ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

SEISMIC RISK ASSESSMENT OF REINFORCED CONCRETE BRIDGES WITH SUSTAINABILITY CONSIDERATIONS

M.Sc. THESIS

Baha Ecmel GÜLER

Department of Civil Engineering

Earthquake Engineering Programme

Thesis Advisor: Assoc Prof. Dr. Mustafa GENÇOĞLU

SEPTEMBER 2015

Anabilim Dalı : Herhangi Mühendislik, Bilim

Programı : Herhangi Program

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

BETONARME KÖPRÜLERİN SÜRDÜRÜLEBİLİRLİK DÜŞÜNCESİ İLE SİSMİK RİSK DEĞERLENDİRMESİ

Baha Ecmel GÜLER

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Baha Ecmel GÜLER, a **M.Sc.** student of ITU **Graduate School of Science** student ID **501081214**, successfully defended the **thesis** entitled "**SEISMIC RISK ASSESSMENT OF REINFORCED CONCRETE BRIDGES WITH SUSTAINABILITY CONSIDERATIONS**", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assoc. Prof. Dr. Mustafa GENÇOĞLU** ....

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Istanbul Technical University

Date of Submission : **26 December 2014**

Date of Defense : **31 December 2014**

To my father,

FOREWORD

Firstly, I would like to express my appreciation to Dr. Mustafa Gençoğlu, my academic advisor. I would like to thank him for his devoted directions. Without his dedication, I wouldn't be able to accomplish my undertaking. I also want to address my gratitude to Dr. Armağan Korkmaz, whose invaluable help and support during this study has been my biggest guide in this journey. My thanks go also to my family members, and friends. Thank you for being there for me when I need you the most.

March, 2015 Baha Ecmel GÜLER

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SEISMIC RISK ASSESSMENT OF REINFORCED CONCRETE BRIDGES WITH SUSTAINABILITY CONSIDERATIONS

SUMMARY

Over the last few years, sustainable design has started to play an increasingly vital role in the construction of bridges. Designing for a sustainable bridge is complex and requires the consideration of many variables, from the design approach, to the materials used to its associated costs over its lifetime.

To get a better grasp on the concept, this thesis is prepared. It contains modeling and the analysis of bridges with the SAP2000 software and synthesizing the existing practices in sustainable structural design applicable to bridges.

The main focus of this thesis is to investigate this newly developed sustainability concept for horizontal structures.

Thesis consists of eight chapters. In the first chapter, introduction and objectives of the study are given. In the second chapter literature review, sustainability, current sustaninability rules are given. In the third chapter applications related sustainability of buildings and bridges are studied separately. Forth chapter gives information about brdidge types used in Turkey. The bridges having two, four and five spans considered for numerical analysis are presented in fifth chapter and the SAP2000 numerical models of these bridges are given in the sixth chapter. The numerical results and behavior of those bridges (piers) are given under vertical and seismic effects. The linear time history analysis of the bridges and the static push-over analysis of piers are carried out. In the last chapter of this thesis the seismic risk assessment of reinforced concrete bridges with respect to sustainability point of view are given.

BETONARME KÖPRÜLERİN SÜRDÜRÜLEBİLİRLİK DÜŞÜNCESİ İLE SİSMİK RİSK DEĞERLENDİRMESİ

ÖZET

Sürdürülebilirlik kavramı çok uzun zamandır aslında mühendislikte kullnılagelen bir kavram olup yapısal davranışın belirlenmesinde de önemli bir rol oynamaktadır. Sürdürülebilirlik kavramının, yapı ve davranış ile birlikte tanımlanır hale gelmesi son yıllarda oldukça yaygın bir hal almıştır. Aynı zamanda, son yıllarda, köprü yapımlarında sürdürülebilir tasarım hayati bir rol üstlenmeye başlamıştır. Sürdürülebilir bir köprü tasarımı kullanılan malzemeden onun ilişkilendirilen kullanım ömrü süresince maliyetini de içeren karmaşık ve birçok değişkeni barındıran bir denklemler dizisidir. Bu dizi içinde, dünyadaki uygulamalara baktığımızda, yapısal davranış çokça dikkate alnımamaktadır. Oysa ki, Türkiye gibi deprem riski altında bir ülkede bu en önemli parametrelerin başında gelmektedir. Sürdürülebilir bir köprü tasarlamak karmaşık olup, pek çok değişkenin gözönüne alınmasını gerektirir. Köprülerin ömür çevrimi diğer bir değişle hayat döngüsü, çevresel ve ekonomik etkiler bakımından farklı yöntemlerle hesaplanabilir.

Köprülerin sürdürülebilir çözümleri için hayat döngüsünün değerlendirilmesi önemli olmaktadır. Ekonomik sürdürülebilir gelişme kavramı, genel tanımı ile, her bir yapısal değeri içine alan ve genel kalkınma konularını, çevresel etki ve irdeleme boyutunda kavramsal olarak ele alan hem gelişme hem de ilerleme konularında oldukça büyük önem taşıyan ile çevre koruma arasında köprüler kurmaya çalışan yaklaşım biçimidir. Dolayısıyla yapıların servis ömrü bakımından çevresel koruma ve aynı zamanda çevresel ve yapısal performans öne çıkmaktadır. Çevresel performansa etki eden başlıca parametreler; havaya, suya ve karaya zehirli madde salınımı, fosil yakıt tüketimi, karbondioksit salınımı, yenilenemeyen enerji kullanımı, global ısınma potansiyeli, asit birikimi ve ozon tabakası incelmesi gibi hususlar olarak belirtilebilir. Bu hususların çözümlerinde en önemli adım problemin ortaya konulması ve sürdürülebilir çözümler aranmasıdır. Sürdürülebilir çözüm tanımlama sürecinde yapının kimliğinin ortaya konması yapının doğru önlemlerle geleceğe taşınması yapının sürdürülebilir davranışının sağlanması konusunda önemli bir adım atılmış olur. Bu adımın eklenmesi ile birlikte yapısal davranış da önemli bir parametre olarak analizler dahilinde dikkate alınmış olur.

