure's durability. Figure 3.4 illustrates the effect of the percent gain in moisture content to the tangential and radial dimensions of a wooden element.

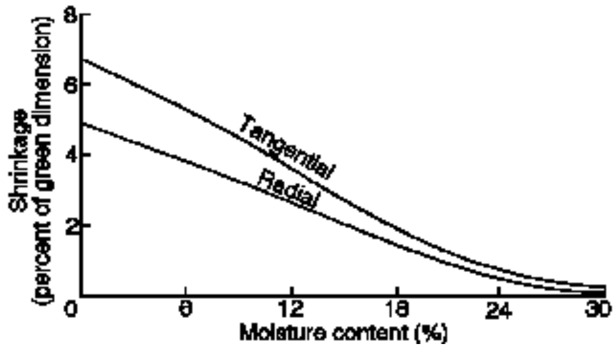

Figure 3.4: The effect of moisture content on the tangential and radial dimensions of a wooden element (Sarkanen et al., 1999).

To conclude, environmental conditions are detrimental when it comes to using wood as a structural element and plays a big factor during design considerations. Figure 3.5 below illustrates an example of material degradation due biological attack. It shows the bottom chord of a wooden truss that has been completely eaten up and resulting in failure of the truss element. Hence, incorporating techniques to decrease the consequences of these factors are vital.

Figure 3.5: Material degradation of bottom chord of wooden truss due to biological attack that resulted in the structural failure of the truss element.

3.1.3 Enhancement Techniques

Natural, chemical and biological factors such as moisture, heat and microorganisms results in degradation of exposed untreated wood back to its preliminary chemical compounds "original building blocks", carbon dioxide and water (Rowell, 2006). Due to the different deterioration mechanisms that wood can undergo depending on the environmental and surrounding conditions, it is important to use protective means to help improve the performance of wooden structures. Change in humidity level and degradation by microorganism result in distortion of the material, which results in instability and reduced strength and compensation of other physical properties.

Using different techniques, wooden structures can be modified to adapt to their surrounding conditions hence enhancing their durability. Some methods that are used to achieve this include using additives such as protective layers, chemically modifying the biological properties of wood or by using protective design such as covering the wood with an impermeable layer. These techniques can be categorized in to two forms:

- Chemical enhancement
    - Chemically modifying the wood element using chemical processes such as acetylation

- Physical enhancement
    - Using external components to further enhance the performance of a wooden structure either by having,
        - Hybrid structure, for example gluing fiber reinforced polymer sheets to wood structures
        - Composite structures, for example glued laminated timber

3.1.3.1 Chemical Enhancement

Through adequate use of chemical agents, wooden structures can be treated and improved chemically to protect them against biological agents and other deteriorating mechanisms (Rowell, 2006). The presence of the hydroxyl group in wood is what makes this material easily responsive to moisture gradient (Bijen, 2003). By chemically modifying the cell wall of wood, one can control its chemical properties and change it permanently. Acetylation and esterification are a few ways that are widely used in chemically controlling the biological properties of wood (Bijen, 2003). Through these chemical processes the resistance of wood to biological attack is greatly controlled and hence the wood's durability is increased. Several experiments have been carried out to study the resistance of chemically modified wood, using linear chain anhydrides, against fungi, termites and marine wood borers.

Acetylation is a chemical process which removes water by forming a chemical compound, usually through the reaction with acid. The extent of this reaction is measured as a weight percent gain, defined as the difference between the weight of wood specimen before and after modification. It was shown that the weight percent gain level of acetylation used, regardless of the type of anhydrides, is what increases the resistance of the wood against microorganisms attack. Furthermore, it is the degree of the cell wall bulking through the formation of chemical compounds that takes place during acetylation that causes the wood to build resistance against biological attacks (Papadopoulos, 2010). In addition to biological resistance, Rowell (2006) has shown that this process also improves the dimensional stability of wood. By increasing the degree of cell wall bulking through acetylation, the moisture content decreases which subsequently increases dimensional stability. Therefore, this chemical reaction serves to both increase biological resistance and enhance dimensional stability. As the moisture content decreases due to this chemical reaction, which is the number one factor of biological attack, wood's resistance to microorganisms increases.

It was shown by Suite et al. (1999), and Hill and Papadopoulos (2002) that it is the weight percent gain of acetylated wood, which causes the build-up in resistance against degradation and not the hydroxyl substitution (Papadopoulos, 2010). An experiment carried out by Papadopoulos et al. (2008) studied the effect of acetylation on Corsican pine sapwood resistance against termites. They quantified the amount of mass lost due to termite attack and compared the effect of different types of anhydrides. Figure 3.6 illustrates the results of these experiments. This graph illustrates that by modifying wood using a series of linear chain carboxylic acid anhydrides, the amount of the amount of mass lost due to termite attack decreases dramatically, ranging roughly from 43% for unmodified wood, to 6% for modified wood using acetic anhydride with weight percent gain of 24%. Moreover, the results show that the type of anhydride used does not affect the amount of material mass lost. For example, comparing the percent of mass loss of type 3, valeric anhydride 16.5%, to type 4, propionic anhydride 16.2%, for the same weight percent gain and different type of anhydride, the termite resistance of wood did not change. On the other hand, comparing type 1 to type 7 both acetic anhydride but with different weight percent gain, the resistance of wood to termite attack increased dramatically, from mass loss of 31% to 8%. Table 3.1 shows the type and weight percent gain used in this experiment (Papadopoulos et al., 2008).

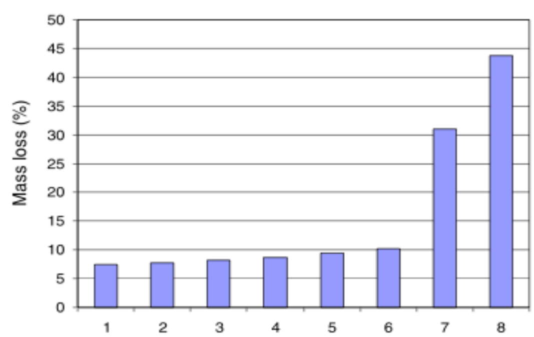

Figure 3.6: This graph shows as the percentage of anhydride used increases, the percentage of mass lost decreases hence, the structure is less vulnerable to deterioration. The x-axis and y-axis represents the type and weight percent gain of anhydride and percent of mass loss respectively.

Type 1	Acetic anhydride 24.1%
Type 2	Acetic anhydride 31%
Type 3	Valeric anhydride 16.5%
Type 4	Propionic anhydride 16.2%
Type 5	Acetic anhydride 16.6%
Type 6	Butyric anhydride 15.8%
Type 7	Acetic anhydride 7.5%
Type 8	Unmodified Wood

Table 3.1: Type and percentage of weight gain of anhydride used in wood in Papadopoulos and Avtzis (2008) studies

External application of chemical products is also commonly used as a protective technique. However, although this method is faster and easily attainable there a lot of disadvantages associated with it. Most of the chemicals used in the protective finishes and coatings are of toxic nature and in many cases their usage are prohibited in many countries. In addition, the use of these products may question sustainability, as the wood specimens can no longer be recycled.

3.1.3.2 Physical Enhancement

Apart from chemical treatments and modifications, wood can also be physically enhanced. There are several other ways that can help improve the performance of wood as a structural material to help withstand greater loads. Due to higher demands for larger and more complex structures it might be necessary to structurally improve the structural behavior of this material. Some of these methods used today are the following:

- Wood-based composites
- Hybrid wood composite

Producing composite sections helps in achieving material characteristics for a specific design requirement. Wood, being a natural material, is very variable and usually features defects along its form; therefore, by using wood-based composites sections one can get rid of these imperfections. Knots, for example, are common flaws found in wood; they are of a circular shape with wood grains spanning perpendicular to the rest of the grains. Figure 3.7 illustrates a knot in a wooden specimen with local cracks surrounding it. Knots causes formation of local stresses and causes weakening of the structure, hence by engineering wood to produce an element where the affect of these defects are reduced can help in improving the structural performance of this material. For example, a log with knot can be cut into smaller segments and glued together to form a composite section, minimizing the effect of this defect (Fridley, 2002). Examples of these composites that have been used structurally are glulam and LVL, which are glued laminated timber and laminated veneer lumber respectively.

Figure 3.7: Local cracks surrounding a knot in a wood specimen

Another commonly used material in the structural industry that has been used as a means of reinforcing wood is fiber-reinforced polymer. The combination of those two elements results in a high-strength hybrid structure. Plevris and Triantafillou carried out a study in 1992 on the structural impact of using thin fiber-reinforced plastic (FRP) sheets glued to wooden beams using epoxy resin. Their experimentally reinforced wood specimen having the FRP sheet bonded externally on to the tension face of the beam is shown in Figure 3.8. Their results show that using fiber-reinforced plastic as an external enhancement can greatly improve the mechanical behavior of the element. Moreover, they have shown, by using a small area of FRP on the tension face of wood, that the moment and axial capacity of the member increases as well as its flexural rigidity. This is illustrated in the graphs shown in Figure 3.9 and 3.10. Figure 3.9 shows that as the area fraction of fiber composite increases, the axial and moment capacity of the hybrid structure increases. Figure 3.10 shows that the greater the area of fiber composite used the higher the bending rigidity of the structure(Plevris and Triantafillou, 1992).

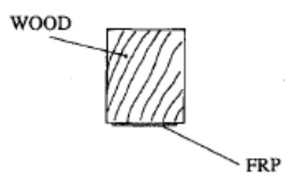

Figure 3.8: Wood specimen physically reinforced on the tension side using FRP

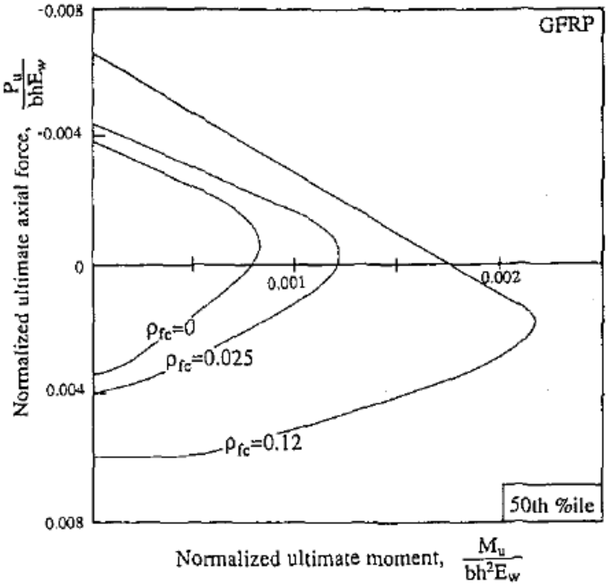

Figure 3.9: Axial and moment interaction diagram with varying area of FRP, its shows the greater the area of reinforcement the higher the axial and moment capacity of the hybrid structure (Plevris and Triantafillou, 1992).

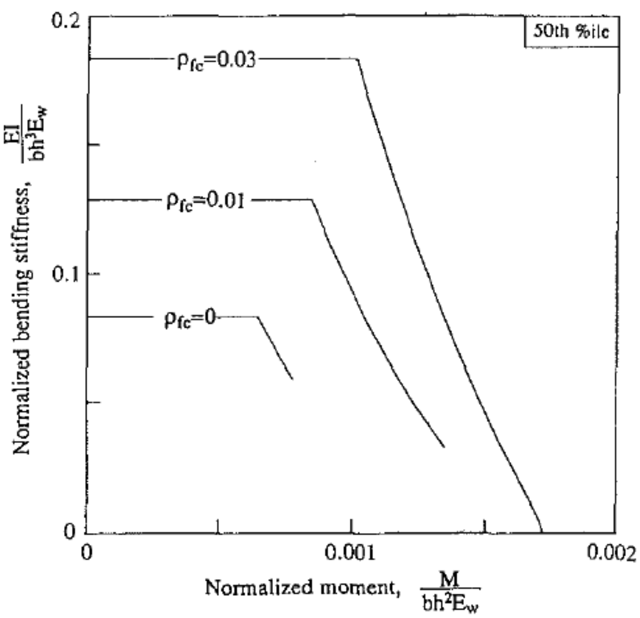

Figure 3.10: Bending Rigidity of wood specimen with varying area fraction of FRP, it shows the larger the area of reinforcement the greater the bending rigidity of the hybrid structure (Plevris and Triantafillou, 1992).

3.1.4 Discussion

Wood has been heavily used as the primary structural material for many decades. This shows the material's capability and diversity to adapt to new needs. In addition to its aesthetic appearance, being a recyclable, renewable and biodegradable material is what makes it desirable from the environmental aspect (Rowell, 2005). However, being a natural material makes it susceptible to various environmental conditions. Therefore, when using wood as a structural material in design one must pay a great attention to the surrounding environment in which it will be used in. Implementing some of the techniques described above for enhancing the structural performance of wood helps reduce the negative impact of the surrounding environment. This would ultimately depend on the client's requirement and the type of structure being built whether it's a permanent or temporary structure and its intended use. Table 3.2 is a summary of the different deterioration mechanisms and enhancement techniques used to help improve the performance of wood as a structural material.

Deterioration Mechanisms	Biological Agents	Fungi
		Insects: beetles, thermites, ants
		Bacteria
	Environmental Conditions	Ultraviolet rays
		Wind
		Percipitation
Enhancement Techniques	Chemical Enhancement	Chemical Modification, acetylation
		External coatings using chemical products
	Physical Enhancement	Hybrid structure, wrapping FRP
		Composite Structure, glued laminated timber

Table 3.2: Summary of a few deterioration mechanisms in wood and enhancement techniques used to improve wooden structure's performance

3.2 Concrete

3.2.1 Concrete as a structural material

The Romans developed one of the earliest forms of concrete using hydraulic mortars. The combination of volcanic deposits with lime and sand produced a water resistant mortar that was extensively used in the construction of hydraulic structures. The volcanic ash used in the production of the Roman mortar was called pozzolana, which was derived from the name of the village from which the ash was collected, Pozzuoli. One of the most iconic structures largely constructed out of concrete and still standing today is the Pantheon in Rome. Built in the second century, the 43-meter diameter dome of the Pantheon was made out of poured Roman concrete (Mindess et al., 2002).

In 1756, John Smeaton was the first to study and understand the material properties that constitute the mortars used in construction. Understanding the material properties was brought to his attention when he was asked to work on the Eddystone Lighthouse in Cornwall, England. Smeaton carried out various experiments, to determine the factors that affected the behavior the cementing materials exhibited to obtain a mortar that resisted salt water. He discovered that the clay content of lime is what determined its resistance to water. Moreover, he showed that replacing pozzolana with artificial additives, such as calcinied iron ore, produces the same hydraulic characteristics (Sickels-Taves and Allsopp, 2005). Smeaton used hydraulic lime and pozzolana in the reconstruction of the Eddyston Lighthouse, which lasted for 126 years before it was replaced (Mindess et al., 2002). Figure 3.11 illustrates an image of the Eddyston Lighthouse.

Figure 3.11: Eddystone Lighthouse rebuilt in 1756 by John Smeaton, being the first to experiment the properties of hydraulic mortar (Mindess et al., 2002).

James Parker, in England 1796, was first to initiate the development of cement similar to what is used today. This was later developed to portland cement by Joseph Aspdin in Leeds 1824. The concrete produced by portland cement looked similar to the stones found in Portland, which resulted in its name. Modern portland cement used today was first developed by Issac Johnson in 1845. He increased the temperature at which raw materials were burnt until clinkered (Mindess et al., 2002; Murdock et al., 1979). The shift from the use of hydraulic lime to portland cement was a result of the speed of construction, quality of strength of mortar and economic growth. Using portland cement increased the rate of construction which compensates for the increase in economic growth and consequently brought in more income. Moreover, it allowed for greater quality control over the type of mortar used (Sickels-Taves and Allsopp, 2005). Figure 3.12 summarizes the driving factors that resulted in the production of portland cement. The first patent for portland cement in the United States was by David Saylor in 1871 although it has been around as early as 1818 (Mindess et al., 2002).

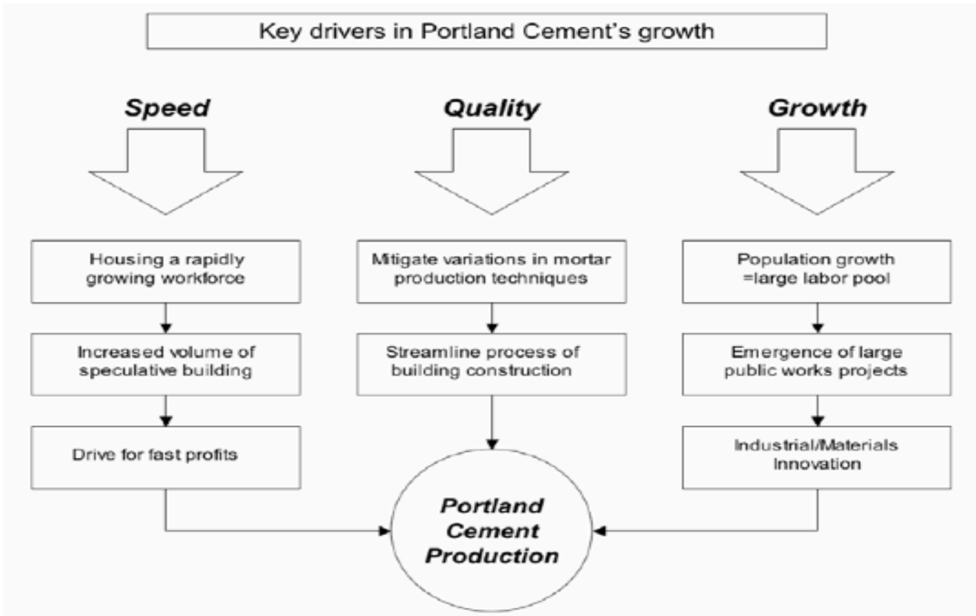

Figure 3.12: Driving factors of portland cement production (Sickels-Taves and Allsopp, 2005).

Concrete used today consists of cement, water, fine and coarse aggregates, and admixtures if necessary. Concrete is a man-made material that is engineered to satisfy the design requirements of a specific structure. The material properties of concrete vary depending on the intended purpose of the structure. For example, concrete used in a hydraulic environment needs to be water resistant, and application of concrete in foundation design needs to be resistant to sulphate attack. The variation in the concrete material properties greatly depends on its ingredients, mixing technique, and construction method. The quality of cement, size and shape of aggregates, the amount of water added, and the use of admixtures in a concrete mix play a vital role in determining the performance and durability of the material (Murdock et al., 1979).

There are several other advantages associated with using concrete as a construction material. Concrete is a pourable material that allows it to take various forms of complex geometry. This makes concrete a desired material in producing aesthetically appealing structures. Moreover, the possibility of casting concrete on site allows it to take advantage of local producers, therefore reducing the cost of materials. However, the use of concrete is limited due to its low tensile strength and ductility. Concrete is a brittle material that needs to be reinforced using steel to allow for tensile capacity. In addition, its low strength to weight ratio results in an increase of the self-weight of the structure to resist higher loads (Mindess et al., 2002). The first to introduce the method of reinforcing concrete using steel is Francois Hennebique and his development was patented in1892. The first application of steel reinforced concrete resistant to fire was on a house for one of Hennebique's clients in Belgium that was completed in 1880(McBeth et al., 1998). Figure 3.13 illustrates the steel arrangement used by Hennebique for reinforced concrete beam design.

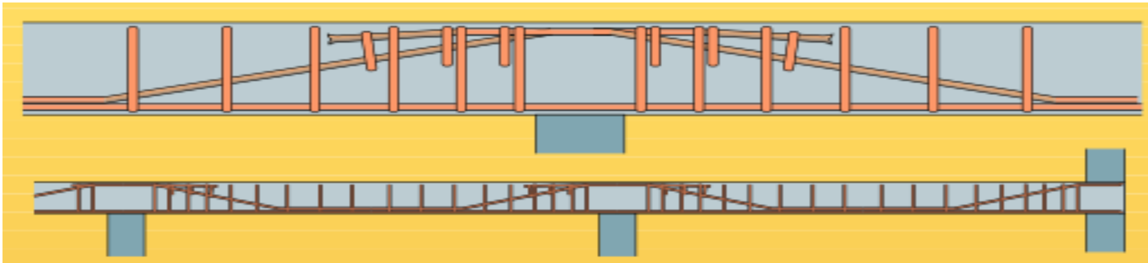

Figure 3.13: Steel arrangements developed by Jacques Hennebique reinforced concrete beam design (McBeth et al., 1998).