Sürdürülebilir köprü tasarımı, köprüye ait daha sonraki adımları da etkileyen önemli bir süreçtir. Köprüler için sürdürülebilirlik hedefleri uzun vadede incelenecek olursa malzeme sarfiyatını minimize ederek daha uzun servis ömrü ve daha düşük bakım ile daha mukavim yapıların oluşturulması olarak belirtilmiştir. Sürdürülebilir inşaat aşamasında göz önünde bulundurulması gereken, enerji sarfiyatı ve emisyondan sorumlu, ulaşım ve işletme olmak üzere başlıca iki husus mevcuttur. Son kategori olan sürdürülebilir yaklaşımlı ve uygulamalı bakım ve onarım olarak değerlendirme de, kısa, orta ve uzun dönem iyileştirmeleri olmak üzere, köprü ömrü boyunca esas kısmı oluşturmaktadır.

Köprü yapımı, inşası, maliyeti, yerleşimi, yapım sırasında çalışacak işçi sayısı, kullanılacak yapı elemanları ve bu elemanların temini ve tesisi gibi bilindik parameterelerin yanına, çevresel etki değerlendirmesini de dahil ettiğimizde oldukça kompleks bir davranış profili ortaya çıkmaktadır. Bu ortaya çıkan profil, uygulamacı açısından karar verme mekanizmasını zorlaştırsa da, uzun zaman içinde alınan jararların daha gerçekçi ve daha doğru olarak ortaya konmasını sağlamaktadır. Bu tez ile bu kavramlar ele alınmış ve ele alınan bu kavramların köprü maliyetleri, davranışları ve uzun süreli kontrolleri gibi parameterlerin ne kadar etkin olduğunun ortaya konması sağlanmıştır.

Köprülerin sürdürülebilirliğinin değerlendirilmesi amacıyla farklı kurumlar tarafından, farklı sistemler geliştirilmiştir. Yeşil yapılar için yeşil dereceledirme sistemleri, toplam çevresel etkilerin ölçülmesi amacıyla hayat boyu değerlendirme yöntemleri ile köprünün başlangıç ve gelecek ekonomi kıyaslamalarını incelemek amacıyla hayat boyu maliyet analizleri oluşturulmuştur. Çalışma kapsamında sürdürülebilirlik uygulamaları içerisinden hayat boyu değerlendirme yöntemine dayanan gaz emisyonu hesaplanması ve köprüler için hayat boyu farklı parametrelerin dikkate alınarak yapıldığı maliyet analizi konularına yer verilmiştir.

Bu tezin ana amacı yatay yapılar olarak adlandırılan köprüler için farklı ve yeni yaklaşımlar ışığında geliştirilmiş sürdürülebilir konseptlerin ve uygulamaların analizlerinde yapısal davranışın dahil edilebilirliğinin aştırılmasıdır. Gerçekleştirilen çalışmanın ana odak noktası, yeni geliştirilen sürdürülebilirlik kavramını köprüler üzerinde uygulamak ve köprülerin sismik davranışını sürdürülebilirlik kapsamında ele almaktır.

Tez toplam sekiz bölümden oluşmaktadır. Tezin birinci bölümünde giriş verilmiş olup, çalışmanın amacı ve araştırma yöntemi üzerinde durulmuştur. Çalışmada öncelikle binalar, köprüler ve diğer yapılardaki sürdürülebilirlik uygulamalarını sürdürülebilir tasarım, sürdürülebilir inşa ve sürdürülebilir bakım olmak üzere üç kategoride inceleyen detaylı bir literatür araştırmasına yer verilmiş ve daha sonra bu çalışmalardan hangisinin uygulanmasının köprüler açısından kullanılabileceğine karar verilmiştir. İkinci bölümde literatür araştırması, sürdürülebilirlik, geçerli sürdürülebilirlik kuralları verilmiştir. Üçüncü bölümde sürdürülebilirlikle ilgili uygulamalar binalar ve köprüler için ayrı ayrı ele alınmıştır. Dördüncü bölümde Türkiye'de bulunan mevcut köpru tipleri verilmiştir. Beşinci bölümde sayısal çözüm için iki, dört ve beş açıklıklı köprüler gözönüne alındığı belirtilmiş, altıncı bölümde bu köprülerin SAP2000 yapısal analiz yazılımının uygulanmasıyla sayısal modellerin nasıl hazırlanacağı konusunda ayrıntılı bilgiler verilmiş, yedinci bölümde köprüler için enine ve boyuna doğrultuda düşey yükler ve deprem etkisinde yapılan zaman tanım alanında doğrusal elastik hesap ve static itme analizi sonucunda elde edilen sayısal sonuçlar tablo ve şekillerde verilmiştir. Beton sınıfları olarak C30, C50 ve C80 malzeme sınıflarından olmak üzere üç farklı yapısal malzeme türünde tekrarlanan analizlerden elde edilen sonuçlara ait yorumlanan ve somut olarak olarak ortaya konan veriler tezin son bölümünde verilmiştir. Sonuçlar genel olarak değerlendirilerek, elde edilen sonuçların sürdürülebilirlik açısından değerlendirilmiş ve önemi vurgulanmıştır.

Yeni köprüler için, uygulamada görev alan mühendislere ve yöneticilere daha sürdürülebilir köprü tasarım ve inşaat işlemleri ile mevcut köprüler için sürdürülebilir bakım uygulamaları sunmayı amaçlayan bu çalışma sonucunda elde edilen bulgulara 8. bölümde ulaşılabilmektedir.

Tezin genel olarak orjinalliği, sürdürülebilirlik kavramını yatay yapılar olarak adlandırılan köprüler için ele alması olmasının yanında deprem gibi Türkiye ve daha bir çok deprem etkisindeki ülke için oldukça önemli bir parametrenin de sürdürülebilirlik denklemi içinde yazılmasıdır. Yapısal davranışı bir bütün olarak ele alan bu yaklaşımda sürdürülebilirlik kavram olarak yapının tasarımında ve inşasında en önemli husus olarak değerlendirilmektedir.

1. INTRODUCTION

1.1 Overview

Sustainable practices are a key component in almost every aspect of our lives; green strategies are now being incorporated in everything from foods to building cars and building engineering structures (Louis, 2010). The general. transportation systems involve substantial investments on behalf of the government and taxpayers, and widespread concern is growing over the critical state of infrastructure (Mistry, 2005). A bridge constitutes a large investment of capital, materials, and energy and is thus associated with significant environmental impact. In addition to design and construction, bridge maintenance is an important issue. Sustainability is a long-term approach that can enable environmental protection and process improvements (EPA, 2012). Thus application of sustainable practices for bridge design, construction, and maintenance can enable an environmentally responsible construction and effective use of resources for this large investment.

Many Department of Transportation (DOT) bridge designers and constructors have explained various environmental sustainable alternatives (ASBI 2007, Hong et. al., 2006). In recent years, DOTs have made a great effort to implement sustainable applications in bridge design, construction, and maintenance in order to achieve their goals in an environmentally- responsible and cost-effective manner. Most of DOTs have taken step in implementing sustainability practices in design, construction, and maintenance of highways and bridges. These are implementing sustainability practices either through the application of sustainable materials or using green rating systems.

This study mostly relates to the bridges in Turkey. The research study consists of six major parts. The methodology adopted to achieve these objectives is organized in Figure 1.1 . Firstly, sustainable practices that are followed buildings, bridges and other sectors, were compiled through an extensive literature review. Then, it was determined which of those practices can also be used for bridges.

Figure 1.1: The Summary of All Chapters.

The summary of all chapters is given below:

Chapter 1, “Introduction” discusses importance of sustainability, research goal and objectives used to accomplish the goal. Chapter 2, “Literature Review”, Chapter 3, “Bridge Models” Chapter 4, “Structural Analysis”, Chapter 5, “Sustainability Applliccations”, Chapter 6, “Results and Conclusions” discuss the summary of results and provides recommendations for future work.

1.2 Need Statement

The built environment has great impact on the natural environment, human health, and economy (EPA, 2010). Incorporating green strategies has seen a large number of environmental, economic, and social benefits. The EPA lists the potential benefits of green buildings, which include enhancement and protection of biodiversity and ecosystems, improving air and water quality, reducing waste streams, conserving and restoring natural resources, reducing operating costs, minimizing strain on infrastructures and improving overall quality of life (EPA, 2010).

Since many of the bridges are approaching their maximum service life, they need to be replaced. All the activities, such as the construction of new bridges, repair, rehabilitation, and replacement of the existing bridges are associated with considerable environmental impact. Therefore, sustainable applications that can reduce environmental impact need to be developed and implemented.

Activities involved in construction have a significant environmental footprint, especially in terms of greenhouse gas (GHG) emissions and energy consumption (Orabi et. al, 2012). Transportation is a vital part of the economy but also a significant source of GHG emissions. It involves large number of construction activities, which directly or indirectly release greenhouse gases, water, and land pollutants. Several studies have focused on measuring the environmental impacts of construction activities and finding ways to minimize these impacts. There has been recent need to adopt methodologies that aim at reducing such impacts and contribute to sustainability. Therefore, this study is necessary for developing a framework for bridges that can be used as a guideline to achieve sustainability.

1.3 Research Goal and Objectives

The overall research goal is to develop a framework, which can be used as a guideline to achieve environmental sustainability in bridge projects and enable various transportation agencies and organizations to be leading states for the green design, construction, and maintenance of bridges. Figure 1.2. shows the research objectives used to accomplish the goal.

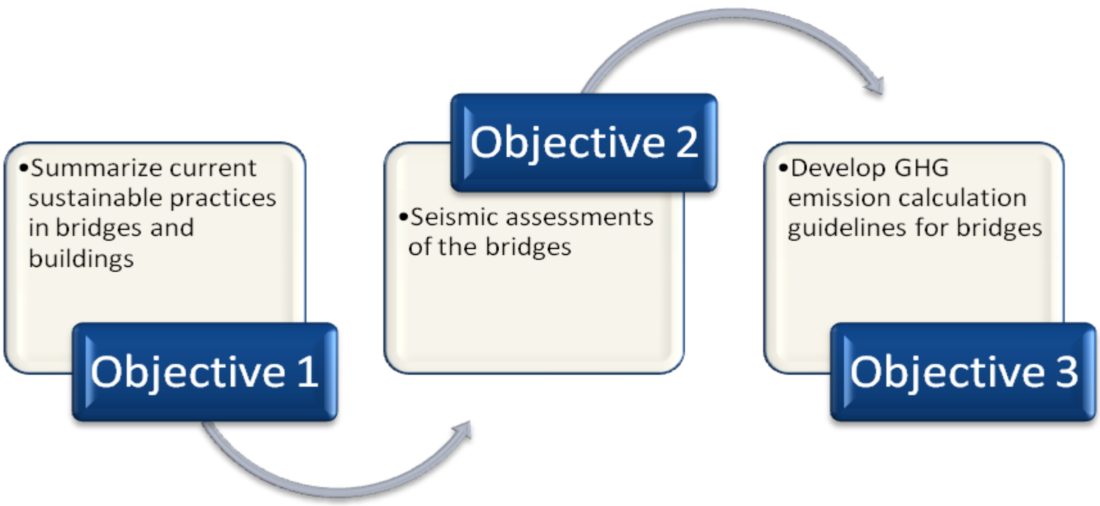


Figure 1.2: Research Objectives.

To achieve Objective 1, a theoretical analysis of jounals, articles, research papers, and theses was done. In this objective, literature is reviewed related to sustainable practices followed in building construction and infrastructure. Various gren rating systems such as LEED®V.3, Envision Rating System by Institute of Sustainable Infrastructure (ISI), INVEST rating system developed by FHWA etc. were reviewed. Sustainable practices followed by various transportation agencies were also studied in detail. Application of sustainable materials in bridge design, construction, and maintenance and LCA applications were studied and construction standards described by EPA, AASHTO, and FHWA etc., were reviewed to establish requirements in the framework.

Based on the detailed content analysis discussed in the Objective 1, the Objective 2 is investigated and the seismic analysis of the selecting bridges are done.

Transportation sector is the second biggest contributor of GHG emissions followed by the industrial sector, which is the biggest contributor of GHG emissions. In 2002, it is estimated that transportation sectors is responsible for 1908 MMT CO_2 Eq., which is 29% of all the key sectors (EPA, 2008). The guidelines include developed of excel based tool that can be used to compute GHG emissions from materials and equipment that can be used in bridge construction projects to achieve Objective 3. GHG emission calculation can be used to evaluate the framework

1.4 Research Methodology

A research methodology has been developed to accomplish the goal. First, literature was reviewed related to current sustainable practices followed in building construction, bridge construction and other sectors. Then it was determined that which of those practices can also be used in the bridge construction projects. At last, GHG emissions calculation guidelines were developed to support the sustainability of bridge projects.