Burj Khalifa, approximately 830 meters tall located in Dubai, is the tallest building in the world standing today that is heavily constructed out of reinforced concrete (refer to Figure 3.14). The ability of constructing skyscrapers of that height makes it important to study the factors that affect the durability of concrete structures. The following sections discuss the various factors that compromise the durability of concrete structures and the techniques used to enhance them.

Figure 3.14: Burj Khalifa, tallest concrete structure in the world.

3.2.2 Deterioration Mechanisms

Concrete is heavily used in construction nowadays. It is essential to understand the different factors that may compromise the performance of the concrete structures and its durability. Investing a large amount of time and money in constructing iconic concrete structures makes it of great importance to ensure the durability of these structures over their lifespan. Over time, the performance of concrete structures decreases due to chemical attacks, surrounding environmental conditions, and human interaction with the structure, resulting in wearing it out. During the design phase and cost assessment of the project the effect of these factors needs to be accounted for to anticipate for necessary maintenance procedures and repair measures that need to be applied over the lifespan of the structure. Accounting for these factors will ensure the durability of the structure over its design lifetime. Common sources of degradation of concrete structures are the following:

- Chemical agents
    - Degradation due to acid attack
    - Corrosion of steel reinforcement in concrete due to carbonation and/or penetration of chloride ions
- Environmental conditions
    - Freeze and thaw cycles
- Physical conditions
    - Load application resulting in plastic deformation of concrete

One of the main sources of degradation of concrete structures is through acidic attack. The interaction of the acid with concrete structures results in the deteriorating the structure's performance over time. It is the alkaline nature of concrete that makes it susceptible to acid attack. Therefore, it is important to identify the sources that result in acidic environments that consequently influence the performance of concrete structures.

Industrial activities, bacterial activities that result in organic and inorganic acids, and acidic air pollutants are all causes of acidic environment. The degree of damage a concrete structure undergoes depends on the strength of the acid, the rate of decomposition of the acid in the solution, and the level of solubility of the salts formed. Acid attack results in decomposing and leaching the components that concrete is composed of. Nitric, chloric, sulfuric, and chromic acids are few examples of mineral acids that result in the decomposition of all hydration products of cement-based materials, thus are highly threatening to the concrete performance. Concrete structures cannot resist the negative affect of an acidic environment on its constituents for a pH value below 5. Although the pH value does not indicate the actual concentration of the acid (Bijen, 2003; Zivica and Bajza, 2001), it could be used as an environmental indicator in which the concrete is interacting with.

An example of a scenario where the material properties are greatly affected is when concrete structures are in contact with water containing excess carbon dioxide. Concrete foundation in contact with water containing a high concentration of carbon dioxide due to the decomposition of carbonate soils by groundwater can cause an acidic attack on the concrete structure. The interaction between the two compounds results in the formation of calcium carbonate, which further reacts with water to form a soluble compound, calcium hydrogen carbonate. This process results in decomposing the hydration products, which are produced during the formation of concrete and define its properties. An illustration of the consequence of this acidic reaction on concrete's material properties is shown in Figure 3.15. Material properties of concrete are greatly influenced by the severity of the chemical attack by acids, which consequently result in the degradation of concrete structures (Hewlett, 2003; Zivica and Bajza, 2001).

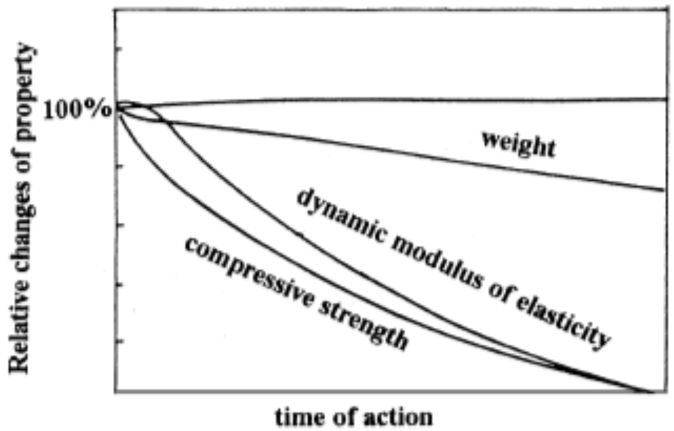

Figure 3.15: Decrease in the material properties of concrete due to an acidic reaction caused by the aggressive amount of carbon dioxide in water (Zivica and Bajza, 2001).

Exposing steel to the environment results in corrosion of the metal due to the interaction with air and water over time. This is another factor that greatly influences the performance of concrete structures is corrosion of steel reinforcement. As previously stated, concrete is weak in tension, thus the use of steel reinforcement helps enhance the performance of concrete structures under tensile forces. Although steel reinforces concrete and enhances its tensile capacity, corrosion of steel results in weakening concrete's structure performance and consequently the durability of the structure. Generally, concrete of high pH level acts as protective coating to its steel reinforcement. It is the loss of alkalinity of concrete that allows for the corrosion mechanism to take place. Corrosion of steel reinforcement is either by the interaction of concrete with atmospheric carbon dioxide or by the penetration of chloride ions into concrete (Bijen, 2003).

The process of carbonation involves the interaction of concrete with carbon dioxide in the air that begins at the surface and penetrates through the concrete's interior. The reaction of carbon dioxide with calcium hydroxide, which is a hydration product, in water results in carboxylic acid. This results in a reduction in the alkalinity level of concrete, which consequently results in corrosion of steel reinforcement in concrete. In addition, penetration of chloride ions in concrete also results in corroding the steel reinforcement. A few ways the penetration mechanism can occur, by placing di-icing salts during winter seasons or when concrete is in contact with salt water, for example, intermediate concrete piers used for a long span bridge. The curing process of concrete, water to cement ratio, temperature, and the type of cement used, are factors that affect the rate at which carbonation and the penetration of chloride ions takes place. Therefore, by using adequate concrete ingredients and proper construction methods the rate of carbonation and the rate of corrosion can be controlled, thus increasing the lifespan of the structure (Bijen, 2003).

Another major cause of degradation in concrete is a consequence of temperature changes due to climate conditions. In a cold climate, low temperatures causes any water held in concrete's pores to freeze. As water freezes it expands by 9 percent, therefore inducing pressure in the concrete structure. If the tensile strength of reinforced concrete is lower than the stresses induced due to the increase of pressure resulting from the freezing of the water pores in concrete, cracking will take place. Cracking of concrete eases the penetration of chloride ions, from de-icing salts used to melt the snow accumulated on concrete structures, which consequently initiates the corrosion of steel reinforcements. Moreover, the use of de-icing salts increases the osmotic gradient, which consequently causes water to diffuse towards the top of the concrete's surface where freezing occurs. During the thawing cycle the pores are filled with water as the ice melts. The freezing and thawing process is a vicious cycle. The mitigation of cracks allows water to diffuse towards these locations were freezing takes place inducing further pressure and consequently propagating more cracks (Bijen, 2003; Neville, 2011).

In addition to crack mitigation, scaling of concrete occurs, which is loss of mortar resulting in the decrease of the weight of concrete structure. This consequently reduces the strength of concrete. An experiment carried out by Mu et al. (2002) for different water to cement ratios of concrete, shows that as the number of freeze and thaw cycles increases, the weight of concrete decreases (refer to Figure 3.16).

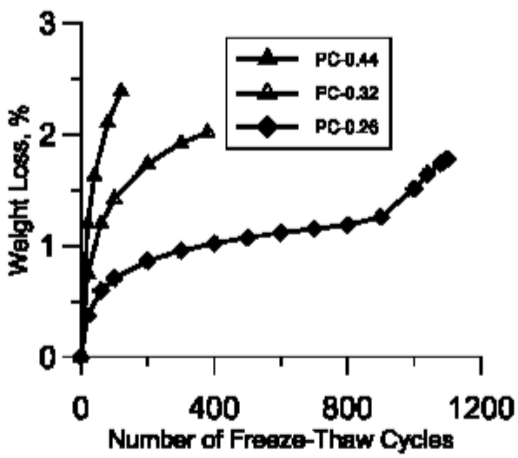

Figure 3.16: Experiment showing the effect of freeze-thaw cycles on the weight of concrete for different water to cement ratio (Mu et al., 2002).

Due to the inelastic behavior of concrete, once loaded concrete structures undergo plastic deformation, which is referred to as creep. As a concrete structure is subjected to a uniform load, creep increases over time without increase in the magnitude of the load applied. Creep can result in cracking of concrete, propagating means for hazardous particles to penetrate into concrete structures resulting in deterioration of the material. In addition, occurrence of creep in prestressed concrete structures can result in loss of some of the tension induced in the cables. Similar to the environmental and chemical agents, the rate at which creep occurs depend on the portion of ingredients used in the concrete mix as well as the methods used in batching and constructing of the mixture. In addition, strength and shape of the concrete structure used influences the amount deformation a structure undergoes due to creep. Increasing the strength of concrete used, and/or the ratio of volume to surface area of a concrete structure decreases the effect of creep deformation (Mindess et al., 2002; Murdock et al., 1979).

Incorporating different safety measures in design to minimize the effect of the different deteriorating mechanism that can ultimately threaten the structure's performance is important to achieve durable designs. This can only be accomplished through proper knowledge of material properties and techniques used to protect structures against harmful factors. Figure 3.17 illustrates the degradation of a concrete pier due to effect of corrosion on the steel reinforcement.

Figure 3.17: Deterioration of a concrete pier due to corrosion of steel reinforcement.

3.2.3 Enhancement Techniques

Using different techniques, reinforced concrete structures can be engineered to adapt to their surrounding conditions and improve their durability. Since concrete is man-made material, the type of materials used and mixing and construction practices are the factors that determine the quality of concrete. Some methods that are used to enhance concrete's durability include using additives such as impermeable layers, varying the proportions of the concrete's ingredients to achieve different properties, use of admixtures, and the use of composite structures. These techniques can be categorized in to two forms:

- Chemical enhancement
  - Varying the proportion of the constituents used in concrete mixtures.
- Physical enhancement
  - Using external components to further enhance the performance of a concrete structures either by,
    - Use of externally bonded fiber reinforced polymers to concrete structures.
    - Injecting epoxy resin in cracks, covering steel reinforcement with epoxy coating

3.2.3.1 Chemical Enhancement

It is evident that the type and proportion of the ingredients used in making concrete are vital to the aspect of durability. Moreover, the curing process that concrete undergoes and the environment in which concrete is prepared greatly affect the material's properties and consequently the overall performance of concrete structures. Depending on the intended use of the structure and surrounding environment, certain considerations need to be accounted for during the engineering of this material.

One of main concrete ingredients that can be controlled to reduce the effect of the deterioration mechanisms on concrete structures is the water to cement ratio. Controlling the extent of permeability concrete exhibits by changing the water to cement ratio can greatly decrease the rate of the different deterioration mechanisms discussed earlier. By decreasing the water to cement ratio below 0.45, the resistance of concrete to acid attack increases (Zivica and Bajza, 2002). Also, plastic deformation of concrete can be reduced by half the amount of deformation that takes place in wet concrete (Murdock et al., 1979). Moreover, the rate of steel corrosion decreases and the resistance of concrete to de-icing salts used during freeze and thaw cycles increases as the water to cement ratio decreases. Although a lower water to cement ratio increases concrete's resistance to deterioration mechanisms, it also decreases the workability of concrete. As a result the right ratio is one were the concrete's properties are enhanced without disturbing the workability of concrete (Bijen, 2003; Murdock et al., 1979). Type of cement and aggregates used, are also key elements in increasing the resistance of concrete structures against deteriorating mechanisms. In fact, the rate at which steel reinforcement in concrete corrodes greatly depends on the type of cement used over any other concrete constituent (Bijen, 2003).

Adequate usage of admixture in concrete mix can help enhance the resistance of concrete against destructive factors, consequently increasing the structure's durability. Admixtures vary in type depending on their intended use. Accelerators, retarders, air-entraining, and water-reducing admixtures are a few types used in concrete mixtures. For example, in the case of resistance against freeze and thaw cycles, the use of air-entraining admixtures can increase the concrete's resistance to frost. However, the presence of air void decreases the strength and stiffness of concrete's material properties, compromising the structure's performance. It is necessary to use admixtures in concrete to obtain specific design requirements that cannot be achieved otherwise; nevertheless, it is important not to undermine other properties of concrete (ACI Committee 201 and American Concrete Institute, 2008; Mindess et al., 2002; Murdock et al., 1979). Another effective type of admixture used in concrete mixtures are water-reducing admixtures. The use of water-reducing admixtures in concrete, obtains a concrete mix of required slump but with a low water to cement ratio. It has been identified that the water to cement ratio is one of the major factors that affect the concrete's resistance to deteriorating mechanisms; hence the use of this type of admixture can enhance the durability of concrete structures (Mindess et al., 2002).

3.2.3.2 Physical Enhancement

The construction practices and the ingredients used in forming concrete are detrimental factors to the material properties and the extent of concrete's resistance to severe surrounding environment. Cracking is one of the major concerns in concrete that occurs due to different deteriorating mechanisms. Corrosion of reinforcement due to penetration of chloride ions, freeze and thaw cycles, plastic shrinkage due to rapid loss of moisture from concrete's surface, are a few mechanisms that causes cracks in concrete structures. Controlling the amount of cracking concrete may undergo can be achieved through proper engineering practices in design and construction.

The use of external surface coatings can be applied to further control cracks from propagating. The application of external impermeable coatings, using hydrophobic agents, or using compounds that penetrates through concrete structure sealing its pores are ways that protect concrete structures against severe environmental conditions. Moreover, the use of epoxy resin injected in the case of small cracks or using overlaying materials can be used in the case of large damages such as shotcrete. Surface preparation of affected concrete area and bonding properties of the material used are crucial for repairing cracks and restoring concrete structures (Bijen, 2003; Mindess et al., 2002).

Another commonly used technique in externally reinforcing concrete structures is the use of fiber-reinforced polymers, FRP, bonded externally to the structure. The application of epoxy resin is used to bond the two materials together. Through proper application of materials and bonding techniques, a composite section is formed that can enhance the material properties of reinforced concrete structures. For instance, with respect to shear resistance of reinforced concrete beams, it was illustrated by experiments carried out by Chen and Teng in 2002, that externally bonding FRP to the beam increases its shear capacity (refer to Figure 3.18 and 3.19) (Chen and Teng, 2003). However, the downside of using FRP is its low resistance to fire, hence fire protection coating is required to enhance the durability of the composite section. Moreover, the performance of FRP and bonding materials used is greatly dependent on the surrounding temperature in which it is applied and must be accounted for (Bijen, 2003).

Figure 3.18: Reinforced concrete specimens using FRP bonded externally to the side of the specimen or in a U shape referred to as U jacketing (Chen and Teng, 2003).

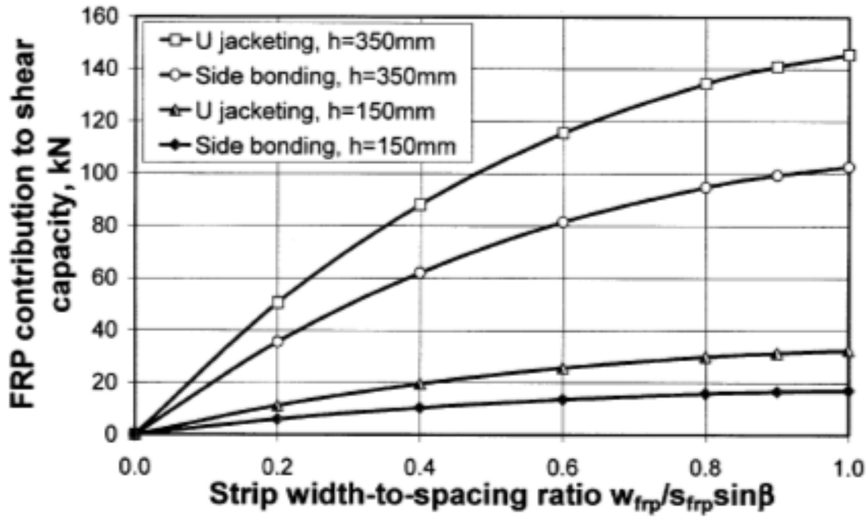

Figure 3.19: The results of the experiment show that as the amount of FRP used, to externally reinforce concrete specimens, increases the shear capacity of the specimen increases (Chen and Teng, 2003).

Other considerations such as increasing concrete's cover, distance between steel reinforcement and edge of concrete, and/or using epoxy coated steel reinforcements in concrete can reduce the rate of the deteriorating mechanism and enhance the durability of concrete structures (Bijen, 2003).

3.2.4 Discussion

Concrete is a heavily used construction material. It is important to identify the factors that result in deteriorating the material and ways to reduce their effect on the structure's performance and durability. Being a man-made material, concrete's properties can be engineered to best suit the design requirements of the structure depending on its intended use and surrounding conditions. Therefore, the proportions of the ingredients, and methods and techniques used in mixing and constructing concrete are detrimental factors to the performance of concrete structures. Through proper engineering practices and knowledge of material composition, concrete can be engineered to last long lifespans. Table 3.3 summarizes a few of the deterioration mechanism in reinforced concrete and enhancement techniques used to improve its performance.

Deterioration Mechanisms	Chemical Agents	Acid attack
		Carbonation
		Penetration of chloride ions
	Enivronmental Conditions	Freeze and thaw cycles
	Physical Conditions	Plastic deformation- Creep
Enhancement Techniques	Chemical Enhancement	Type and proprtion of concrete ingredients used in mixture
		Use of admixtures
	Physical Enhancement	Composite structure, wrapping FRP
		External coatings

Table 3.3: Summary of a few deterioration mechanism and enhancement techniques for reinforced concrete structures.

3.3 Steel

3.3.1 Steel as a structural material

One of the earliest applications of metal in structures was the use of iron chains in suspension bridges in China (Tyrrell, 1911). Iron mixed with impurities such as carbon, manganese, sulphur, and copper forms different types of metals that vary in material properties. Cast and wrought iron are two forms of iron that were widely used before being replaced by steel. Essentially, the variation in carbon content is what differentiates the three types of metal (Bates and Association, 1984).

The application of cast iron in construction dates back to the late eighteenth century. In 1779, the first bridge in the world to be constructed entirely out of cast iron was the Iron Bridge located in England built by Abraham Darby. The Iron Bridge was the only bridge that was able to withstand the flood in 1795 that destroyed all other bridges along the Severn River. Figure 3.20 shows an image of the Iron Bridge spanning over the Severn Bridge in Coalbrookdale, England. What followed was the use of wrought iron in construction.

Figure 3.20: Iron Bridge built in 1779, was the first bridge in the world constructed fully out of cast iron.

Wrought iron, which consisted of a lower carbon content compared to cast iron, and hence less brittle, was structurally used roughly between 1850-1910. A few iconic structures in the world that are constructed out of wrought iron are the Eiffel Tower built in 1889, and the Garabit Viaduct arch bridge built in 1884 spanning the Truyère River in France, both built by French architect and engineer Gustave Eiffel, (Billington, 1985). It was not up until 1850 when structural steel began to take over the application of wrought iron and eventually replaced it.

Steel compared to wrought iron has higher carbon content but lower than that contained in cast iron. Initially steel was produced using the cementation-process, which involves the addition of carbon to wrought iron resulting in blister steel. An English watchmaker, Benjamin Huntsman, discovered the process of improving the quality of blister steel, to crucible steel, which involved the removal of slag particles. At the time, the cost of producing steel was very costly and labor intensive. It was not up until the Bessemer Invention, developed by a British metallurgist Sir Henery Bessemer patented in 1855, when the mass production of steel at a lower cost was possible. The Bessemer Invention was later replaced by the open-hearth process (Spoerl, 2007). The Brooklyn Bridge, built in 1883 by John A. Robelling, was the first steel-cable suspension bridge in the world (Talbot, 2011). At the time of construction, the Brooklyn bridge spanned the longest distance using steel truss deck and cables (Billington, 1985).