As discussed in this chapter, sustainable construction is a key component in sustainable development. Any bridge project should be executed in such a way that sustainability is incorporated in every stage including design, construction, and maintenance. Sustainability is about balancing what is beneficial to people, while considering what is economically sound and environmentally compatible. Implementing sustainable approaches may increase the project cost, however it may be warranted when all external cost are considered (NYSDOT, 2008). Climate change, energy use, environmental impacts, and limits to financial resources for transportation infrastructure are major global concerns. It requires new approaches to planning, designing, constructing, operating, and maintaining transportation solutions and systems (AASHTO, 2009). There are various practices followed at design, construction, operation, and maintenance levels. Many DOTs excel in certain and are concerned with the sustainability triple bottom line as well as the implications for mitigation and adaptation to climate change (AASHTO, 2009). The focus of this research study is to develop a framework that will assist transportation engineers and managers develop more environmentally sustainable design and construction processes for new bridges, and sustainable maintenance practices for existing bridges.

2. LITERATURE REVIEW

2.1. Literature Review Categories

In this chapter, literature is reviewed as shown in Figure 2.1. The first category reviews literature about current sustainable practices in bridge design, construction and maintenance by consulting articles, theses, books, journals and magazines. The second category reviews literature about major existing Green Rating Systems such as LEED V.3 (USGBC, 2009); EnvisionTM Rating System (ISI, 2012), GreenLITES Certification System (NYSDOT, 2008), Sustainable Self-Highway Evaluation Tool (FHWA, 2012). Other green rating system for bridges developed by Lauren R. Hunt was also reviewed. The other categories focus and summarize the existing literature related to LCA and LCCA applications.

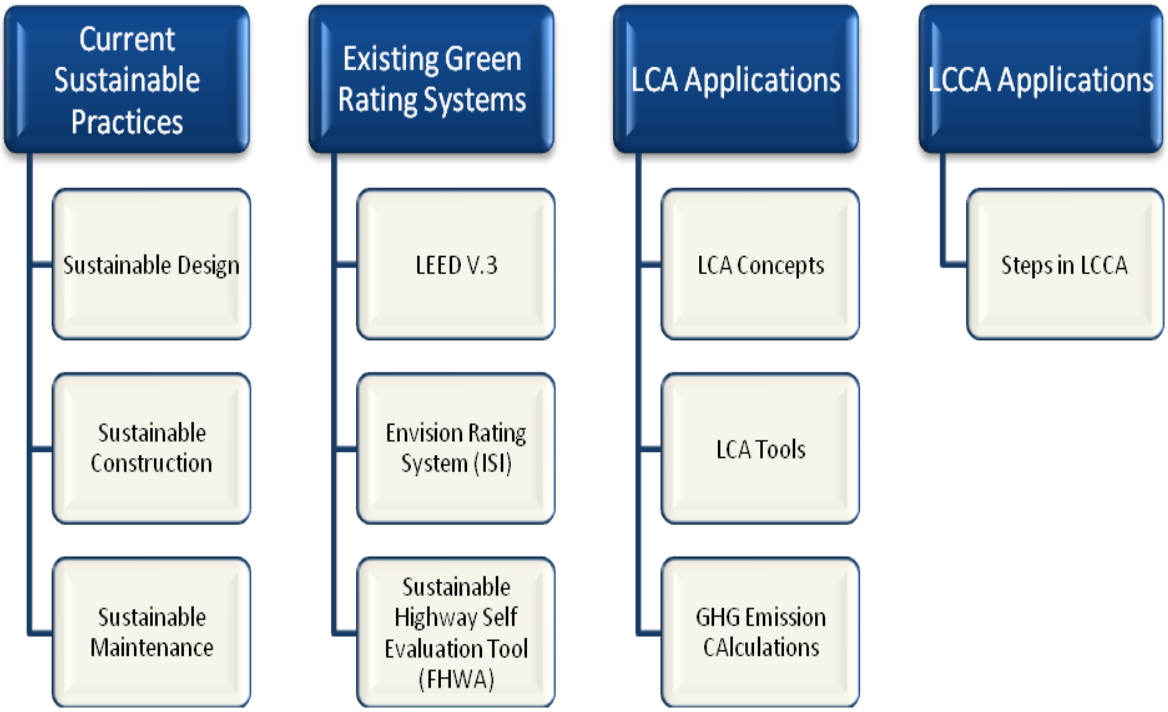


Figure 2.1: Literature Content Analysis.

2.2. Sustainability Overview

Sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own need” (WCED, 1987). Since, buildings contribute 39% of all carbon dioxide (CO_2); sustainability is increasingly adopted by the building industry with the motivation to reduce the environmental impacts. Several tools have been developed to serve the building industry for sustainable design and construction: green building rating systems such as the Leadership in Energy and Environmental Design (LEED®), life cycle cost analysis (LCCA), and life cycle assessment (LCA). These tools can also be applied to bridge design, construction and maintenance to make new and existing structures more environment friendly in the long run, in other words more sustainable.

From 2005 to 2008, green building construction increased dramatically from 2% to 20% of overall construction (McGraw Hill Construction, 2012). Although, LEED® rating system is only used for buildings but some useful metrics are also applicable to bridge sustainability assessment (Whittemore, 2010). A sustainable bridge can be defined as the one that is “conceived, designed, constructed and maintained, and eventually put out of service in such a fashion that these activities demand as little as possible from the natural, material and energy resources from the surrounding community” (Whittemore, 2010).

A sustainability assessment system is important to (NYSDOT, 2008):

a) Encourage public involvement in the transportation planning process;
b) Protect and enhance the environment;
c) Conserve energy and natural resources;
d) Preserve or enhance the historic, scenic, and aesthetic project setting characteristics;
e) Integrate smart growth and other sound land-use practices;
f) Encourage new and innovative approaches to sustainable design.

Sustainability can be explained under 1) structural sustainability 2) environmental sustainability in the context of bridges.

The structural sustainability, in American Concrete Institution (ACI) fall 2010 Convention, stated that: "A structural sustainable concrete bridge should provide an overall life of 100 to 150 years"; “They should have minimum of shrinkage (plastic, drying, chemical shrinkage) and cracking". For example use High Performance Concrete (HPC) to minimize dry shrinkage use saturated lightweight aggregates for internal curing for the promotion of hydration to minimize shrinkage and cracking. HPC should have other optimum concrete characteristics such as low water/cement ratio, high flexural strength. “Long service life of bridge decks over 100 years can be achieved with low shrinkage, low permeability HPC, compared to only 20 years for normal strength concrete decks.” (ACI, 2010).

Although structural sustainability is important, the focus will be on environmental sustainability of the bridges. Environmental sustainability deals with the environmental impacts of the products or the process in all life cycle stages of the bridge, i.e. to measure the environmental impacts and performance of the products or process over the design, construction, use, maintenance and, disposal stages (EPA, 2006). The following sections expand on the environmental aspect of sustainability for bridges.

2.3. Current Sustainable Practices

A number of articles, theses, journals, books and magazines were consulted to review current sustainable approaches in bridge design, construction and maintenance. This section describes methodologies and approaches used to assess sustainability. The current sustainable practices are reviewed in three categories, which are sustainable bridge design, sustainable bridge construction and, sustainable bridge maintenance.

2.3.1. Sustainable design

Design of the bridges is an important phase where most of the decision taken can have impacts on later stages. Incorporating sustainability approaches and methods in the design stage is important for achieving sustainability. For example site selection, material selection for design, service life design, span arrangement, substructure type, geometry, foundation types are some of the factors that should be taken into consideration during the design stage and alternative ways are usually considered to achieve sustainability.

Lounis & Daigle (2007) compared the environmental benefits of High Performance Concrete Decks (HPC) and Normal Performance Concrete (NPC) bridge decks. It was found that construction of HPC structures results in reduction in the number of maintenance and repair actions that will result in a reduction in both materials and energy consumption as well as in a reduction of CO_2 emissions and waste production. In terms of environmental impact, it is estimated that the HPC deck alternative yields a reduction of 65% in the CO_2 emissions compared to the normal concrete deck. It was also found that based on the onset of corrosion as the end of service life criterion, the HPC deck alternative incorporating SCMs has a service life that can vary from 3 to 10 times the service life of normal concrete deck having the same water-to-cementitious materials ratio (Lounis & Daigle, 2007).

High service life design requires the designer to explore outside the current codes, evaluate environmental loading and establish material performance over a long period, requiring extrapolation of current knowledge of climate and material properties as well as the extrapolation of material deterioration models (Connal, 2009).

Sustainability objectives for bridges can also be best accomplished by ensuring durable bridges with long service life and low maintenance inputs that, on a whole-of-life basis, minimize material consumption over the long term. It is likely that such a bridge also has the lowest whole-of-life economic cost (Connal, 2009).

There is need for concrete durability design. Reinforced concrete and pre-stressed concrete bridges, which are exposed to aggressive environments, are affected by the corrosion of steel due to ingression of chlorides and due to carbonation. Chloride ingression has been formulated on the assumption that it would occur by ionic diffusion. Another factor, which decreases the durability of the structure, is carbonation. The primary concern is for superstructure elements. It decreases the PH value of concrete due to which the passive iron oxide layer, which protects reinforcement from corrosion, is not maintained. To achieve long life of a bridge, selection of good quality of concrete; selection of greater cover to reinforcement;

provision of electrical continuity for reinforcement in substructure element and; Good detailing to enable compaction of concrete, along with good vibration and subsequent curing during construction, to ensure a dense layer of cover concrete are considered important factors (Connal, 2009).

Materials play an important role in sustainability and number of research studies has been conducted to determine sustainable properties of materials. Steel bridges offer numerous advantages contributing to sustainability. Steel is recyclable material and it can be recycled and reused multiple numbers of times without affecting its structure or properties. It promotes management of sustainable resources. It minimizes the effect on local community, as steel components are manufactured offsite. Selection of steel ensures reduced energy consumption and CO_2 level emissions as shown in Table 2.1.

Table 2.1: Reduced Energy Consumption and CO_2 Level Emissions.

	Steel Sections	Steel Plate
Embodied CO_2	0.762 tCO_2/t	0.919 tCO_2/t
Embodies Energy	0.762 tCO_2/t	0.919 tCO_2/t

Transportation industry uses alternative materials in the construction of pavements as they are currently using bulk materials such as natural and fine aggregates. Materials including industrial by-products, concrete aggregates, old asphalt pavement, scrap tires, fly ash, steel slag, and plastics are often used as alternate materials for natural aggregates. These materials are best used for their environmental suitability, recyclability and sustainability in concrete and road pavement applications, as well as their environmental impact on surface and ground waters. Many types of products result in the creation of large quantities of solid waste materials (SWMs). Many of these SWMs remain in the environment for long periods of time and cause waste disposal problems. Existing landfills are reaching maximum capacity and new regulations have made the establishment of new landfills difficult. Disposal cost continues to increase while the number of accepted wastes at landfills continues to decrease. Use of use of industrial by-products in the construction of transportation networks can contribute to sustainable development (Kassim, Simoneit, & J.Williamson, 2008).

Currently, industrial by-products (such as fly ash, steel slag, plastics, and scrap tires) are used as substitutes for natural aggregates in road construction. Various solid wastes that have been used in several highway applications for sustainability considerations are bag-house fines, blast furnace slag, carpet fiber dusts, coal bottom ash/boiler slag, coal fly ash, contaminated soils, flue gas desulfurization scrubber material, foundry sand kiln dusts, mineral processing wastes, municipal solid waste incinerator ash (Kassim, Simoneit, & J.Williamson, 2008).

Other practices that are considered to contribute to sustainable design are longer spans, high strength, more durability-better long term performance, and smaller cross-sectional area; use of high performance composites: fiber reinforced polymers (FRP), FRP wraps used for rehabilitation projects; use of aluminum as light weight bridge decks results in 80% lighter deck than concrete and is more corrosion resistant, requires fewer welds than steel thus reducing potential failure points; use of high performance steel, for example a new grade of steel: hps-485w which results in increased toughness, superior weldability and high corrosion resistance; using hybrid designs results in 17% weight savings, 11% cost savings (Gilbertson, 2008).

2.3.2. Sustainable construction

There are two main processes during construction stage, which are responsible for energy consumption and emissions. These are a) Transportation and b) Operation. In a normal life cycle, main transportation operations occur ‘‘to site’’, ‘‘from site’’ and “on site”. For the evaluation of energy releases during transportation, average distance travelled and fuel efficiency of the vehicles which travels to and from the site are considered (Pacheo & Campos, 2010). Energy consumption during construction operations is an important factor that should be considered. Energy consumption is found considering the weight of equipment, energy it consumes per hour of operation and the duration of a construction of a typical bridge deck (Pacheo & Campos, 2010).