Steel, like concrete, is a man-made material engineered to suit particular design requirements. The material properties that steel exhibits are what makes this material desirable in structural engineering. For instance, steel's high strength to weight ratio makes it a suitable material to span long distances without the use of a large quantity of materials, making it a favorable choice in the bridge construction. Also, steel's high tensile strength and properties makes it a suitable for reinforcement in concrete. Furthermore, the use of different connection methods bolts or welds, possibility of prefabricating structural elements and the various shapes and sizes that steel can be rolled into are a few other advantages associated with using steel as a structural material. Simone de Beauvoir, a pedestrian bridge located in Paris, is an example of a fairly recent construction made primarily out of steel (refer to Figure 3.21).

Figure 3.21: Pedestrian bridge, Simone de Beauvoir, in Paris constructed using steel sections.

Steel is extensively used in construction today. Understanding the different mechanisms that can possibly diminish the structure's performance and identifying the different measures that can be used to minimize these affects is important. Therefore, by studying the possible degradation mechanism a structure may undergo depending on its intended use and surrounding factors, certain safety measures can be accounted for that will improve the overall durability of the structure.

3.3.2 Deterioration Mechanisms

Steel, like concrete, is heavily used in the design and construction of many structures standing today. Understanding the material properties and the factors that may result in loss of the structure's performance is essential. Identifying the different factors and their causes, and the different measures that can be accounted for to diminish the adverse effect of these factors will help in improving the durability of the structure. Inadequate connection details, defects during the fabrication of steel, and corrosion due to environmental conditions, and biological attack are a few deteriorating mechanisms that may compromise the structure's performance.

Accounting for these factors during the design of steel structures and anticipating necessary maintenance procedures and repair measures that would need to be carried out in the cost assessment of the project, improves the overall durability of the structure. Common sources of degradation of steel structures are:

- Chemical composition
  - Intergranular corrosion
- Environmental conditions
  - Atmospheric corrosion
  - Hydrogen embrittlement
- Biological agents
  - Sulphate reducing bacteria

Corrosion is one of the main deteriorating mechanisms in steel structures. There are several different types of corrosion mechanisms that vary depending on the surrounding conditions and material composition, which ultimately leads to degradation of the material. Therefore, the environment in which steel structures interact and material composition governs the rate of deterioration the structure may undergo.

Lack of homogeneity in metal structures can result in an increase in the rate of degradation at the microscopic level. Substantial differences in material properties between the crystal grains and crystals formed during the solidification process of the melted elements that the metal is composed of are a result of inhomogeneity of the metal structure. This form of deterioration is referred to as intergranular corrosion that can greatly affect the material properties of the metal and ultimately the failure of the structure (Ricker et al., 1994)

Surrounding conditions greatly influences the extent of corrosion exposed steel can experience. It is the electrochemical process due to the interaction of the steel structure with its surrounding environment that leads to atmospheric corrosion. Temperature, relative humidity and water are few factors that result in corrosion of metallic structures. For instance, exposed steel in costal regions of high relative humidity and temperature can result in accelerating the rate of corrosion. The salt and dust particles in the air cause condensation on the metal surface that decreases the electrical resistance of the metal, hence increasing the corrosion rate. Steel exposed for a period of time in an environment susceptible to corrosion can result in weathering. Corrosion of metal greatly influences the structure's performance. This is of great importance in the case of application of steel reinforcement in concrete structures. As previously stated, degradation of steel reinforcement in concrete due to corrosion can compromise the overall structural properties since weathered steel greatly decreases the bonding strength between the steel and concrete (Bijen, 2003; Dafloua et al., n.d.).

Rust development on the metal is an indicator of corrosion taking place. Being visible to the eye makes this deterioration mechanism easily detectable allowing for necessary interventions to take place to protect the structure from further degradation. However, this is not the case with all types of deterioration mechanisms that effect steel structures. For example, hydrogen embrittlement is a type of corrosion mechanism that can severely damage steel structures with no visible indication to its progression. Hydrogen embrittlement is caused by the diffusion of hydrogen atoms into the material, which consequently weakens the metal and resulting in brittle failure of the structural component. One way of causing hydrogen contamination is during the process of welding. Since hydrogen is very soluble in molten metal, the high temperatures associated with the welding process causes in an increase in the absorption rate of hydrogen in the metal. The diffusion of hydrogen in the atomic form into the material can result in the accumulation of gas in hollow spaces and producing cracks.

The constituent of steel is another factor that influence the effect of hydrogen embrittlement on the structure's performance. The high strength to weight ratio that steel exhibits as a material property allows for the design of lower weight structures of higher strength. Although the diffusion of hydrogen decreases as the strength of steel increases, the distribution of hydrogen within the material is critical. For high strength steel, local concentration of hydrogen can occur which can result in damage of the structure (Bijen, 2003; Eliaz et al., 2002; Woodtli and Kieselbach, 2000).

Another source of corrosion in steel structures is the presence of microorganisms. Sulphate-reducing bacteria are anaerobic bacteria that generate corrosive environments for metal exposed to water containing sulphur. Corrosion of steel occurs due to the conversion of iron to iron sulphide, hence the production of hydrogen sulphide due to the presence of sulphate-reducing bacteria causes the initiation of corrosion in steel structures (Charng and Lansing, 1982; Yuzwa and Eng, 1991).

Lack of incorporating safety measures in the design of steel structures and inadequate usage of material can result in diminishing the overall durability of the structure and in some cases fatal accidents. In 1967 the Silver Bridge spanning the Ohio River collapsed due to stress and fatigue corrosion of connecting elements. This was a fatal accident that killed 46 people; Figure 3.22 illustrates the aftermath of the collapse of the Silver Bridge (Zoli and Steinhouse, 2007).

Figure 3.22: Silver Bridge collapse in 1967 due to failure of connecting elements by corrosion killing 46 people (Zoli and Steinhouse, 2007).

3.3.3 Enhancement Techniques

Corrosion of the pin-hanger assembly led to the failure of the Minaus River Bridge in Connecticut, killing three people in 1983 (Karbhari and Shulley, 1995; Lichtenstein, 1993). Corrosion can severely damage our surrounding infrastructure depending on the surrounding conditions the structure is interacting with. Due to lack of proper maintenance procedures and protective measures, corrosion can result in weakening of the structure over time. Because steel is a man-made material, the composition and formation process of steel is important in reducing the effect of corrosion at the microscopic level. In addition, the use of different types of protective coatings can be applied to steel structures to enhance the structure's durability. These techniques can be categorized into two parts:

- Chemical enhancement
    - Galvanizing→ metallic coating of steel structures to protect against corrosion
    - Paint or organic coating
    - Use of protective biofilm to protect against corrosion caused by microorganisms
- Physical enhancement
    - Using external bonded composite epoxy systems to further enhance the performance of steel structures.

3.3.3.1 Chemical Enhancement

The use of protective coating in steel is important to retard the effect of corrosion on metal structures. It begins with preparing the metal surface to place the protective layer. The cleaning process can either be mechanical by the application of a force to the surface or chemical using alkaline cleaning agents. Inadequate cleaning of the metal surface may result in failure of the protective layer in its early stages.

There are different types of coatings that can be applied on clean metal surfaces that reduce the adverse effect of corrosion on metallic structures. The type of coating applied on the surface of the structure varies depending on the type of formation developed between the coating and the metal surface, physical or chemical film formation. Conversion coatings, such as iron or zinc phosphate, are applied on steel structures to increase the structure's resistance to corrosion through a chemical reaction between the metal surface and the applied coat results in the formation of the protective layer through a chemical formation process. Organic coatings and metallic coatings are also used in increasing the resistance of steel structures against corrosion. Zinc-bearing paint is an example of organic coatings used in protecting the structure against corrosion. The process of galvanization includes coating steel structures with a metal that corrodes prior to steel. A metal that is used extensively in galvanization is zinc. The passivation of zinc further reduces the rate of corrosion. Hot dip galvanizing is the process used in coating steel structures with metallic coatings, which is the process of dipping steel elements into a bath of molten zinc. Steel frames, steel ducts, reinforcement bars and structural steel are a few examples in which galvanization process is applied to protect the structure against corrosion (Bijen, 2003).

The composition and the formation process of steel structures play an important role in structure's susceptibility to corrosion. Inhomogeneity of the metal structures due insufficient use of heat treatment and alloys in the metal formation causes intergranular corrosion in the structure that can ultimately compromise the durability of the structure. Moreover, the composition of steel structures may increase its vulnerability to hydrogen embrittlement; this is the case of steel of high tensile strength (Ricker et al., 1994; Woodtli and Kieselbach, 2000).

Corrosion due to microorganism attack is of particular importance to sewage treatment facilities, underground pipe and nuclear power plants. The uses of cathodic protection and coatings, and biocide treatment of steel pipes are few ways used to protect the structure against corrosion influenced by microorganisms. Furthermore, the use of protective biofilm using antimicrobial-producing bacteria inhibits the growth of sulphate-reducing bacteria (Mansfeld et al., 2004).

3.3.3.2 Physical Enhancement

Physical enhancement of steel structures is a reinforcement technique used in improving the performance of steel structures. Corrosion of steel structures results in cracking and loss of section, which may question the structural integrity of the structure. Deterioration of steel structures results in an increase of stresses acting on the structure to an extent that the capacity of the structure is not sufficient to withstand the applied forces. Steel bridges are exposed to the environment throughout the year, hence face a greater risk of deterioration compared to other steel structures. One way of physically enhancing the structure's performance is the use of composites.

The high strength to weight and stiffness to weight ratio makes the use of composite adequate in the repair and the rehabilitation of structures. In addition, the high resistance to corrosion makes these materials favorable in structural application. Composite in the form of carbon or glass fiber reinforced epoxy system can be used. However, as previously stated, the bonding mechanism between the fiber and the structure is critical for the composite to be beneficial in enhancing the structure's performance. There are several different bonding scenarios that can be used between the composite and the steel structure; Figure 3.23 illustrates a few of the possibilities. The type of bonding and composite used in the repair of steel structures is greatly influenced by the environment with which the structure is interacting. Hence, understanding the effect of different environmental conditions is important in determining the composite that would best suit the structure (Karbhari and Shulley, 1995).

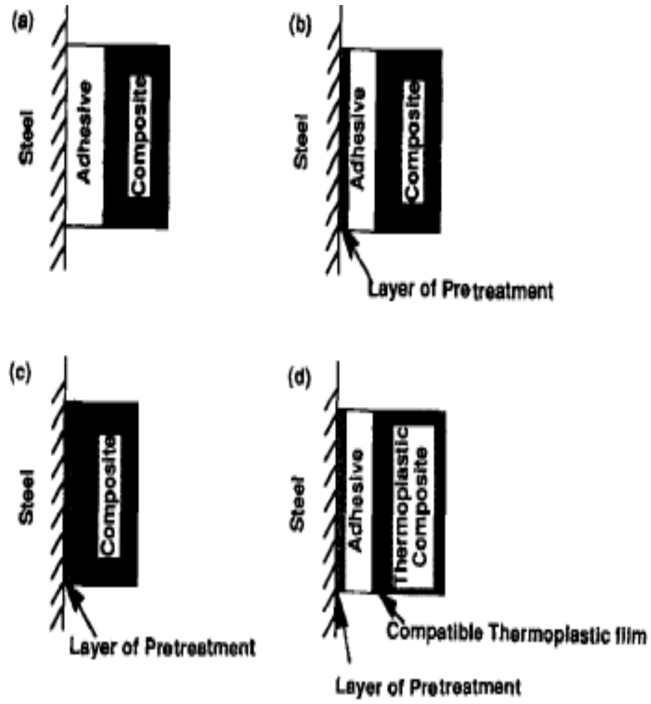

Figure 3.23: Different bonding scenarios that could be used between to physically enhance steel structures using composites (Karbhari and Shulley, 1995).

3.3.4 Discussion

Similar to concrete, steel is a man-made material that is heavily used as a construction material. It is important to identify the factors that result in deteriorating the material and ways to reduce their effect on the structure's performance and durability. Depending on the surrounding conditions and the material properties, steel structures can undergo different types of corrosion mechanism that can severely affect the structure's performance. Through proper engineering practices and knowledge of material composition, steel can be engineered to last long lifespans. Table 3.4 summarizes a few of the deterioration mechanism in steel structures and enhancement techniques used to improve its performance.

Deterioration Mechanisms	Chemical Composition	Intergranular Corrosion
		Hydrogen Embrittlement
	Enivronmental Conditions	Atmospheric Corrosion
		Hydrogen Embrittlement
	Biological Agents	Sulphate-Reducing Bacteria
Enhancement Techniques	Chemical Enhancement	External coatings
		Chemical composition and formation of steel
		Protective biofilm- Antimicroba-producing bacteria
	Physical Enhancement	Composite structure, wrapping FRP

Table 3.4: Summary of a few deterioration mechanism and enhancement techniques for steel structures.

3.4 Material Comparison

It has been established that the type of material used in construction plays a significant role in achieving durable designs. The type of material selected for a project greatly depends on the client and/or architect's requirements. Therefore, engineers must work alongside the client to make recommendations on the type of material used to best fit the scope of the project based on their experiences and knowledge. The driving factors from an engineer's perspective for choosing the type of material to be used are the intended use of the structure, the surrounding environment, accessibility to the material, allocated budget for the project, and experience of designers involved in the project. Thus, developing a sense of the material properties that wood, steel and concrete exhibit, based on strength and stiffness, will further assist the designers in making recommendations to the client, and during the decision-making process.

3.4.1 Factors affecting properties of wood

Wood varies in its material properties depending on its species. Being a natural material composed of concentric layers, the strength of wood varies according to the direction in which the load is applied with respect to the grain. As mentioned earlier, the natural growth characteristics of wood such as knots, checks and wane, which result in local stress concentration cause further variation in its material properties. The type of species chosen may depend on the availability of the wood around the area of the site. This limits the designers to the specific material properties associated with that species. According to Canadian Standard CAN/CSA 086-01, "Engineering Design in Wood", wood is categorized into four different species that are further classified into different grades. The different grades characterize the application of the wood. For example, the grade of light framing wood differs from wood used in structural beams.

In addition, as previously stated, a factor that greatly influences the material properties of wood is the percentage of moisture content, as this affects the stability level of a wooden element. Although wooden specimens can be engineered, to enhance their material properties, for instance glued-laminated timber, wooden specimens are still controlled by the properties of the wood species used.

The material properties of wood are variable and are dependent on its species, grade, direction of load application and intended use. The different categories of wood species and grade are illustrated in table 3.5 and 3.6 respectively (Canadian Standard Association- CAN/CSA-086-01, 2005).

Species combinations	Stamp identification	Species included in the combination
Douglas Fir-Larch	D Fir-L (N)	Douglas Fir, Western Larch
Hem-Fir	Hem-Fir (N)	Pacific Coast Hemlock, Amabilis Fir
Spruce-Pine-Fir	S-P-F	Spruce (all species except Coast Sitka Spruce), Jack Pine, Lodgepole Pine, Balsam Fir, Alpine Fir
Northern Species	North Species	Any Canadian species graded in accordance with the NLGA rules

Table 3.5: Different categories of wood species (Canadian Standard Association- CAN/CSA-086-01, 2005).

Grade category	Smaller dimension, mm	Larger dimension, mm	Grades
Light Framing	38 to 89	38 to 89	Construction, Standard
Stud	38 to 89	38 or more	Stud
Structural Light Framing	38 to 89	38 to 89	Select Structural No. 1, No. 2, No. 3
Structural Joists and Planks	38 to 89	114 or more	Select Structural No. 1, No. 2, No. 3
Beam and Stringer	114 or more	Exceeds smaller dimension by more than 51	Select Structural No. 1, No. 2
Post and Timber	114 or more	Exceeds smaller dimension by 51 or less	Select Structural No. 1, No. 2
Plank Decking	38 to 89	140 or more	Select, Commercial

Table 3.6: Different grades of wood associated to its intended use in construction (Canadian Standard Association- CAN/CSA-086-01, 2005).

3.4.2 Factors affecting properties of steel

In contrast to wood, steel and concrete are man-made materials. The strength of concrete and steel can be designed such that they suit the desired purpose. Hence, the material properties that they exhibit along their spans are of a greater consistency compared to wood.

Steel is known for its high strength to weight ratio, which makes it adequate for long-span structures such as bridges. Under high stresses, steel is one of the few materials that can still behave elastically compared to other materials used in construction. In addition, under high tensile stresses, steel can undergo large deformations before failing which makes it a ductile material (McCormac and Csernak, 2011). This property is highly favorable as it reduces the probability of a catastrophic structural failure.

The level of ductility steel exhibits relies on its constituents. Steel contains an alloy of iron in combination with other elements including carbon. Structural behavior of steel can range from brittle to ductile, depending on the percentage of carbon. Although ductile behavior of material is preferred to prevent sudden failure of structural elements, higher strength steel, and thus lower ductility, is also required to resist higher loads applied to the structure. Therefore, designers typically need to determine what is just the right percentage of carbon content to be used such that the material properties of steel would lie within an acceptable range between the two behaviors (McCormac and Csernak, 2011). A typical stress-strain graph of steel illustrating the different behaviors this material undergoes as the load increases is shown in Figure 3.24. The stress-strain graph of high carbon content steel is illustrated in Figure 3.25 showing a brittle failure of the structure as the load increases.

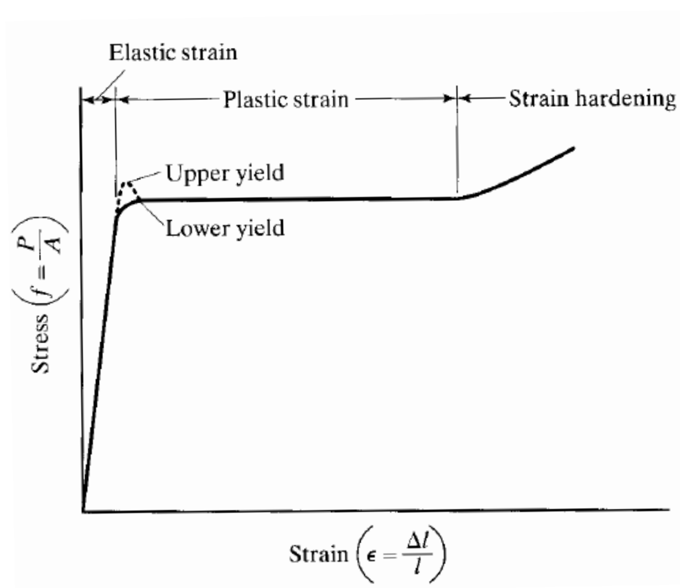

Figure 3.24: Stress-strain curve of steel showing the different behaviors the material undergoes as the load increases (McCormac and Csernak, 2011).

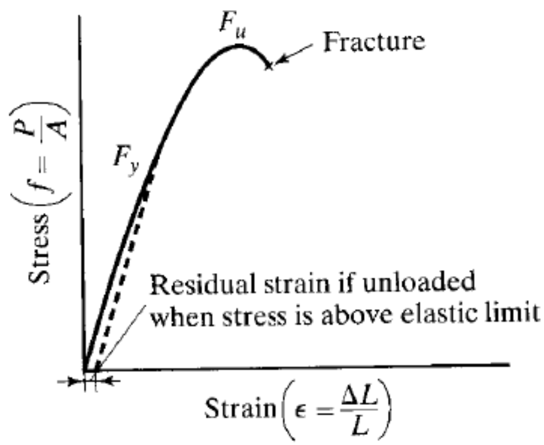

Figure 3.25: Stress-strain curve of steel undergoing a brittle failure due to high carbon content (McCormac and Csernak, 2011).

3.4.3 Factors affecting properties of concrete

Concrete, from a constructability point of view, is more flexible compared to steel and wood. The reason is the ability for concrete to be either casted-in-place or prefabricated. However, unlike steel, concrete's material properties vary greatly with time. Therefore, on-site concrete construction can cause an increase in properties' variability due to changes in surrounding conditions over the period of construction (Mindess et al., 2002).

Compared to steel, concrete is a brittle material and has a low strength-to-weight ratio. The latter property means that a large mass of concrete is required to compensate for its low strength, therefore making it less practical for long-span structures. As mentioned earlier, the tensile strength of concrete is very low compared to its compressive strength; therefore, in design the tensile strength of concrete is obtained through steel reinforcement.