Different road equipment such as trucks and other vehicles are used during construction operations to transport materials to and from site, which consumes fuel and release wastes to atmosphere. Non-efficient fuel vehicles can increase fuel consumption and also releases GHG emissions. Similarly, various non-road construction equipment such as excavators, bulldozers, compactors, pressure washers, cement and mortar mixers, pumps, trenchers, rollers and other construction equipment used during operation consumes fuel and releases energy.

Air emissions from construction equipment contribute significantly to the degradation of the environment. Therefore, it is imperative to use such type of equipment, which produces lesser emissions than conventional ones. "Non-road engines are all internal combustion engines except motor vehicle (highway) engines, stationary engines (or engines that remain at one location for more than 12 months), engines used solely for competition, or engines used in aircraft. The non-road standards cover mobile non-road diesel engines of all sizes used in a wide range of construction, agricultural and industrial equipment" (EPA, 2004). So, Non-road equipment is used in construction and not on roads like cars, buses etc.

Accelerated bridge construction technique is an innovative approach greatly contributing towards sustainability. Accelerated construction is used to achieve the construction of structures in a shortest possible time while decreasing delays and traffic disruption. It is not just building structures rapidly but also entails a variety of techniques, processes, and technologies to achieve the desired result of reducing congestion due to construction while improving quality. These techniques are used for the construction of new bridges and also the replacement of existing bridges (Ralls, 2007). Using precast bent caps, precast columns, precast deck panels, precast barriers, prefabricated trusses, precast abutments, retaining walls and footings allows manufacturing to take place in a controlled environment thereby reducing impacts to traffic and reducing environmental impacts. The main reason for using such techniques is to reduce on-site construction time and mobility impact time (FHWA, 2012).

2.3.3. Sustainable maintenance

Bridge maintenance is major part of a bridge life cycle. There are number of activities involved in bridge maintenance which may have significant impacts on environment. Bridge maintenance usually includes short-term fixes, medium-term fixes and long-term fixes.

Short-term fixes include capital preventive maintenance (CPM). It applies lower-cost treatments to slow the deterioration rate, maintain or improve the functional condition and extend the pavement's service life.

Medium term fixes includes rehabilitation. Rehabilitation is the application of structural enhancements, such as multiple course resurfacing or concrete pavement repairs, that improves the roadway or overlaying a bridge deck and superstructure repair to improve a bridge.

Long-term fixes include reconstruction/replacement. Reconstruction is the entire building of the roadway. Replacement refers to replacement of the bridge deck, super structure replacement or replacement of whole bridge (MDOT, 2011).

Many attempts have been made to reduce number of maintenance activities to reduce environment impacts associated with them. Use of durable materials prolong service life of bridge components and thus reduce future maintenance activities. High performance structural materials and FRP can be used to design bridges for more durability thus reducing future maintenance activities (Tang, 2004). Efficient inspection technologies should be used to properly assess the condition of bridges timely so that proper actions can be taken regarding maintenance actions. Use of efficient inspection technologies can ensures improved data quality while simultaneously controlling the cost of data collection. Further development and evaluation of improved visual inspection procedures, innovative nondestructive testing methods, and automated methods to gather and manage data should be encouraged (Hearn et. al., 2008).

The focus should be more on quantitative assessment of performance of bridge performance rather than visual inspections and condition ratings. A variety of permanent sensors can be installed on bridges, which can automatically detect the data with the change in chemical and electrical properties of materials related to deterioration, aging in coatings and changes in service environment or exposure. Sensors can report to wireless networks and data can be analyzed and deterioration can be detected automatically by computer workstations (Hearn et. al., 2008).

2.4 Existing Major Green Rating Systems

Since the focus of this study is sustainability in bridges, various major green rating systems currently used were reviewed. These green rating systems are developed mostly for buildings and highways. The existing green rating systems are as follow;

2.4.1 LEED (2009)-new construction

Leadership in Energy and Environmental Design (LEED®) is a rating system for design, construction and operation of sustainable buildings. It was developed by the USGBC in 1998. This rating system was mainly developed to define and measure Green Buildings. So far, USGBC has developed five versions i.e. version 1.0 in 1998, version 2.0 in 2000, version2.1 in 2002, version 2.2 in 2005 and version 3.0 in 2009. The latest, LEED® version 3.0 is currently used for existing and new commercial, residential and institutional buildings. Since its inception in 1998, USGBC has grown to encompass more than 24,662 projects in the United States and 30 countries covering over 1.627 billion square feet of development area which shows the impact and wide recognition for LEED® around the globe.

The rating system is divided into six main categories with additional points awarded for innovation. These categories are based on energy consumption, location, environmental principles and material used. They are: Sustainable Sites, Water Efficiency, Energy and Atmosphere, Indoor Environmental Quality, Material and Resources, and Innovation in design. These categories are further divided into various credits. Each credit has certain requirements, listing strategies to fulfill those requirements. The rating system has a total of 100 base points and four certification levels i.e., certified, silver, gold and platinum. There are four certification levels are developed in LEED rating system as shown in Table 2.2.

Table 2.2: LEED System

Certification Level	Score Range
Certified	40-49
Silver	50-59
Gold	60-79
Platinum	80 and above

Certain credits can be adopted from LEED® 2009 rating system to develop the rating system for bridges. The factors considered in analyzing the sustainability of buildings are materials, water, energy, location and indoor air quality while the critical factors that apply to bridges are location, materials, water and traffic impacts. Whittemore (2010) explained the equivalent goals for sustainable bridges by comparing them with the sustainable goals for buildings. His analysis explained the useful metrics from LEED® 2009 that can be taken to define and measure sustainability in bridges. So, some useful metrics can be extracted to define sustainable bridges.

2.4.2 EnvisionTM rating system by ınstitute of sustainable infrastructures

The institute for sustainable infrastructure (ISI) developed a new rating system to evaluate the sustainable infrastructure projects. This rating system evaluates the sustainability for wide range of infrastructure including bridges. ISI was formally launched in 2011 and introduced a rating system that was developed by a working group from American Council of Engineering Companies (ACEC), American Public Works Association (APWA) and American Society of Civil Engineers (ASCE).

Envision is an objective and comprehensive framework that describes criteria, which can influence the project elements, and processes, which can significantly influence the outcome of the infrastructure project and its impacts on the environment. Not only has it focused on environmental, social and economic performance, but the overall delivery of the infrastructure project. This rating system promotes project management and business strategy for sustainable infrastructure solutions.