The compressive strength of concrete varies from 20-50MPa and could reach up to 80MPa and higher, in some cases, if the nature of the project requires it. The compressive strength value, f_c', of concrete is governed mainly by the water to cement ratio. Moreover, other factors that affect the crushing strength of concrete include (Murdock et al., 1979):

- Degree of compaction: affects the percentage of void present in concrete
- Type and quality of cement used
- Type and surface texture of aggregates used
- Curing process: drying out of concrete in its early stages may result in a dramatic decrease in its compressive strength
- Temperature in which concrete is placed: the higher the temperature, the greater is the rate of hardening
- Age of concrete: the strength of concrete increases over time

Another interesting distinction between steel and concrete is the change in the material's stiffness relative to its designed strength. In the case of concrete, as its compressive strength increases, its stiffness, defined by the modulus of elasticity, increases. Equation (1) illustrates the relation between these parameters for normal weight concrete: as the compressive strength of concrete increases, its stiffness increases (Neville, 2011). However, this is not the case for steel. In fact, by increasing the yield strength of steel, through increasing the carbon content, can result in the material exhibiting brittle behavior.

$$E_c = 57000(f_c')^{0.5} \; in \; psi \quad (1)$$

The variation in the material's modulus of elasticity with respect to its corresponding strength is illustrated in Figure 3.26 and 3.27 (Carmo et al., 2013; McCormac and Csernak, 2011).

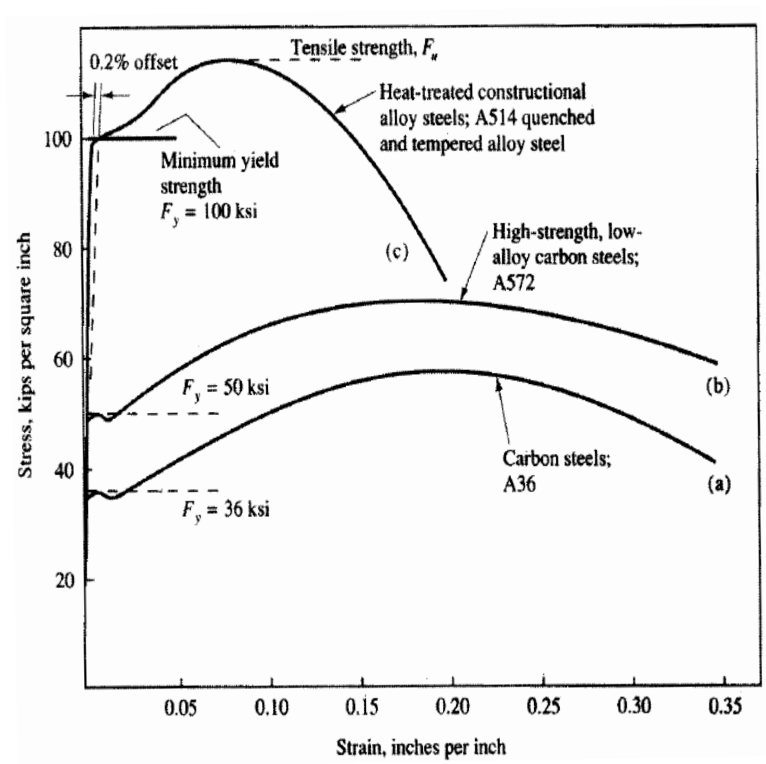

Figure 3.26: Stress-strain curve for steel showing that E remains constant as the yield strength increases within the elastic region (McCormac and Csernak, 2011).

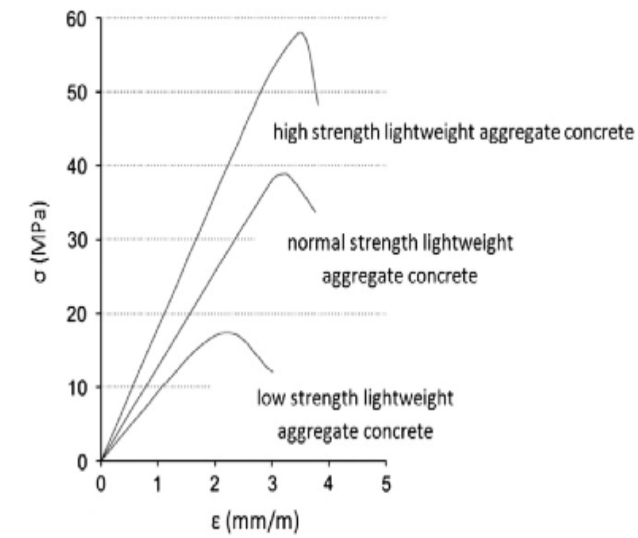

Figure 3.27: Stress-strain curve for concrete showing that E increases as the compressive strength of concrete increases (Carmo et al., 2013)

3.4.4 Numerical Model

To further illustrate the strength and stiffness of wood, steel, and concrete, a simple design example is carried out. This exercise involves comparing the weight (in kg), cross-sectional area (in cm^2), and cost of material (in \$) for each material based on flexural strength and flexural deflection design requirements. The analysis and design of the beam is based on the Canadian standards for wood, steel, and reinforced concrete design.

3.4.4.1 Analysis and Design Comparison

The model considered is the analysis and design of a simply supported beam spanning a pedestrian bridge that is around 3.5 meters wide. Figure 3.28 illustrates the plan view of the pedestrian bridge with 4 equally spaced beams. The analysis was carried out for varying spans of the bridge, and varying magnitudes of applied pressure. Furthermore, the design was based on the flexural strength and deflection of the structure selected for the three different material properties: wood, steel and reinforced concrete. The material properties used in the design are shown in table 3.7. The cross-sectional shape of the beam influences the design of the structural elements. In this exercise, a rectangular cross-section is assumed for the design of wood and reinforced concrete beams, and wide flange (w-section) cross-section is used in the design of steel beams.

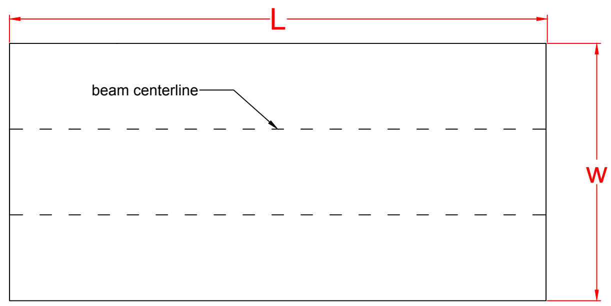

Figure 3.28: Plan view of pedestrian bridge used for the numerical model analysis.

Wood- D-Fir, Grade SS	Bending Strength	f_b	18.3 Mpa
	Modulus of Elasticity	E	12000MPa
	Density	γ_w	530kg/m^3
Reinforced Concrete	Compressive Strength	f_c'	30MPa
	Modulus of elasticity- Conrete	E_c	24650MPa
	Yield Strength of steel reinforcement	f_s	400MPa
	Modulus of Elasticity	E_s	200000MPa
	Normal Density Concrete	γ_c	2400kg/m^3
	Mass per length of 35M reinforcement	m/l	7.85kg/m
Steel	Yield Strength	f_y	345MPa
	Modulus of Elasticity	E	200000MPa
	Density	γ_s	7850 kg/m^3

Table 3.7: Material properties used for the design of wood, steel and reinforced concrete beams.

With respect to the flexural strength analysis, the beam was designed to resist the maximum moment. In the case of a simply supported beam with a uniformly distributed load (refer to Figure 3.29) the maximum moment occurs at mid-span. The method used to determine the maximum moment the beam is required to resist is given by equation (2).

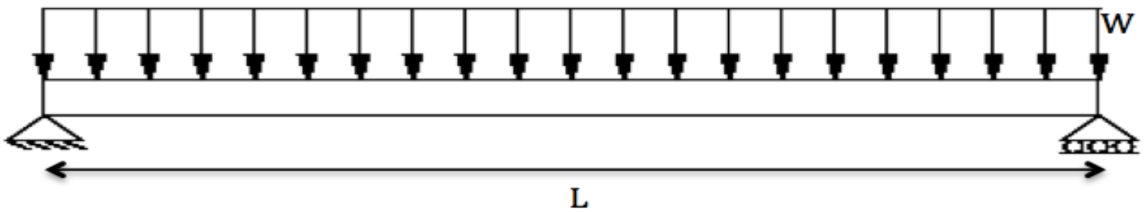

Figure 3.29: Simply supported beam with a uniformly distributed load applied along its span.

$$M_f = \frac{wL^2}{8} \quad (2)$$

In equation (2), "w" is the uniformly distributed load acting along the span of the beam (kN/m) and "L" is the length of the beam in meters. Knowing the maximum moment, the beam can be designed for different material properties and subsequently the required weight of the structural element is obtained. This design is based on the strength of the material used (refer to appendix A for detailed calculations). Graphs 3.30 and 3.31 provide plots for the required weight for flexural strength design of a simply supported beam for wood, steel, and reinforced concrete for varying applied pressure acting on the bridge, and varying beam spans respectively.

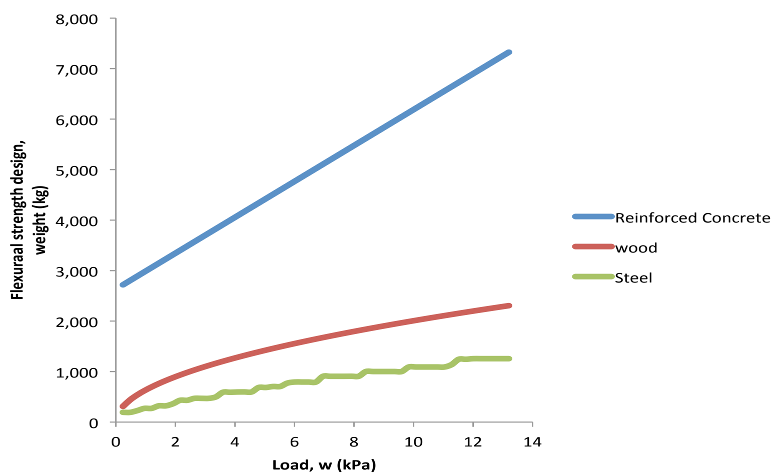

Figure 3.30: Required design weight for flexural strength of wood, steel and reinforced concrete for varying applied load (w) and a constant span (L) of approximately 15m

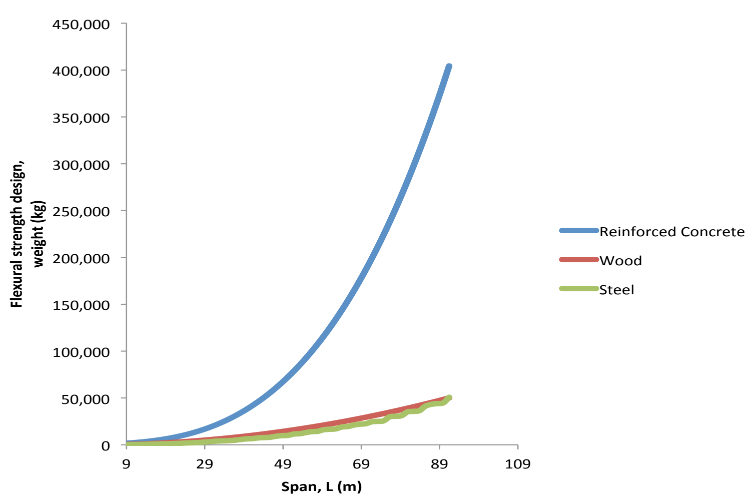

Figure 3.31: Required design weight for flexural strength of wood, steel and reinforced concrete for varying span (L) and a constant load (w) of approximately 5kPa

Looking at the effects of the two variables, span of the bridge and applied pressure, the following conclusions can be drawn:

- Comparing the two graphs for flexural strength design for load and span variation:
  - The design weight increases much more dramatically with increasing span compared to increasing applied pressure. The reason is the maximum moment varies proportionally to the square of the span of the bridge and linearly to the applied load. Therefore, varying the span of the bridge has a greater influence on the design.
- Comparing the different plots (wood, steel, and reinforced concrete) within each of the graphs above for flexural strength design:
  - Steel requires a much smaller design weight in both cases compared to reinforced concrete to resist the same moment applied. This further illustrates the high strength to weight ratio that steel exhibits as a material property. Hence, for flexural strength considerations, steel is a stronger material compared to both wood and reinforced concrete.
  - Due to the variation in material density, the required design weight of wood is closer to steel compared to concrete, although with respect to volume, wood requires a larger design volume than steel (refer to appendix A).

Similar to the strength design, the beam was analyzed and designed to meet flexural deflection requirements which is based on the material's stiffness. The beam is designed to meet a specific deflection criterion that depends on the intended use of the structure and type of the material used. In this example the deflection criterion L/400 (units of length) is used for all three materials. Knowing the maximum deflection of the beam, the required moment of inertia to meet the deflection criteria can be calculated. Then, depending on the cross-sectional shape of the beam, the corresponding cross-sectional dimensions are calculated. For a simply supported beam with a uniform distributed load applied, the maximum deflection occurs at mid-span and can be calculated using equation (3).

$$\Delta_{max} = \frac{5wL^4}{384EI} \quad (3)$$

In equation (3), "w" is the uniformly distributed load acting along the span of the beam (kN/m), "L" is the length of the beam in meters, "E" is the modulus of elasticity (MPa), and "I" is the moment of inertia (mm^4) which depends on the cross-sectional shape of the beam. Equating equation (3) to the deflection criterion requirement, the

moment of inertia for the three different material properties is calculated, and the corresponding cross-sectional dimensions are obtained and the weight is calculated. This design is based on the stiffness of the material used (refer to appendix A for detailed calculations). Graphs 3.32 and 3.33 provide plots of the required weight (in kg) for flexural deflection design of a simply supported beam for wood, steel, and reinforced concrete for varying applied pressure acting on the bridge and varying beam spans respectively.

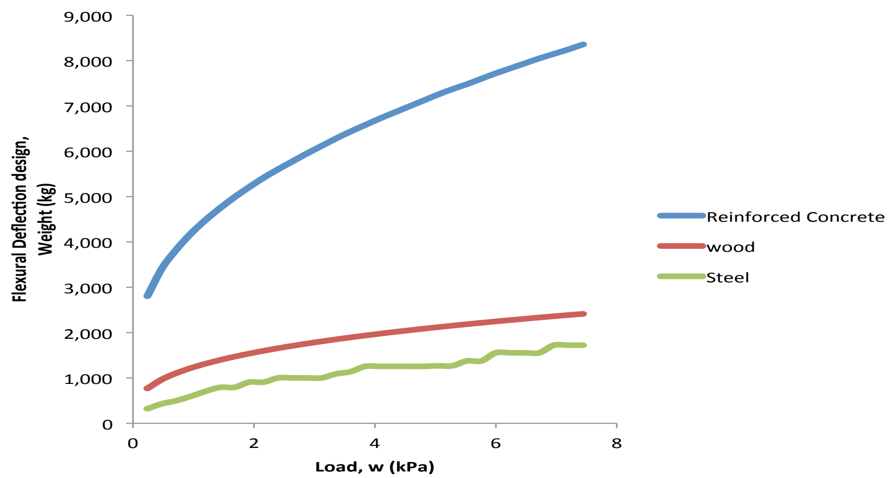

Figure 3.32: Required design weight for flexural deflection of wood, steel and reinforced concrete for varying applied load (w) and a constant span (L) of approximately 15m

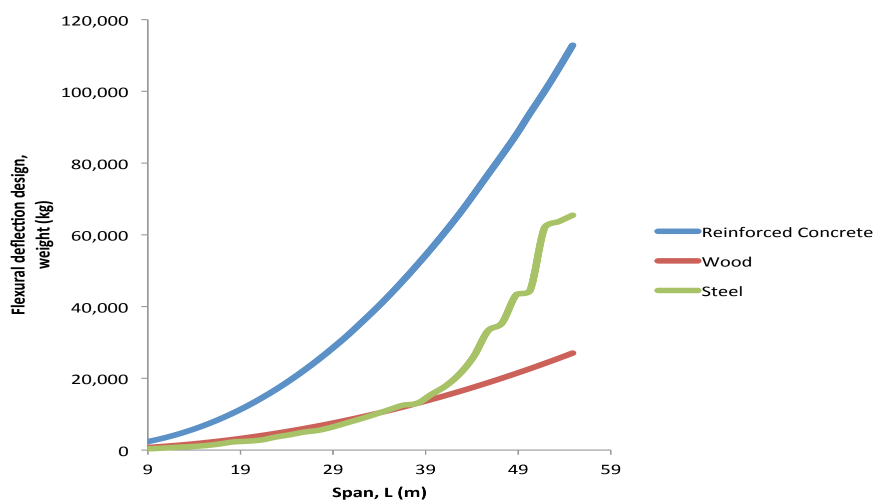

Figure 3.33: Required design weight for flexural deflection of wood, steel and reinforced concrete for varying span (L) and a constant load (w) of approximately 5kPa

Looking at the two varying parameters, span of the bridge and applied pressure, the following conclusions can be drawn:

- Comparing the two graphs for flexural deflection design for load and span variation:

    - The design weight required increases much more sharply as the span of the bridge increases compared to increasing the applied pressure. The reason is the maximum deflection varies proportionally to the fourth power of the span of the bridge and linearly to the applied load. Therefore, varying the span of the bridge has a greater influence on the design.

- Comparing the different plots within each of the graphs above for flexural deflection design:
    - Similarly to the flexural strength design of the beam, steel requires a much lower design weight in both cases compared to reinforced concrete to meet the same deflection criterion.
    - Due to material density variation, wood and steel are closer in the required design weight compared to reinforced concrete. However, with respect to volume of material, steel is much lower than wood and reinforced concrete. Hence, for flexural deflection considerations, steel is a stiffer material compared to wood and reinforced concrete (refer to appendix A).

Moreover, flexural deflection is what governed the design of the beam for all three materials, and varying parameters (span and load applied). The reason is that as the span of beam increases, material stiffness and cross-sectional geometry of the beam is what will govern the design of the structure for the applied load case to meet the specified deflection criteria (L/400). Since wood exhibits a lower stiffness compared to steel and reinforced concrete, the cross-sectional area required for flexural deflection design of wood is greater than that of the other two materials. This shows that using wooden beams is less practical for deflection-controlled designs (refer to appendix A). However, since wood has a much lower density compared to steel and concrete, the required design weight of wood is closer to the design weight of steel but much lower than concrete.

Another interesting plot that further illustrates the properties of concrete is the total cross-sectional area of material required, to design the beam for the specified load and varying span, compared to using steel and wood (refer to Figure 3.34). Usually, the required cross-sectional surface area of concrete is smaller than that of wood but greater than steel. However, this is not true as the span of the beam increases beyond a specific value. In this case, beyond a threshold of approximately 50 meters span, the required area of reinforced concrete is greater than that of wood for flexural strength design requirements. Although it is unrealistic to have a beam spanning for 50 meters, this shows that concrete becomes a less suitable material for larger spans.

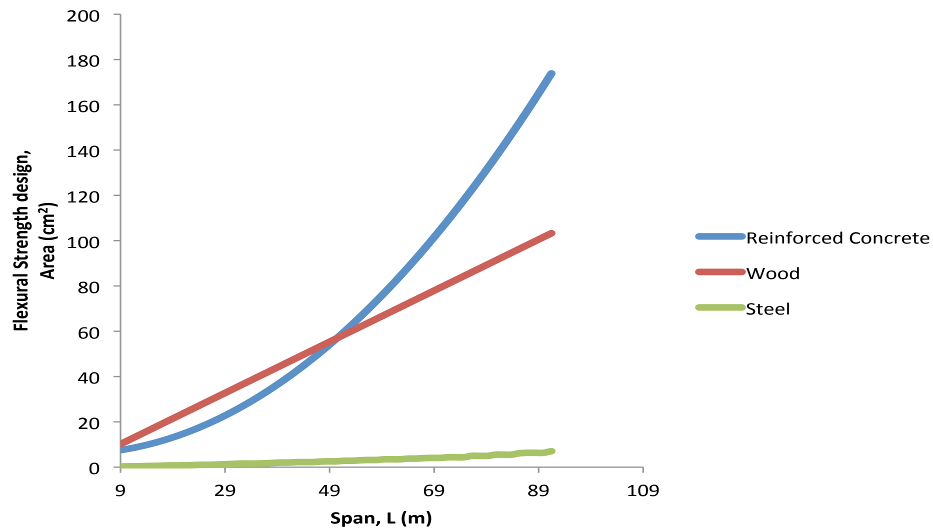

Figure 3.34: Required design area for flexural strength of wood, steel and reinforced concrete for varying beam spans. Beyond a beam span of 50m, wood requires less cross-sectional area compared to reinforced concrete

Generally, according to the structural system and material properties used in this model, it was determined that steel showed stronger and stiffer material properties compared to reinforced concrete, and wood. However, one should keep in mind that the analysis of a structure greatly depends on:

- End constraints: In this case a simply supported beam was considered
    - Determinate versus and indeterminate structure
- Type of loading: In this case a distributed load was applied along the span of the beam
    - Asymmetrical loading
    - Concentric applied loads
    - A combination of distributed and concentric loading
- Type of structure: In this case a simple beam is used
    - Truss
    - Composite section
- Material properties and geometry
    - Type of wood species used
    - Compressive strength of concrete
    - Yield strength of steel
    - Cross-sectional shape of beam

    - Solid versus hollow section
    - Circular versus rectangular section

The properties listed above influence the analysis and design of the structure. Although this model does not generalize for all the cases mentioned above, it does show the relative strength and stiffness of the materials for the specified scenario. Moreover, the aim of this exercise is to compare the material properties rather than the complexity of the various structural systems. As a starting point, idealizing a structure and doing simple calculations one can quickly develop a sense of the type of material that would be most suitable for the project based on strength and deflection requirements. Further considerations will need to be taken into account based on environmental conditions and budgetary restraints.

3.4.4.2 Cost Comparison

Cost being the "bottom line" in the decision-making process of a project, it is important to compare the cost of the three different materials used in construction. Moreover, in some scenarios the material cost is what governs the choice of material used for a structure. Other than the cost of materials, the cost of fabrication, of shipping the materials and assembling the structure plays a significant role in determining the overall cost of the project, which in turn influences the cost of the structure's durability. The following are a few factors that will need to be accounted for with respect to cost (Sarma and Adeli, 2002):

- Cost of material, this includes:
    - Structural members: column, beams, bracing, slabs
- Cost of transportation of the materials
- Cost of fabrication:
    - Truss versus beam
    - Cast-in-place concrete versus prefabricated panels
    - Cost of formwork for concrete structures
    - Composite sections
- Cost of connections used
    - Weld versus bolt
    - In shop welding versus on site
- Cost of assembling and erecting the structure
- Maintenance cost, varies depending on
    - Type of material used
    - Purpose of the structure

- Surrounding conditions

As illustrated earlier, as the initial cost increases, the cost of durability increases. Therefore, to meet a point where the cost of the project is optimized, compromises will have to be made. It is evident that the type of material used is the limiting factor in the cost of the project, from cost of purchasing the material to all the other factors that are associated with it. A cost comparison based on the numerical model illustrated earlier is carried out using the various material prices listed in Table 3.8, refer to Appendix A for the conversion factors used to plot the graphs. In this exercise, the cost used to evaluate the effect of the material type on the cost of achieving durable design only considers the cost of purchasing the material and does not account for the cost of fabrication and construction of the different materials. For instance, using precast instead of cast-in-place concrete greatly impacts the price of concrete, however this is not accounted for.

Material	Cost
Concrete	$109.91/ton
Steel	$49.56/CWT
Wood	$429.98/MBF

Table 3.8: Cost of material for concrete, steel and wood. This data was collected from the following source Engineering News-Record, 2013.

Based on the numerical model described above, steel was most suitable for the design based on its material properties; however, this is not the case when it comes to cost comparison. Graph 3.35 and 3.36 shows that the cost of using steel is higher than wood and reinforced concrete, although it required the least cross-sectional area based on its material properties. Though steel would be structurally more suitable from the design aspect, the high cost associated with buying steel may compromise the overall cost of the project's durability.

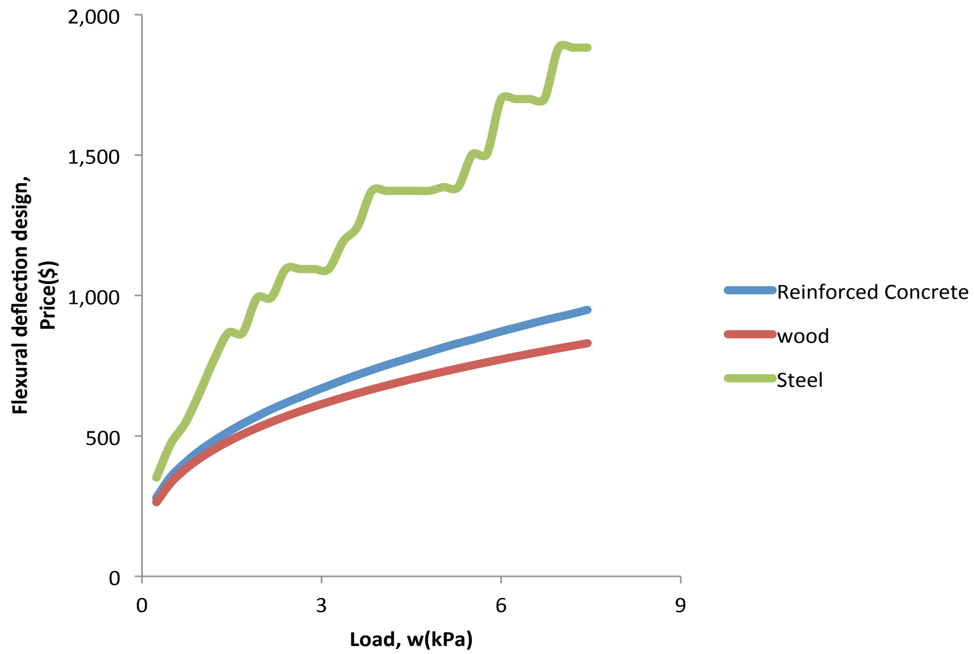

Figure 3.35: Cost of wood, steel and reinforced concrete based on flexural design for varying applied load

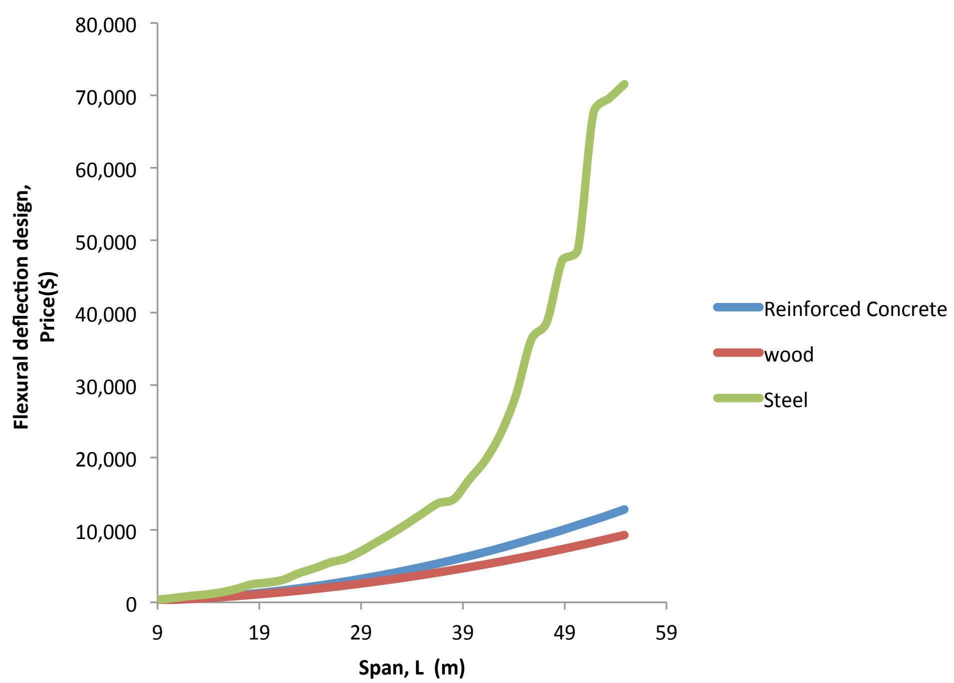

Figure 3.36: Cost of wood, steel and reinforced concrete based on flexural design for varying beam span

3.4.5 Discussion

Being able to quickly determine the best-fit material required for the project based on design requirements, strength or stiffness, and budgetary restraints, can ease the decision-making process and aid designers in making recommendations to the client to achieve durable designs. Further understanding of the material properties, and knowing their associated economical value, should also be factored in. Apart from stiffness and strength of the different materials, other factors that influence the structure's performance need to be accounted for with respect to the overall durability of the structure. Some of these factors are, ease of fabrication, resistance to fire, and material consistency. Table 3.9 compares the different materials to certain properties that influences durability.

Properties	Wood	Steel	Concrete
Fire-resistant	Very low: Protective coating used	Low: excellent heat conductor may ignite other materials close to it. Fire-proof coatings is necessary in buildings and bridges and also the use of sprinkler sytems	High
Fabrication	Faster to fabricate compared to steel and concrete	Can either be prefabricated or assembled on site. Welding members is time consuming and requires good experience	Can either be pre-casted or cast-in place, pre-cast concrete is done in controlled environment: hardening of concrete is time-dependant
Strength to weight ratio	Low	High: adequate for long-span structures such as bridges	Low
Ductility	Low	High	Low
Tensile strength	Low	High	Low
Compressive strength	Low	Buckling issues due to high strength to weight-> very slender column	High
Consistency	Low: varies depending on the natural characteristics of the species used	High	Low: for example varies depending on the type and surface texture of aggregates used
Cost	Low-> easily accessible, natural material	High: man-made material	Lower than steel: man-made material

Table 3.9: Comparison of material properties of wood, steel and concrete that influences durability (based on McCormac and Csernak, 2011; Mindess et al., 2002).

Chapter 4 Case Study

Historical structures play an important role in the history and the culture of a country. Therefore, it is interesting to study a historical structure and see the effect of using alternative construction materials, for the same design requirements, on the structure's performance, constructability, and durability. Furthermore, by studying these structures, as a lot of them still stand today, we can further enhance our knowledge and learn how engineering has evolved over the years.

To further study the different material properties, a case study on a wooden-covered bridge was carried out. Covered wooden bridges are of significant importance in the history of America, and in the advancement of engineering. More specifically, the arch elements of the Colossus Bridge that spanned over Schuylkill River in Philadelphia were analyzed, and designed using alternative construction materials. Finally, the advantages and disadvantages of using alternative materials, and its affect on durability were identified.

This chapter begins with studying the history of covered wooden bridges in America, investigating the different types of structural systems used in the design and how they evolved over the years. This is followed by the analysis and design of the arch elements of the Colossus Bridge using different structural materials. Finally, the effect of using different structural materials in the design of a covered wooden bridge are compared with respect to the durability aspect of the structure.

4.1 History of covered wooden bridges in America

The construction of covered wooden bridges in America started in the late eighteenth century and continued till the early nineteenth century (Marston, 2006). According to the Covered Wooden Bridge Manual issued by the United States department of Transportation, there exist less than 900 covered wooden bridges that still stand today out of 14,000 that existed at some point in time in America. Moreover, more than fifty percent of the covered wooden bridges in the world that are still standing today are located in the United States of America (Pierce et al., 2005).

The need for crossing bodies of water resulted in the construction of long-span structures primarily made out of wood. Wood was the primary construction material used at the time before adapting to the use of steel and concrete in construction that took over in the late nineteenth century (Duwadi and Ritter, 1997). The idea of covering the bridge was first established by Judge Richard Peters, who thought that by covering the bridge, the life-span of the structure will increase by an average of fifteen years (Allen, 1959). The main purpose of covering the roof and the sides of the bridge was to keep the main structural components dry during wet seasons. As previously stated, wood is susceptible to moisture; its effect may result in threatening the structural performance of the bridge. Some of the other reasons for covering wooden bridges that were identified by author Eric Sloane in his book, *The First Covered Bridge in America*, were for the users' safety by keeping the deck dry, another reason was covering the bridge provided it with a barnlike look and eased the crossing of the bridge for farm animals, also covering the bridge attracted more users and hence brought in more money through tolls (Sloane, 1959).

The Permanent bridge over the Schuylkill River in Philadelphia, a three-span 550 feet arched truss, was the first covered wooden bridge in America, built in 1805 by Timothy Palmer. The bridge was opened to the public before the idea of covering it was suggested by Judge Richard Peters, which raised awareness of durability (Allen, 1959). This reflected the designers and builder's consciousness of the severe impact weather conditions may have on wooden structures. Figure 4.1 shows a sketch of The Permanent Bridge illustrating the structural system it was composed of, and how it looked like with its sides and roof covered.

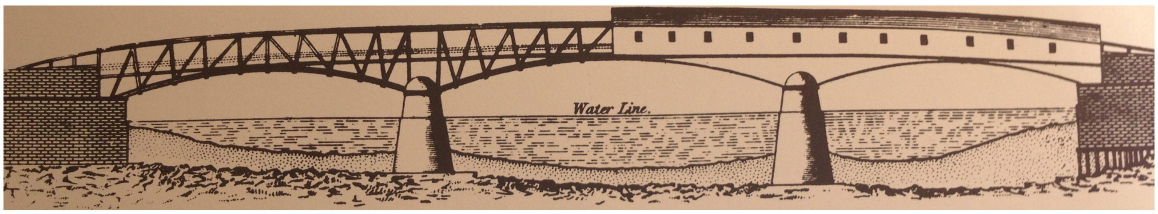

Figure 4.1: The Permanent Bridge over the Schuylkill River in Philadelphia, built by Timothy Palmer in 1805, known to be first covered wooden bridge in America (Allen, 1959).

There are numerous iconic covered wooden bridges that once spanned over many streams in America. The skilled designers, most of carpentering background, constructed bridges that covered long spans that were known to be the longest at the time of their construction. Some of these bridges are the Colossus Bridge, McCall's Ferry, and Blenheim Bridge. The Colossus Bridge is another covered wooden bridge that spanned over the Schuylkill River in Philadelphia north of the Permanent Bridge that was built by Timothy Palmer. This bridge was known to have the longest clear span in the history of American and European bridges at the time. Built by Lewis Wernwag in 1812, it spanned a total of 340.25 feet with no intermediate piers. McCall's Ferry Bridge, built in 1815 by Theodore Burr, had a single clear span of 360 feet bridging over the Susquehanna River, and took over the "longest bridge" title from The Colossus up until 1818 when the bridge was destroyed by ice (Allen, 1959). The Colossus Bridge was later destroyed by fire in 1838 and replaced by a suspension bridge designed by Charles Ellet in 1842 (Griggs, 2010). Up until recently, the Blenheim Bridge was known to be the longest single span covered wooden bridge in the world, 228 feet long. It was built by Nicholas Power in 1854 spanning over Schoharie Creek in North Blenheim, New York (Graton, 1990). Destroyed by hurricane Irene in 2011, the Blenheim Bridge was one of the few double-barrel covered wooden bridge in the world (Eckholm, 2011). Today the state of Pennsylvania is considered to have the largest number of covered wooden bridges in America, having approximately 26 percent of the bridges that are still standing (Pierce et al., 2005).

4.1.1 Evolution of the structural systems of covered wooden bridges

It is important to identify the key components that covered wooden bridges are composed of; this is illustrated in Figure 4.2. Like all bridges, covered wooden bridges consist of a specific structural system, which varies in configuration, and a bridge deck resting on abutments. The addition of the roofing and siding cover are what distinguishes these bridges, and their main purpose is to protect the wood against degradation and decay. The main feature of a covered wooden bridge is its structural system that is composed of a longitudinal truss of a specific configuration. The type of longitudinal truss is what identifies covered wooden bridges. A few of the most widely used longitudinal trusses are, kingpost, queenpost, multiple kingpost, Burr, Town, Long, and Howe truss.

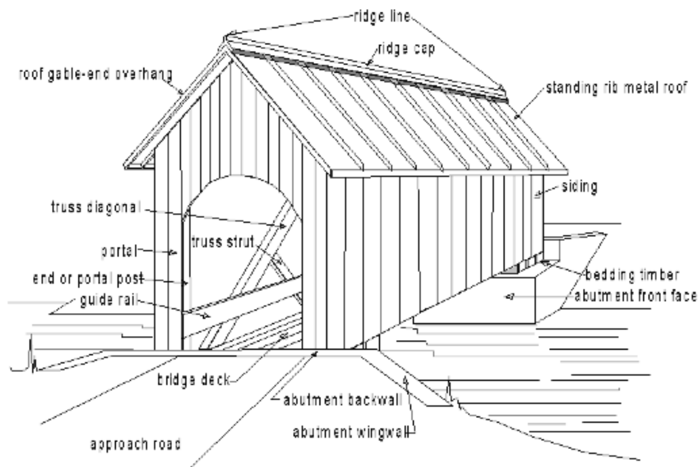

Figure 4. 2: Various elements that covered wooden bridges are composed of (Pierce et al., 2005).

Kingpost, queenpost, and the multiple kingpost trusses are the earliest configuration of longitudinal trusses that were used in the construction of covered wooden bridges in North America. Essentially the queenpost truss is an expansion upon the kingpost configuration; it consists of an additional top chord and two vertical members instead of one. Moreover, queenpost truss can span longer distances compared to a kingpost's truss due to the additional members it consists of (Pierce et al., 2005).

The need to span longer distances resulted in developing the simple configurations into more complex structural systems made out of wood. These systems included the Burr, Town, Long, and Howe truss, all of which were patented by their builders. It is important to note that, typically, the members of a truss carry the forces axially, however this is not the case with many of the heavy wooden trusses. This is a result of the connection details used to connect the truss elements. In some cases, either the members of wooden trusses are continuous over their connecting point, or the members are not connected along their centerlines resulting in eccentric loadings. The result of either one of the scenarios or a combination thereof, results in the members transferring shear and bending forces (Pierce et al., 2005).

The most commonly-used longitudinal truss is the Burr truss, developed and named after Theodore Burr. He was the first to obtain a U.S. patent in 1806 for his timber truss design. In the United States 224 covered wooden bridges are categorized as Burr truss out of 880 bridges that still stand today (Pierce et al., 2005). The longitudinal truss of a Burr covered wooden bridge is comprised of two structural systems: arches, and multiple kingpost trusses. It is the combination of the two systems, multiple kingpost truss sandwiched between two arches that allows it to span longer distances, and resists heavier loads. In such design, it is important to pay attention to the connection details as the load is divided between the two structural components: arches, and truss. The arches are connected on either sides to the vertical members of the truss, and can either be directly connected to the abutments or to the bottom chord of the truss, which is directly connected to the abutments (Pierce et al., 2005). An example of a Burr bridge that still stands today is the Pine Grove Bridge in Lancaster County, Pennsylvania. Figure 4.3 shows a snapshot of the interior of the Pine Grove Bridge, illustrating the structural system of the Burr arch truss. An analysis carried out on the Pine Grove Bridge by Schafer and Lamar in 2004 showed that under uniformly distributed load, the arch is the dominant structural element, while the truss is effective in carrying moments under asymmetrical loading. The interaction of the dual systems helped in increasing the rigidity of the structure, hence decrease the deflection the bridge may undergo when loaded (Lamar and Schafer, 2004).

Figure 4.3: Interior view of the Pine Grove Bridge illustrating the structural system of the Burr arch truss (Lowe, 2002a)

Another highly used longitudinal truss is known as the Town truss (refer to Figure 4.4). It was developed by and named after architect Itheil Town in 1820. Town received his first patent after developing the Town lattice truss configuration. According to the covered bridge manual, there are a total of 135 Town lattice truss covered wooden bridges out of 880 that are still standing today in America (Pierce et al., 2005). Unlike the Burr, the Town truss does not consist of an arch and is made up of overlapping wooden members forming a lattice pattern connected together using trunnels, which are pegs that are 1.5-2 inch in diameter. The lattice arrangement makes this truss highly indeterminate, hence a redundant structure making it less prone to failure and therefore increasing its design working life. A Town truss can adapt easily to span various distances, and is easily constructible making it a more economical configuration. The Cornish-Windsor Bridge, built in 1866, is the longest multi-span Town lattice covered wooden bridge still standing today, spanning over the Connecticut River (Marston, 2005).