Envision evaluates the sustainability of a wide range of civil infrastructure projects vital to our communities, to protecting the environment, and will award and recognize projects that meet that goal. The system will evaluate and score existing infrastructure and serve as a goal for new and renovating projects to achieve (ISI, 2012).

2.4.3 Sustainable highways self-evaluation tool

INVEST is a self-evaluation tool developed by FHWA is a web-based collection of criteria, allows states to integrate sustainability in transportation projects. It is a voluntary tool and can be used by state and various stakeholders to measure sustainability of transportation projects. FHWA's INVEST can help transportation agencies and organizations integrate sustainability practices in transportation projects and provide practitioners to evaluate sustainability in their transportation projects as it provides information and techniques to integrate sustainability best practices. It is developed with input from state and local transportation agency officials and staff and professional organizations such as AASHTO and ASCE. FHWA is continually updating this tool as the transportation sustainability advances. It is divided into three main categories: planning and process criteria, project development criteria and operations and maintenance criteria. A total of 61 criteria are described under these categories. This rating system can also be used as a benchmark to develop a rating system specifically for the bridges (FHWA, 2012).

2.5 Life Cycle Assessment (LCA) Applications

2.5.1 Background of LCA applications

Life cycle assesment (LCA) is a method of measuring the total environmental impact of a manufactured product or manufacturing process (See Figure 2.2). It is from extracton of raw materials to end-of-life, reflecting the "cradle-to-grave" concept (Buonopane, 2008). The Environmental Protection Agency defines LCA (also known as cradle-to-grave analysis, eco balance, life cycle analysis) as the evaluation of "the environmental effects associated with any given activity from the initial gathering of raw material from the earth until the point at which all residuals are returned to the earth." Some typical environmental effects (or impacts) are energy use, global warming potential, and natural resource depletion (Buonopane, 2008). "The term "life cycle" refers to the major activities in the course of the product's life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required to manufacture the product" (EPA E. P., 1993)

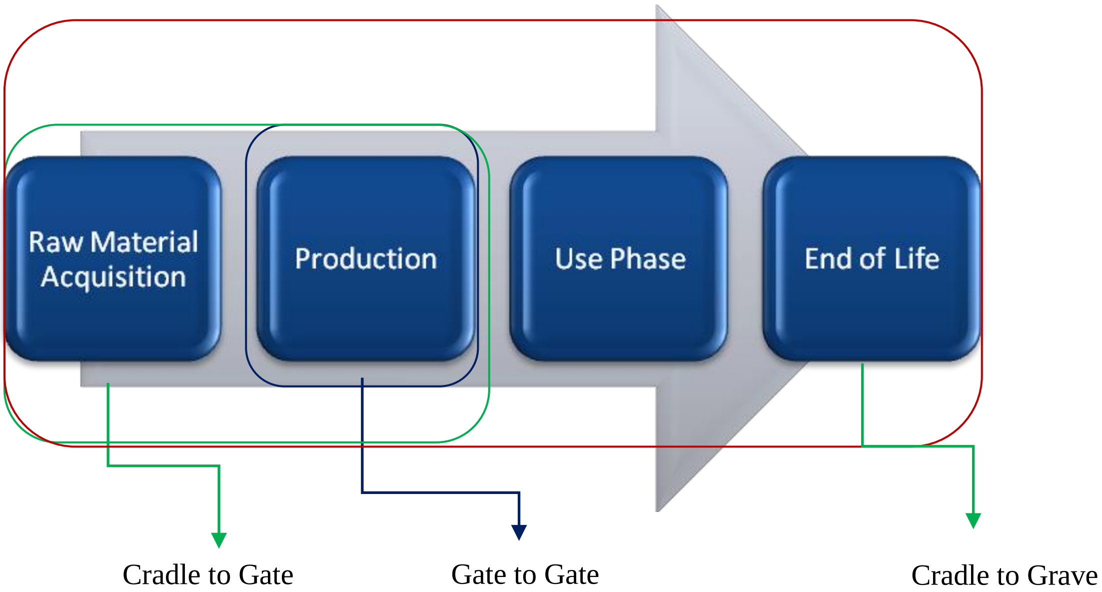


Figure 2.2: LCA Stages.

Simply, LCA is a way for analyzing products through all its all life cycle stages to determine their environmental impacts. An ideal life cycle would account for all phases of the product what is called the cradle to grave approach. In a similar way, LCA has different stages which are shown in the Figure 2.2.

2.5.2 Bridge LCA

The life cycle of the bridges play an important role in determining the sustainability of the system. Life cycles can be evaluated in terms of environmental or economic impacts. Assessing the life cycle can help us become more aware of sustainable solutions for bridges. Life-cycle models, weather through assessments, inventories or cost analysis, are complex and rely on consistent and available historical information.

In simple words, LCA is a method to assess the environmental performance of the product or a process over its life cycle. The use of a product throughout its life cycle may have many negative impacts on the environment.

The following are some of the terms, which are measured to assess the environmental performance of the product (Trusty, 2006):

a. Toxic releases to air, water and land;
b. Fossil fuel depletion
c. CO_2 emissions
d. Non-renewable energy use
e. Global warming potential
f. Acidification and Acid Deposition
g. Nutriphication/Eutrophication of water bodies
h. Stratospheric ozone depletion

GHG emissions are one of the major contributors to the negative impacts to the environment and, the main focus of this study developing guidelines for determining GHG emissions or the carbon footprint of the bridges. Guidelines for calculation of GHG emissions are based on LCA methodology. It is well known that bridge construction project involves large number of products and processes. Cement is the most common material used in large quantity in construction. Cement is highly energy intensive material (Worrel, Price, Martin, Hendriks, & Meida, 2001). It consumes as well as release high amount of energy into the surroundings during all life cycle stages like raw material extraction, transportation to manufacturing facility, manufacturing, packaging, transportation to site, use, maintenance and disposal. Cement production is energy intensive and accounts for 5% of global anthropogenic CO_2 emissions (Worrel, Price, Martin, Hendriks, & Meida, 2001) and significant levels of SO_2, NO_x, particulate matter and other pollutants. Similarly, different products and products release significant amount of GHG emissions during their life cycle. Therefore, it is imperative to calculate the GHG emissions of these products and processes using LCA approach and investigate strategies to reduce these emissions.