Figure 4.4: A Town lattice truss bridge spanning over the Squam River and built in 1990 by Milton Graton and Sons.

In 1830, Colonel Stephen H. Long patented the Long truss configuration, which consists of a top and bottom chord that is divided into rectangular sections each consisting of a set of cross diagonals. The concept of pre-stressing was introduced in the development of this truss. This was achieved by using wooden wedges placed between the chords, vertical, and the diagonal members of the truss (refer to Figure 4.5) (Marston, 2005; Pierce et al., 2005). The use of the wedges allowed the forces to be distributed over a larger area hence decreases the magnitude of the stresses acting on the members of the truss. If necessary, the dimensions of the truss and the initial camber introduced in the bridge were easy to modify by using the wedges (Pierce et al., 2005). Hence, the use of wedges in design eases the adaptation of the structure to necessary design changes. In America 27 Long truss covered wooden bridges still stand today out of 880(Pierce et al., 2005). The low number of long trusses was probably due to the development of the Howe truss that came soon after, which resulted in not using the Long truss configuration as much.

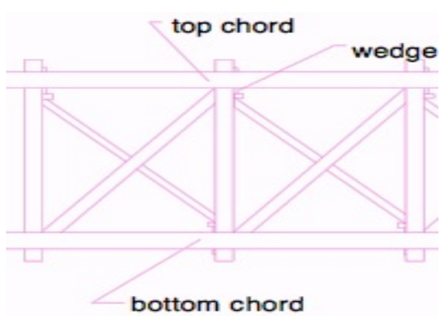

Figure 4.5: Long truss configuration showing the placement of the wedges that are used to pre-stress the truss elements (Pierce et al., 2005).

Figure 4.6: Eldean Bridge in Troy, Ohio, illustrating the configuration of a Long truss (Lowe, 2002b)

Similar to Long's truss configuration, the Howe truss patented in 1840 by William Howe, used the same truss arrangement as Long but incorporated the use of metal elements in the design (Pierce et al., 2005). The addition of metal to the design is what differentiates the Howe truss from Long's truss configuration. In the Howe truss arrangement, wrought iron rods replaced the rectangular wood sections that were used as vertical members. Wrought iron has a higher tensile capacity than wood and is a ductile material. These two properties helped improve the overall structural system of the bridge and as a result enabled covered wooden bridges to span longer distances and carry heavier loads. In the American history of covered wooden bridges, the Howe truss was the first to integrate the use of metallic structural elements (Marston, 2005). In America 143 out of 880 covered wooden bridges that still stand today use the Howe truss configuration. Figure 4.7 illustrates the interior of a Howe truss configuration, indicating the location of the wrought iron rods used, in the red oval.

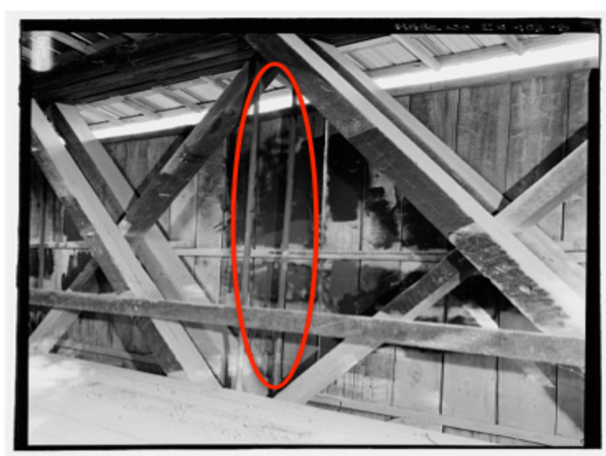

Figure 4.7: Pine Bluff Bridge in Indiana, illustrates the use of wrought iron rods as vertical tension members (highlighted in red) in the Howe truss configuration (Rosenthal, 2004).

The structural systems used in the design and construction of covered wooden bridges has evolved over the years, which demonstrates the builders' efforts in developing durable designs. It started with discovering the advantage of covering wooden bridges in protecting the structural elements from degradation and its positive impact on the lifespan of the structure. It followed by using different structural detailing that helped in developing efficient and more economical structures. Finally, the introduction of metal structural members to span longer distances and carry heavier loads was introduced. This reflects the builder's understanding to the material properties, adequate usage of materials, and proper design detailing to achieve durable designs.

4.1.2 Historic American Engineering Records

Many of the covered wooden bridges were lost due to natural disasters, lack of maintenance, or replaced with bridges engineered to withstand new design requirements of automobile loads. This resulted in loosing more than 90 percent of the covered wooden bridges (Marston, 2005). The need to protect these structures is of great importance to preserve the cultural and engineering history of America.

As many of these bridges were not documented at the time they were built, a substantial amount of effort has been invested in documenting them. The Historic American Engineering Record, HAER, has carried out many surveys between the years 2002 to 2005 in an attempt to preserve and protect the covered wooden bridges throughout the nation. Data was collected on various structural parameters, including the dimensions of wooden members of trusses, the type of longitudinal truss used, the location of the bridges, as well as AutoCAD drawings with various sectional views illustrating the details of the bridges. As many of these bridges were built to accommodate different design loads, it is necessary to enhance the bridge, if necessary, to withstand the design loads used today. Therefore, guidelines and procedures are developed to aid designers and engineers in the process of rehabilitation.

The fact that a few of the covered wooden bridges still stand today makes them of interest to the study of durability. The time period in which the design and construction of these historical structures took place satisfied different design criteria than those relevant today. Therefore, it is necessary to adapt the design of covered wooden bridges to meet current design codes and satisfy structural integrity to ensure the public's safety and make them of use today. Moreover, regular maintenance procedures need to be carried out to further protect these structures.

4.2 Analysis and design of the Colossus Bridge using alternative materials

Many of the covered wooden bridges builders' were carpenters, and wood was an accessible material; thus, the use of wood as the primary structural material was of great convenience at the time. However, due to low strength and stiffness that wood exhibits and its low resistance to fire, many of the covered wooden bridges were lost due to extreme natural disasters such as hurricanes, floods or fire.

With that in mind, we shall now consider the effect of using alternative construction materials in the design of a covered wooden bridge. Comparing the mass required to design a structure using different materials, and the benefits associated with using each in the case of extreme events, will further help in understanding the influence of the type of material used on the durability of the structure.

For this exercise, consider The Colossus Bridge built in 1812 by Lewis Werwang. As previously mentioned, the Colossus Bridge was the longest covered wooden bridge at the time with a single clear span of approximately 340.5 feet. The bridge consisted of three arched trusses with a versed sine of approximately 20 feet (Griggs, 2010; Nelson, 1990); refer to Figure 4.8 for the bridge configuration. As previously stated, there are no original drawings that detail the exact dimensions of the bridge, instead all the dimensions used for the purpose of this analysis are based of research papers that recreated the model of the bridge.

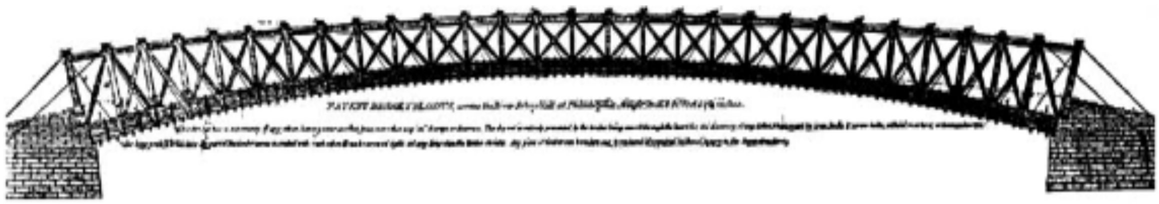

Figure 4.8: Configuration of the Colossus Bridge built in 1812 by Lewis Werwang (Griggs, 2010).

To begin, consider a specific load case scenario acting on the bridge. The analysis is then carried out based on the end constraints and the specified load. Assuming under uniformly distributed load, the arch carries no moment and the forces are carried axially through the arches, the maximum axial force acting on the arch can be calculated. This is followed by designing the arch to carry the maximum axial force using three different materials: wood, steel, and concrete. Finally the volume, mass and cost of materials required to design the arch are calculated and compared. To further illustrate this exercise, Figure 4.9 shows an idealization of The Colossus Bridge under the specified load and the end constraints used for the analysis and design of the bridge. Using Matlab, a plot of the axial forces acting along the arch was generated, and the maximum value was designed for. The plot is illustrated in Figure 4.10 (refer to appendix B for the calculation details).

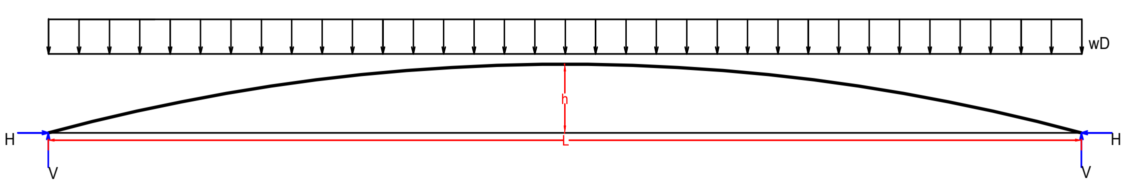

Figure 4.9: The model used to analyze The Colossus Bridge under uniform distributed load

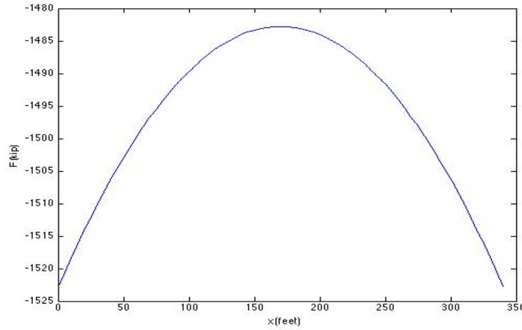

Figure 4.10: Axial force diagram for a uniformly distributed load of 100psf acting along the bridge (plotted using Matlab).

The maximum axial force acting along the arch for a uniformly distributed load of 100 pounds per square feet was calculated. With this value, the arch was designed using three different structural materials. Table 4.1 summarizes the results of the volume (in m^3) and mass required (in kg) of an arch designed in wood, steel, and concrete to resist the maximum axial force of 1523 kips (6775kN) and the cost (in$) of the materials if constructed today (refer to Appendix B for the material properties and cost of material used for the calculations).

Material	Volume (m^3)	Mass (kg)	Cost ($)
Wood	51.4	27,243	9,366
Reinforced Concrete	23.6	60,038	7,281
Steel	2.1	16,125	17,624

Table 4.1: Volume (in m^3), mass (in kg) and cost (in $) required for the middle rib design of The Colossus Bridge using wood, steel and concrete

The results show that steel would require the least volume and weight compared to concrete and wood. Moreover, the total mass is largest if the arch were constructed out of concrete compared to steel and wood. This shows that the strength to weight ratio of concrete is low and is compensated by the additional self-weight added to the structure. With respect to the cost of materials, if the arch were designed today in wood, steel and concrete, concrete would be the cheapest material to use compared to steel and wood. Although this design exercise illustrates the high strength to weight ratio that steel exhibits, making it a favorable structural material with respect to design requirements and amount of material usage, the high cost associated with using steel is what would probably compromise its application.

With all that in mind, concrete would probably be a better option. Apart from the higher compressive strength concrete exhibits compared to wood, there are other advantages associated with using concrete in the design of the bridge that ultimately improves its durability. As previously stated, the Colossus Bridge was destroyed in 1838 due to fire, in the case the structure was made out of concrete, the risk of the bridge being destroyed due to fire would be much lower, since concrete has a high fire resistance. Furthermore, concrete can easily be cast into any geometrical shape desired compared to other construction materials.

It is interesting to see the effect of using alternatives materials to redesign historical structures. If the Colossus Bridge were built today, wood would probably not be the choice of material. Although one load case scenario was considered for in this example it indicated that concrete would be a more suitable structural material under the load case applied. Moreover, the low cost of concrete and its material properties would further compliment the structure's durability.

Apart from the material cost, concrete can easily be casted into any geometrical shape compared to steel and wood, which decreases the overall cost of fabrication. In addition, the associated maintenance cost of concrete is cheaper than wood. The maintenance procedures that need to be carried out on wooden structures would be much more frequent compared to concrete structures since wood is much more vulnerable to its surrounding conditions. The combination of all these factors enhances the durability of the structure if it were constructed using concrete. This illustrates the significance of material choice on the overall durability of the structure.

4.3 Discussion

It is interesting to see how durability of structures has been an ongoing concern. The issue of durability was reflected in the design of covered wooden bridges. The builders at the time based on their knowledge and experience with using wood have realized the positive impact of covering the main wooden structural elements of the bridge on its lifespan. The awareness of durability in the design and construction of wooden bridges was initially raised by Judge Richard Peters in 1812 and was implemented for the first time in the design of The Colossus Bridge. Moreover, the evolution of the longitudinal trusses used in the design of covered wooden bridges illustrated that by adequate design detailing and knowledge of material properties efficient designs can be developed that improves the structure's performance and decrease the amount of material used and therefore the overall durability of the structure. Finally, the design exercise illustrated the advantages of using alternative materials for the design of a covered wooden bridge for a specific scenario that will further improve the durability of the structure.

Chapter 5 Conclusion

Accounting for durability is necessary to maintain our surrounding infrastructures throughout their life span. The choices made during the design phase of a project greatly influence the overall durability of the structure. Lack of durable design may result in a structure losing performance to an extent where structural integrity is no longer satisfied, potentially leading to fatal accidents. Identifying the key individuals involved in the decision-making process and the different factors that affect the structure's performance and overall cost is vital in achieving durable designs.

By defining a clear scope of work for a project, the factors that may compromise the structure's durability are identified. These factors need to be clearly outlined, as they may be detrimental to the behavior of the structural components and material properties. Moreover, these factors influence the decisions taken by the individuals involved in each stage of the project. Based on one's knowledge and experience, effective decision-making can be applied to best suit the structure's surroundings and satisfy the owner's requirements. The definition of durability, the different stages of a project that impact durability, and the factors that influence the durability of a structure are further addressed in Chapter 2 of the thesis.

The evolution of materials has indicated designers' effort in producing durable designs. The choice of materials used has a great impact on the performance and cost of the project. Understanding the material properties and its behavior depending on the intended use of the structure and surrounding conditions aids engineers in their decisions and recommendations to the client. It is important to have a good background in material properties and behavior to further incorporate durability into a structure's design and execution. In addition, using different techniques to further enhance the material properties and the structure's performance improves the overall durability of the structure. Chapter 3 of this thesis studies the deteriorating mechanisms of the different construction materials used and the various methods that can be used to enhance durability of structures.

Ultimately, it is the overall cost over the structure's life cycle that is affected by defining the extent of attained durability that the owner is willing to invest in. Furthermore, the overall cost of maintaining a specified durability varies, depending on many project-specific factors such as the type of materials used and type of maintenance procedures implemented. Every decision made throughout the project's life cycle affects durability of the structure and ultimately its associated cost. As a result, compromises need to be made to achieve durable designs that satisfy the project's budget yet maintaining the structure's performance throughout its life span. Different design examples that illustrate the effect of cost in achieving durability are illustrated in Chapter 3 and 4 of the thesis.

Comparing the different materials widely used in construction will aid engineers in identifying the benefits associated with each. Through different design examples, the advantages of using different materials with respect to material properties and cost were illustrated in this thesis.

It is necessary for engineers to provide appropriate means to ensure safety of design first and foremost, even under severe conditions, and to reduce long-term costs. Comparing the different materials and illustrating the different properties that each material exhibits enhances the soundness of the choices made on the durability of the structure. The work of this thesis placed side by side the three different structural materials widely used in the construction industry and compared them with respect to the various deteriorating mechanism each is susceptible to and the different techniques used for improving their performances. It further illustrated the effect of various choices made throughout a project on achieving durable designs from both a structural and an economical point of view. However, there are several other factors that may affect the durability of structures, many of which cannot be quantified. Therefore, carrying out different experiments to further compare the effects of various factors on the different structural materials and on the structure's performance is necessary. In addition, expanding this study by incorporating the effects of different fabrication and construction methods used on achieving durable designs will further emphasize the importance of incorporating durability in maintaining our infrastructure, reducing costs, and ensuring public safety.

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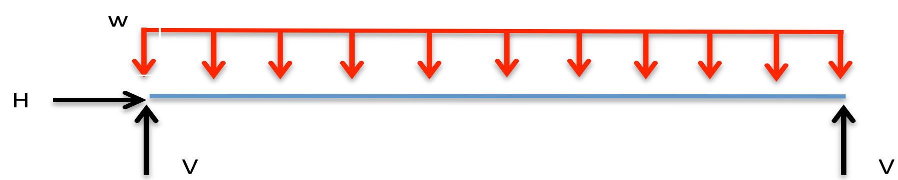
Appendix A

In section 3.4 the comparison of materials was based on the material properties of wood, steel and reinforced concrete. The analysis and design of a simply supported beam was based on the flexural strength and deflection requirements. The beam was designed to resist the maximum moment and deflection, which in this case occurs at midspan. Depending on the cross-sectional geometry, the dimensions were determined. The beam was designed and analyzed for various span and applied pressure. Finally the different materials were compared based on the area, weight and cost of material required for the design. In the case of concrete and wood rectangular cross-sections were considered, and in the case of steel wide flange beam were designed for.



Equation of maximum moment for a simply supported beam:

$$M_R = \varphi f_y S$$

$$M_f = \frac{wL^2}{8}$$

$$M_R \geq M_f$$

Equating M_r to M_f, the section modulus, S, can be calculated. S varies depending on the geometrical configuration of the beam.

Equation of maximum deflection for a simply supported beam:

The required deflection criterion the beams are designed for is

$$\Delta_R = \frac{5wL^4}{384EI}$$

$$\Delta_f = \frac{L}{400}$$

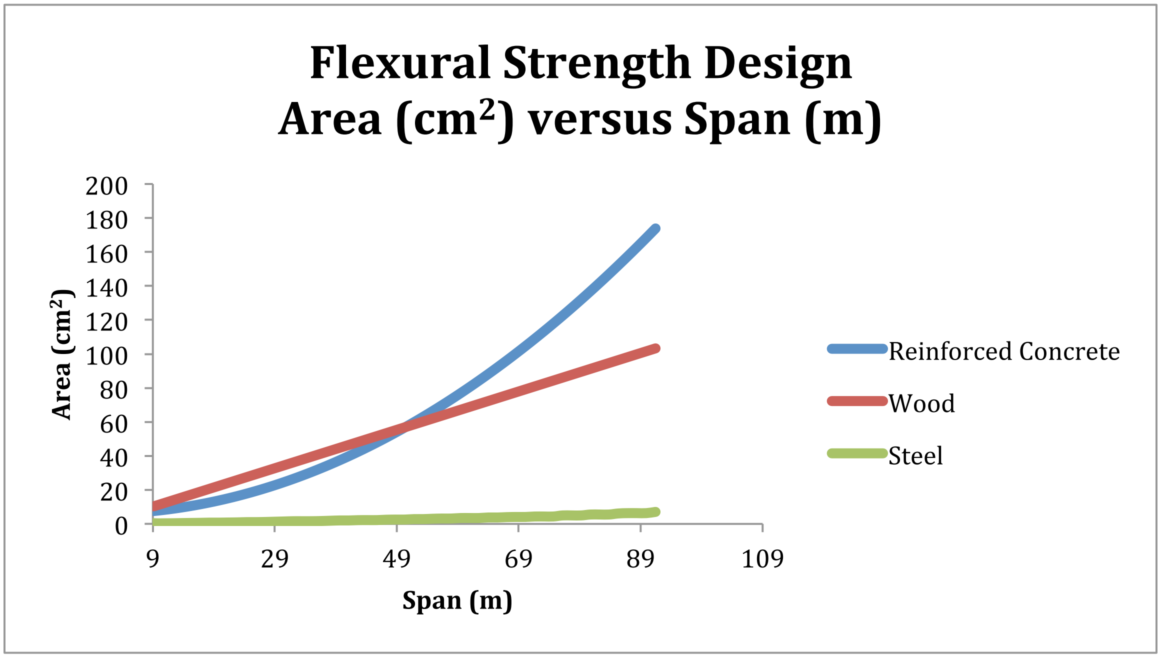
$$\Delta_R \geq \Delta_f$$

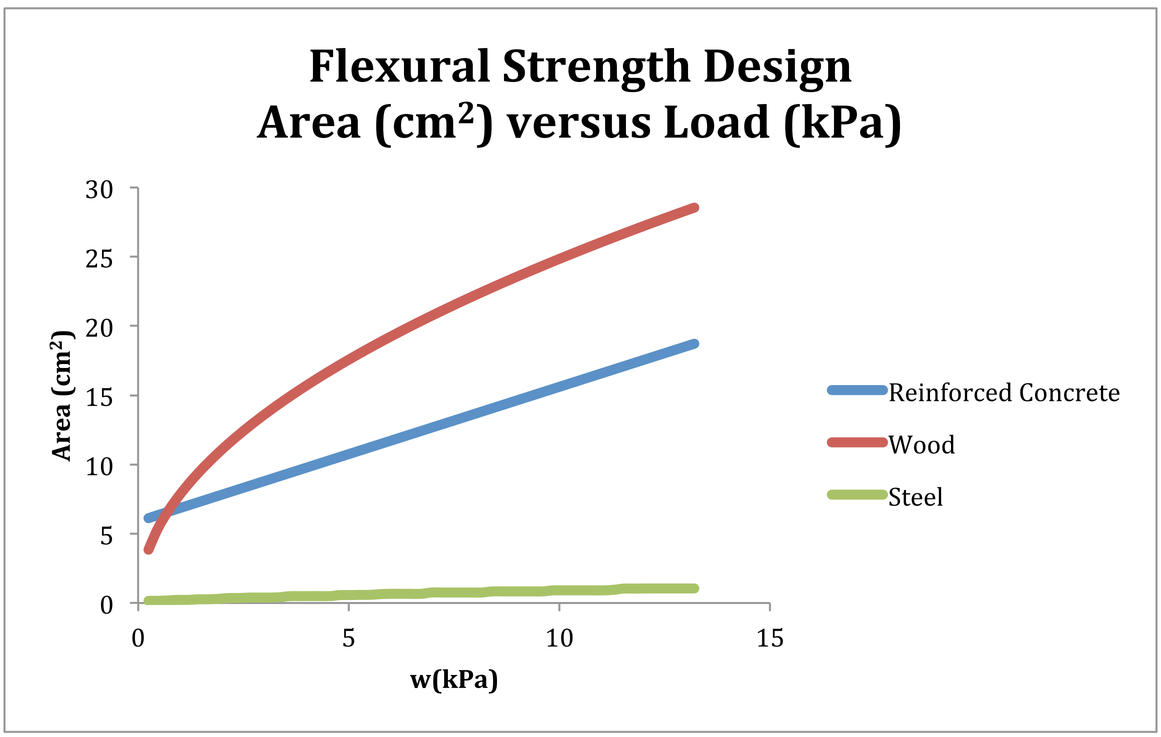
Equating Δ_R to Δ_f, the moment of inertia, I, can be calculated. I varies depending on the geometrical configuration of the beam.

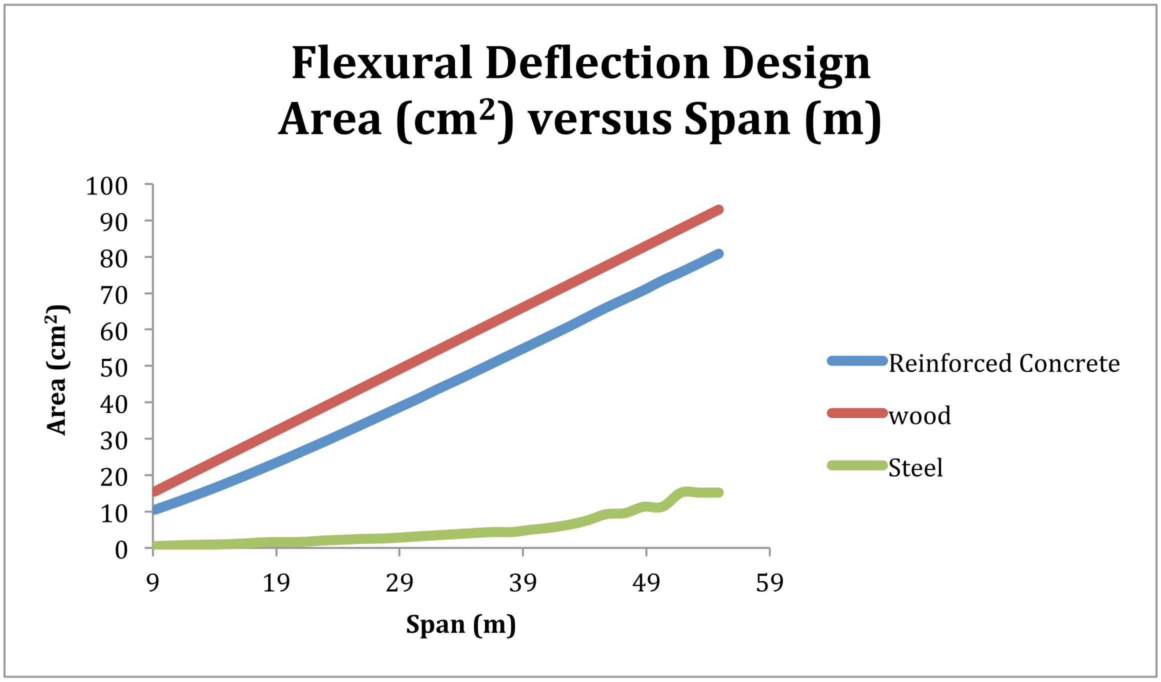
For varying spans and applied pressure the required design area, weight and cost of material is calculated and compared for the three materials. In the case of varying the span a uniform distributed load is applied of approximately of 5kPa. In the case of varying the applied pressure the span is kept constant and is approximately equal to 15m.

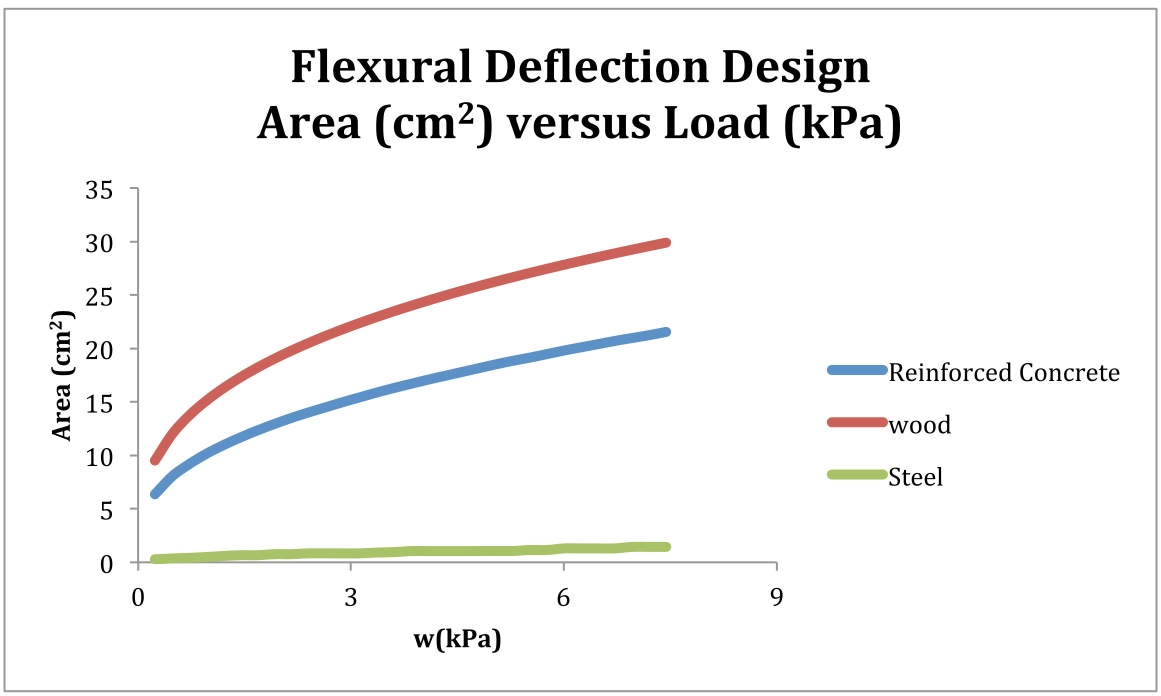
Area

Flexural Strength



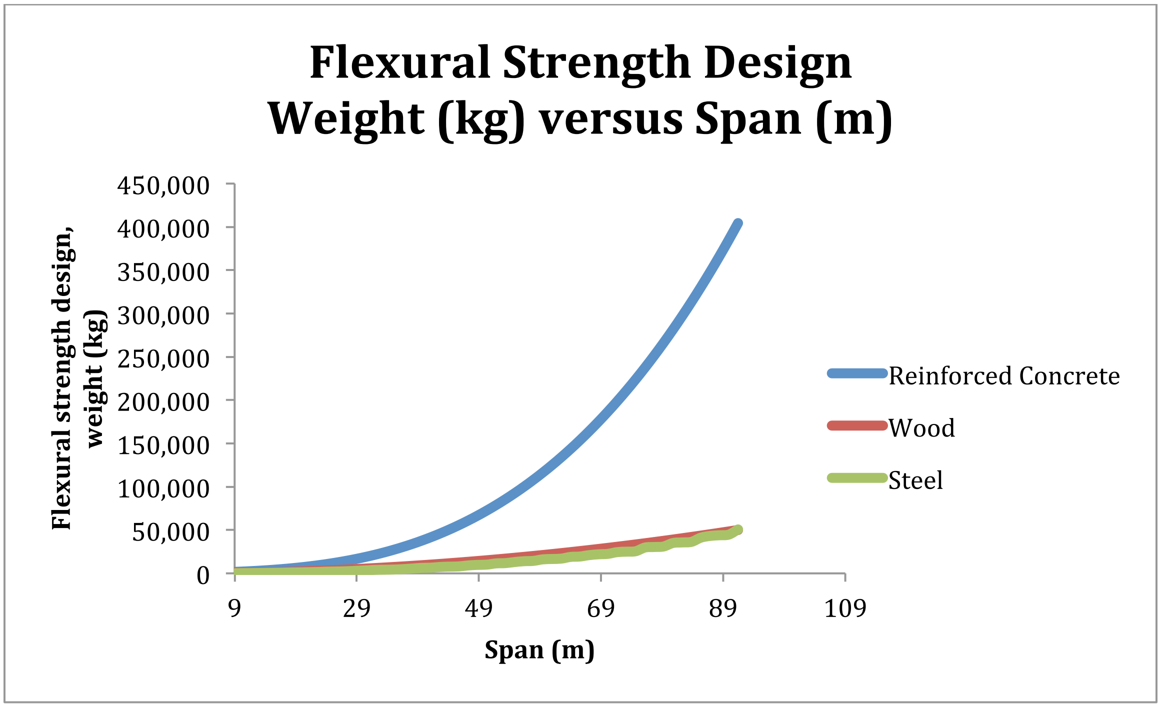


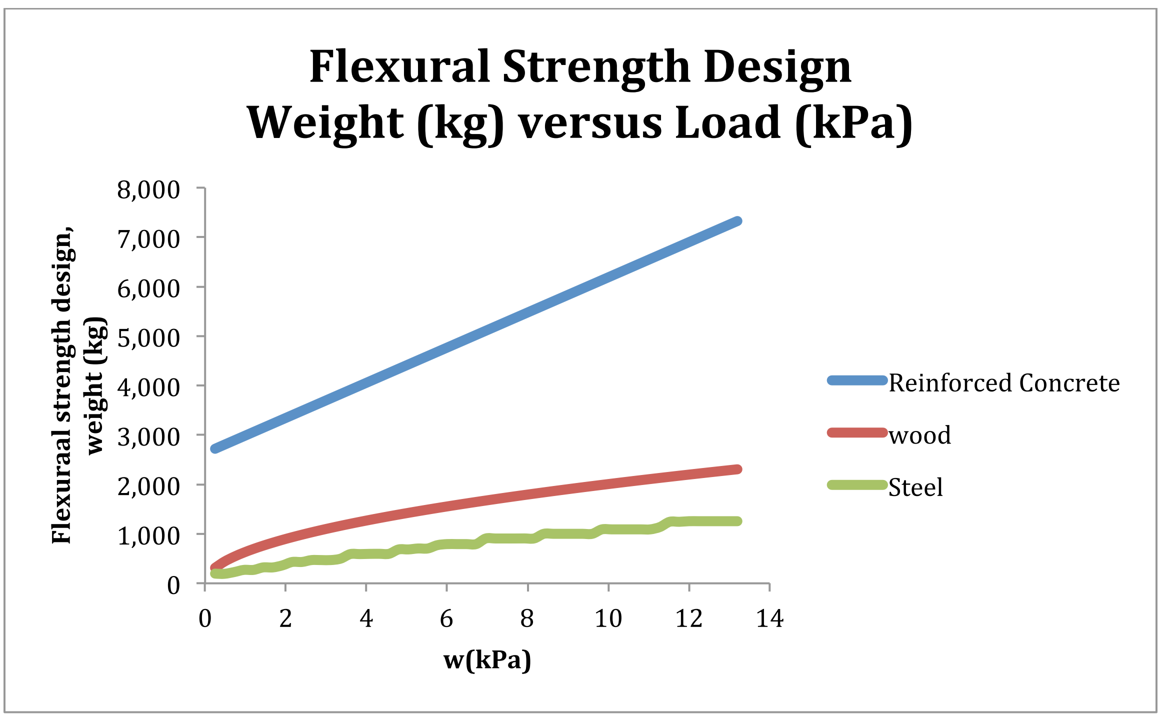

Flexural Deflection Design
Area (cm²) versus Span (m)
100
90
80
70
60
50
40
30
20
10
0
Area (cm²)
9
19
29
39
49
59
Span (m)
Reinforced Concrete
wood
Steel


Flexural Deflection Design
Area (cm²) versus Load (kPa)
35
30
25
20
15
10
5
0
Area (cm²)
0
3
6
9
w(kPa)
Reinforced Concrete
wood
Steel

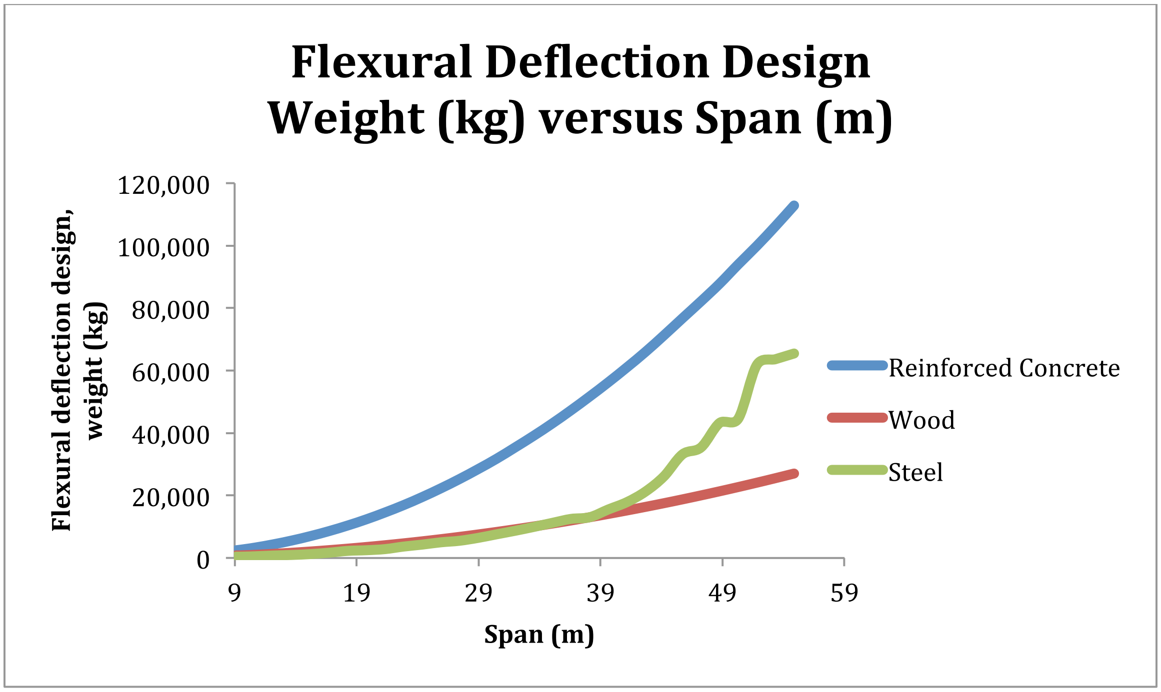
Weight

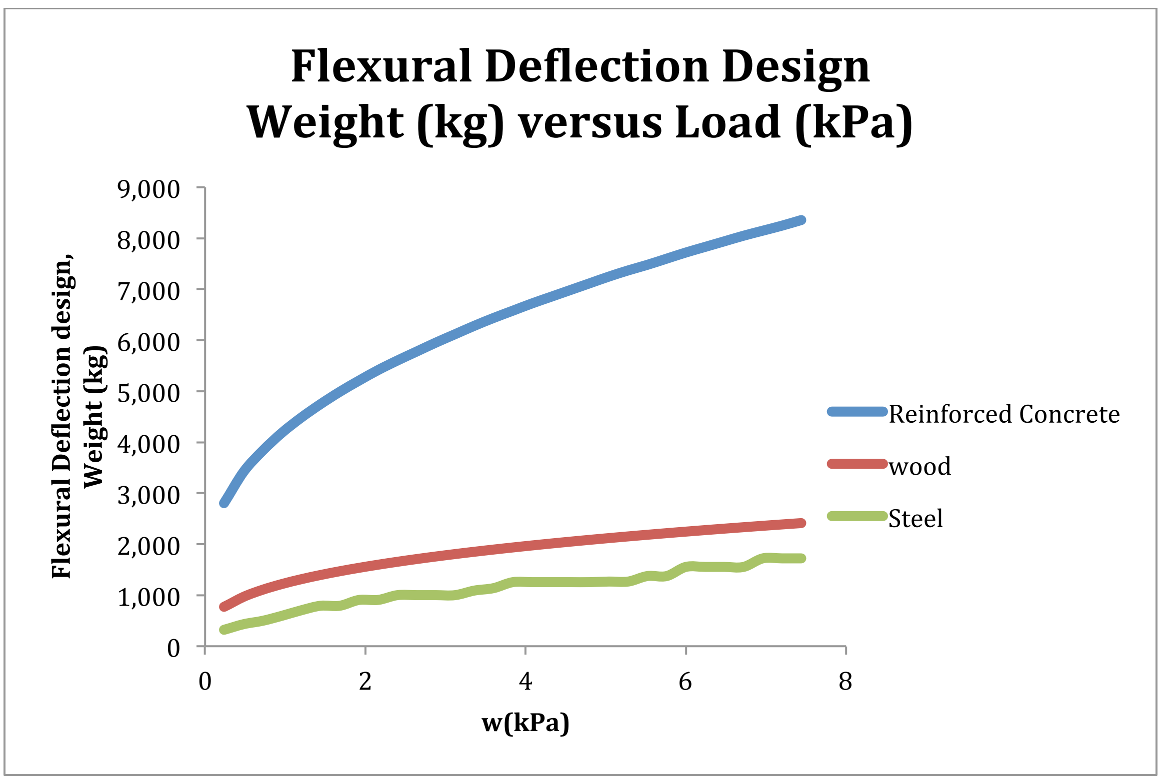
Flexural Strength





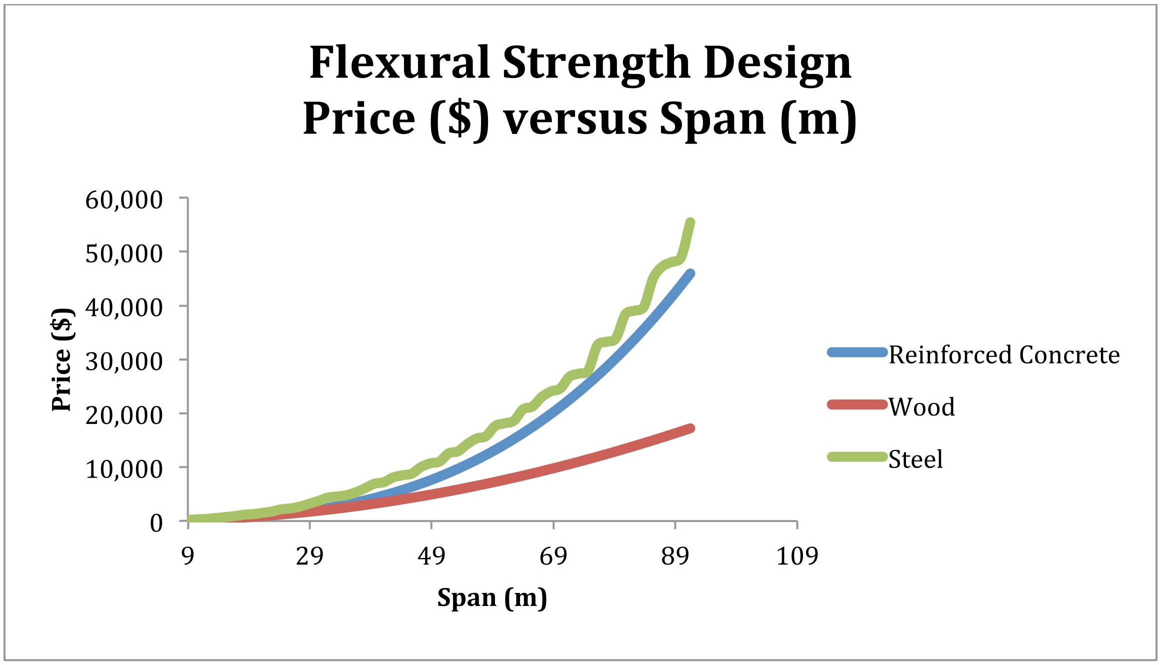
Flexural Deflection

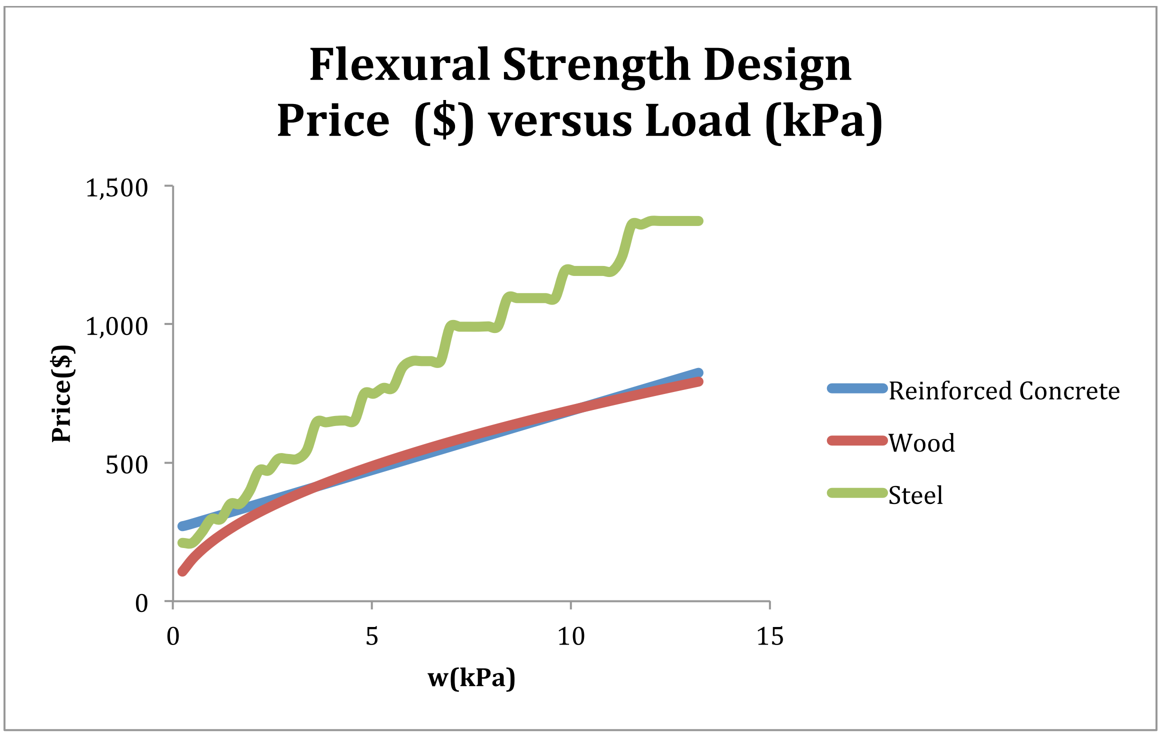




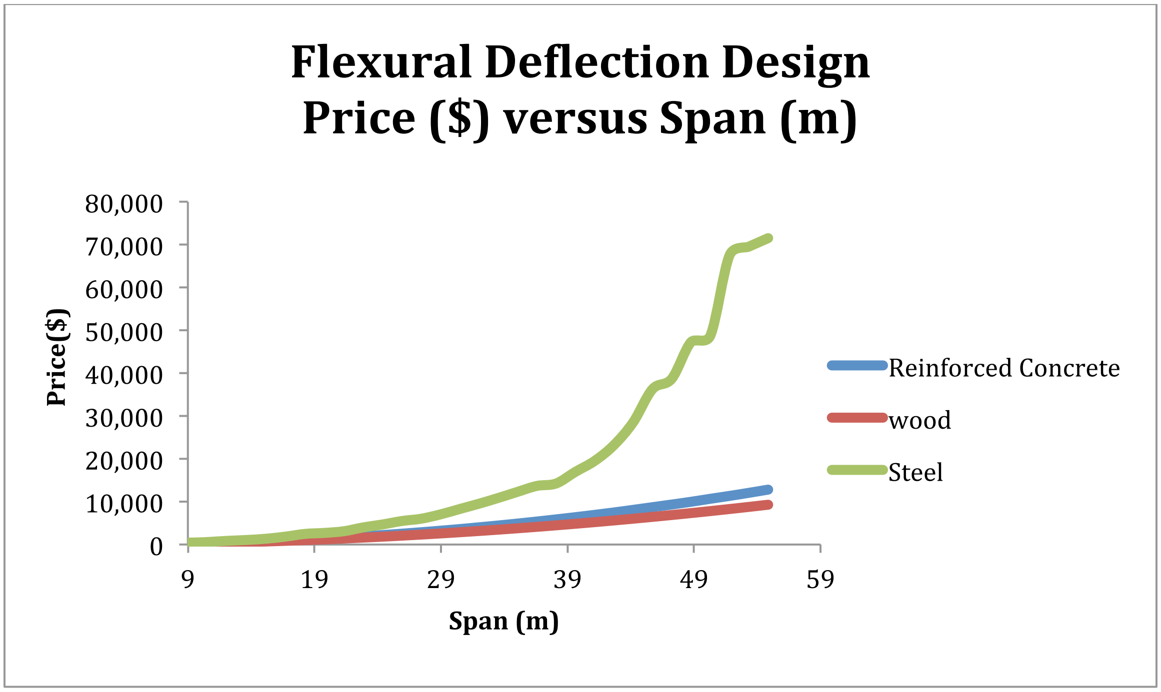
Cost

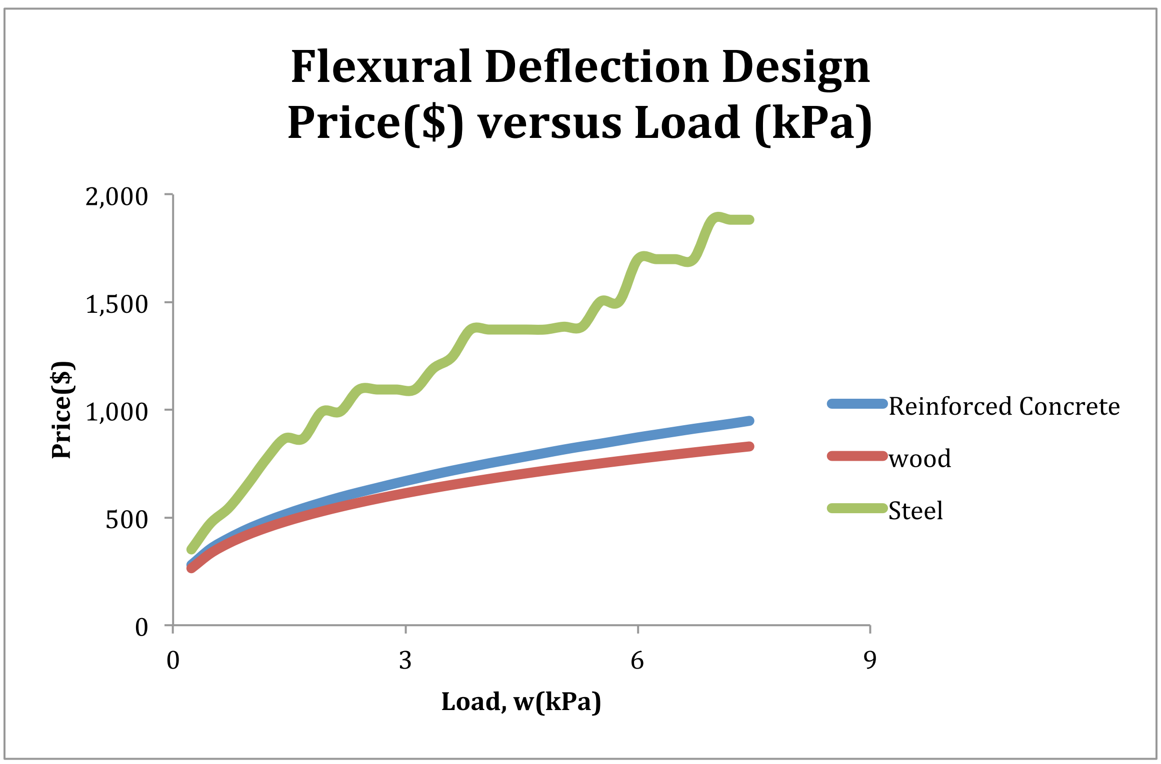
Flexural Strength





Flexural Deflection





The results show the following:

- The graphs for design cross-sectional area show that steel requires the least cross-sectional area compared to reinforced concrete and wood. This illustrates the flexural strength and stiffness of steel is greater than the other two materials.
- Due to density variation of the three different materials the design weight of reinforced concrete is greater compared to steel and wood. This illustrates that the strength to weight ratio of concrete is low and is compensated by the additional dead weight.
- Although this model illustrates that steel requires less material compared to reinforced concrete and wood, the cost of steel is much higher than wood and reinforced concrete and therefore increases the cost of durability.

Appendix B

Due to lack of sufficient information and drawings of the Colossus Bridge, the analysis and design of the bridge were based of assumptions. This may not be an accurate representation of how the actual bridge was designed at the time, and are likely sources of error.
For this exercise, two different approaches were used to analyze the bridge for a uniform distributed applied load:
The arch was analyzed and designed to carry the forces axially transferring no moment
The arch was analyzed and designed as a three hinged parabolic arch

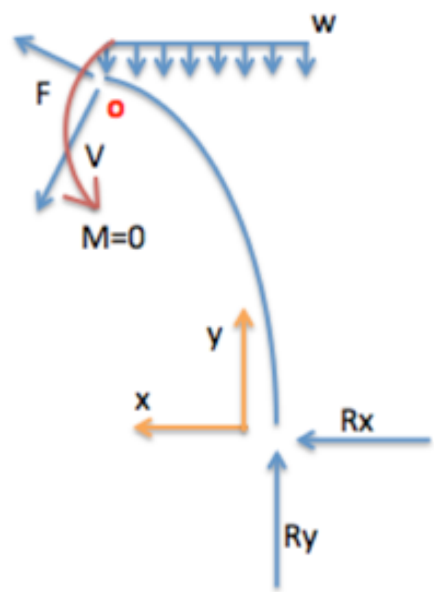
1. Analysis and design of the arch for Zero moment

For a uniformly distributed load assume the load is carried axially through the arch with zero moment, the equation of the curve is:

$\Sigma M = 0$

$$R_y \times x = \frac{w \times x^2}{2} + R_x \times y$$

$$\Rightarrow y = \frac{1}{R_x}(R_y \times x - \frac{w \times x^2}{2})$$



Due to symmetry

$$R_y = \frac{wL}{2}$$

$$R_x = \frac{wL^2}{8h}$$

$$\therefore y(x) = \frac{4hx}{L^2}(L - x)$$

Knowing the equation of the curve the length of the arch can be determined:

$$Length\ of\ curve = \int_0^L \sqrt{1 + (\frac{dy}{dx})^2}\ dx$$

$$\frac{dy}{dx} = \frac{4h}{L} - \frac{8hx}{L^2}$$

Computing the length of the curve for x varying from 0 to the span of the bridge (340 feet and 3.75 inches) results in,

$$Length\ of\ curve = 343.3feet = 104.7$$

Analysis of the Colossus Bridge- Matlab code

```
% Analysis of the Colossus Bridge 1812

% First assumption, under uniformly distributed load along the span of the
% Bridge, consider the system acts as an arch and the load is carried
% axially

TW=17; % Average tributary width, the ribs at top of the curve are 13
% feet apart and 21 feet apart at the abutments, taking the average of
% the two distances results in the Tributary width of the middle rib to be 17feet

wD=100; % dead load in psf

w=(1.2*wD)*TW;

L=340+3.75/12;% Length of arch

d=19+11/12;% versed sine

V=w*L/2*10^-3;% Vertical reaction at the abutments

H=w*L^2/(8*d)*10^-3;% Horizontal reaction at the abutment

theta=[];% angle along the curve at every 5 feet

F=[] % axial force acting along the curve at every 5 feet

i=1

for x=0:5:L

   theta(1,i)=atan(-8*x*d/L^2+4*d/L)
   F(1,i)=-H/cos(theta(1,i))

   i=1+i
end

plot (0:5:L,F,'color','b')
xlabel('x (feet)');
ylabel('F (kip)');

% Determining the length of the curve
syms x

fun=(1+(-8*x*d/L^2+4*d/L)^2)^0.5

Lc=int(fun,x,0,L)

double (Lc*12*25.4*10^-3) % length of curve
```

Designing the Colossus Bridge using wood, steel and concrete:

Based on the papers written about the history and the structural system used in the design of the Colossus Bridge built in 1812, the following assumptions are made:

- Bridge consists of three arched trusses (ribs)
- Each truss consists of 28 panels
- The lower arch is braced vertically by the truss and horizontally by the deck, assumed to be braced at the 28 truss panel locations- no slenderness issues
- 75 percent of the wood used in the construction of the Colossus Bridge is yellow pine, which according to CSA 086-01 "Engineering Design in Wood", exhibits the same properties as Douglas Fir

Material properties used in the design of steel, wood, and concrete arch

Wood- D-Fir, Grade SS	**Bending Strength**	f_b	18.3 Mpa
	Modulus of Elasticity	E	12000MPa
	Density	γ_w	530kg/m^3
Reinforced Concrete	**Compressive Strength**	f_c'	30MPa
	Modulus of elasticity- Conrete	E_c	24650MPa
	Yield Strength of steel reinforcement	f_s	400MPa
	Modulus of Elasticity	E_s	200000MPa
	Normal Density Concrete	γ_c	2400kg/m^3
	Mass per length of 35M reinforcement	m/l	7.85kg/m
Steel	**Yield Strength**	f_y	345MPa
	Modulus of Elasticity	E	200000MPa
	Density	γ_s	7850 kg/m^3

Cost of materials if the arch was constructed today (Engineering News-Record, 2013)

Material	Cost
Concrete	$109.91/ton
Steel	$49.56/CWT
Wood	$429.98/MBF

- **Wood**

$$\sigma = \frac{P}{A}$$

Compressive strength of wood (D-Fir) is 13.8MPa, $\sigma = 13.8MPa$ (CSA 086-01, "Engineering Design in Wood", Table 5.3.1D) and maximum axial force is $P = 6775kN$ solving for A,

$$A = \frac{6775kN}{13.8MPa} = 491 \times 10^3 mm^2$$

Total volume of a wooden arch, V

$$V = A \times Length\ of\ curve = 51.4\ m^3$$

Total mass of wooden arch, m

$$m = V \times 530\ {}^{kg}/_{m^3} = 27{,}243kg$$

Total cost of wooden arch used today ($430/Mbf=$182.2/m^3), $

$$cost = 51.4m^3 \times \frac{\$182.2}{m^3} = \$9{,}366$$

- **Reinforced Concrete**

$$\sigma = \frac{P}{A}$$

Compressive strength of concrete is 30MPa, $\sigma = 30MPa$ and maximum axial force is $P = 6775kN$ solving for A,

$$A = \frac{6775kN}{30MPa} = 226 \times 10^3 mm^2$$

Total volume of a concrete arch, V

$$V = A \times Length\ of\ curve = 23.6m^3$$

With respect to the weight of steel reinforcement, approximately 2% of the cross-sectional area of concrete can be assumed to be the total cross-sectional area of steel reinforcement. Since the density of steel is three times that of concrete, the weight of steel reinforcement can be estimated as 6% of the total weight of concrete.

Total mass of reinforced concrete arch, m

$$m = V \times 2400\ {}^{kg}/_{m^3} \times 1.06 = 60{,}038kg$$

Total cost of concrete arch used today ($110/ton), $

$$cost = 60{,}038kg \times \frac{1ton}{907kg} \times \frac{\$110}{ton} = \$7{,}281$$

- **Steel**

$$\sigma = \frac{P}{A}$$

Strength of steel is 345MPa, $\sigma = 345MPa$ and maximum axial force is $P = 6775kN$ solving for A,

$$A = \frac{6775kN}{345MPa} = 19.6 \times 10^3 mm^2$$

Total volume of a steel arch, V

$$V = A \times Length\ of\ curve = 2.05m^3$$

Total mass of steel arch, m

$$m = V \times 7850\ {}^{kg}/_{m^3} = 16{,}125kg$$

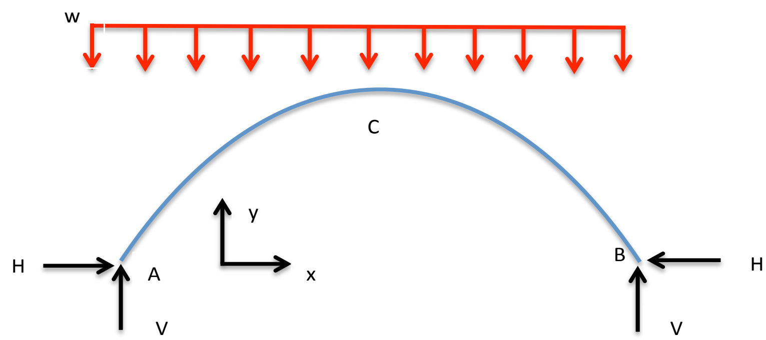
Total cost of steel arch used today ($49.56/CWT=$1093/tonne), $

$$cost = 16{,}125kg \times \frac{\$1093}{tonne} \times \frac{1tonne}{1000kg} = \$17{,}624$$

2. <u>Analysis and design of a three hinged parabolic arch:</u>

In the case of a three hinged parabolic arch (C being at midspan) with a uniform distributed applied load, the equation of the arch:

$$y(x) = \frac{4hx}{L^2}(L - x)$$



Knowing that the moment is zero at C and due to symmetry the reactions V and H can be determined,

$$H = \frac{wL^2}{8h}$$

$$V = \frac{wL}{2}$$

Calculating the moment along the arch:

$$M = \frac{-w \times L^2}{8h} y + \frac{wL}{2} x - \frac{wx^2}{2}$$

$$\Rightarrow M = \frac{-w \times L^2}{8h}\left[\frac{4hx}{L^2}(L - x)\right] + \frac{wL}{2} x - \frac{wx^2}{2} = 0$$

This shows for a three-hinged parabolic arch with a uniform distributed load applied, the arch carries no moment and the forces are carried axially. Therefore under uniform distributed load, assuming the arch carries no moment is equivalent to assuming a three-hinged parabolic arch.