Since GHG emissions can be calculated based on LCA methodology therefore it is important to review the LCA concepts and applications. A number of LCA studies had been made and extensive literature is published recently. Singh, Berghorn, Joshi and Syal (2011) had made a systematic compilation of all the Construction-LCA related literature and presented its structured review. These research work reviews the literature in four major categories: LCA applications for construction products selection; LCA applications for construction systems/process evaluation; LCA tools and databases related to the construction industry; and LCA methodological developments related to the construction industry. Current challenges for using LCA in construction are discussed and potential areas for future research are highlighted (Syal et. al., 2011). This study gives a good idea of the LCA methodologies and databases for LCA.

An integrated LCA-LCCA model was developed and applied on highway overpass bridge deck, and two alternative bridge deck designs were compared. The model is applied to alternative concrete bridge deck design options: one conventional steel reinforced concrete bridge deck with mechanical steel expansion joints and the other an SRC deck with Engineered Cementetious composite (ECC) link slabs. Factors or indicators important in evaluating the sustainability such as life cycle energy, greenhouse gas emissions, agency, rehabilitation, social, construction-related user delay costs and environmental pollutant damage costs are quantified for both systems over a 60 year bridge design life. The integrated model consists of two integrated elements; life cycle inventory analysis and life cycle cost model of agency and social costs. They are further integrated into the factors that characterize the infrastructure system. These indicators are evaluated for total 60-year service life with a traffic flow rate of 35,000 cars per day in each direction. Study shows that ECC link slab system has a 37% cost advantage over the conventional system, consumes 40% less total primary energy (Kendall & Keoleian, 2008).

LCA approaches can be used to analyze the impacts of requirements of credits in the rating system. In research study conducted, individual credits within the LEED program were critically analyzed using life cycle approach. A case study of building was conducted to measure life cycle energy consumption and solid waste generation to analyze the impacts of implementation of LEED requirements (Scheuer & and Keoleian, 2002).

LCA approaches can be integrated into LEED. Lloyd described that USGBC has recognized the benefits of using quantitative and holistic life cycle information and an "LCA into LEED" program has been initiated to determine how best to integgrate LCA into LEED Building for Economic and Environmental Sustainability (BEES) which is an LCA software tool developed by National Standards of Intitute and Technology takes a life cycle approach to building materials and focus on both life cycle environmental and cost data. It was shown that BEES can be used to integrate LCA itno LEED (Lloyd, 2005).

There are two ways to conduct an LCA - using an input-output based LCA, or a process based LCA. Economic input-output based LCAs are based on economic transactions and resource interactions between an exhaustive set of economic sectors. "The Economic Input-Output Life Cycle Assessment (EIO-LCA) method estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy. It is one technique for performing a life cycle assessment, an evaluation of the environmental impacts of a product or process over its entire life cycle".

EPA has developed a report, which gives an overview of sources and magnitude of construction and GHG emissions and ways to reduce them. The opportunities to reduce GHG emissions are presented based on best available sources and information. EPA describes that Fuel selection, equipment idling, electricity use, equipment maintenance, equipment selection and material recycling are the construction activities that results in GHG emissions and have the most influence on contractors potential ability to affect emissions. Similarly, material selection, employee commuting, materials shipment and vegetation removal have some influence and site selection and structural design and performance have little influence (EPA, 2004).

Emphasis on recycling and reusing of materials is placed as GHG emissions released during the manufacturing and transportation of the construction materials are avoided. Therefore, recycled materials should be used on the project like Fly ash, blast furnace slag and recycled steel. Fly ash and blast furnace slag can be used as supplemental cementitious materials and replace a portion of the cement. The emission factor of such type of blended cement is greatly reduced. Table 2.3 shows the environmental impact score of the traditional Portland cement and the blended cement (Huntzinger & Eatmon, 2009). The software tool SimaPro was used to assess the environmental impact score of the two types of cement using LCA methodology. It can be seen that use of blended cement reduces GHG emissions by 21.6% (Huntzinger & Eatmon, 2009). Also, recycling steel reduces GHG emissions and saves energy by 56% (West, 2012).

Table 2.3: Environmental Impacts

Environmental Impact Category	Traditional Portland Cement	Blended Cement
Green House	0.088	0.069
Acidification	0.043	0.034

2.5.3 Available LCA Tools

LCA tools are the applications to conduct LCA of construction products and systems. These can be used to quantify energy and material usage, as well as quantification of environmental releases across all the life cycle stages. LCA tools can widely be used for environmental labeling, product environmental improvement, ecodesign and policy evaluation (Menke, Davis, & and Vigon, 1996). Menke, Davis and Vigon (1996) identified comprehensive list of 37 LCA tools and the related literature was reviewed.

LCA tools measures the environmental impacts primarily across a five set of environmental indicators which are fossil fuel use; global warming potential, toxic releases to air; toxic releases to water and solid waste generation. Mukherjee and Cass (2011) surveyed GHG impact assessment tools shown in Table 2.4 and classified according to the institution type such as Academic tools, Government and Industry.

Table 2.4: GHG Impact Assessment Tools

Institution Type	GHG Impact Tools		
	Life Cycle Assessment	**Emission Calculators**	**Rating/Points Systems**
Government	NREL-LCI	SGEC Tool	FHWA Self-Evaluation Tool
Academic State	EIO-LCA PaLATE	Road Construction Emission Model GreenDOT	Greenroads GreenLITES I-LAST
Industry	SimePro Aspect	CHANGER e-CALC AggRegain	Greenroads™

2.6 LCCA Applications

A bridge is generally considered a significant component of a transportation system and requires periodic repair and maintenance. Consequently, it represents a long-term and multi-year investment. Bridge management refers to the various activities of planning, design, operation, and maintenance that determine how a bridge is configured throughout its service life. The specific application of LCCA to bridge management depends on the specific character of bridges and on availability of data for estimating values of key parameters influencing the life-cycle cost of a particular bridge (Hawk, 2003). LCCA is presently the most common tool used to make a sensible decision in selecting the lowest cost and the best performance alternative. "LCCA is a set of economic principles and computational procedures for comparing initial and future costs to arrive at the most economical strategy for ensuring that a bridge will provide the services for which it was intended" (Hawk, 2003).

It enables the entire cost comparison of various design alternatives and brings it to a logical decision. In addition to the initial cost, all pertinent costs (user, repair, maintenance, etc.) that occur throughout the service life of a bridge are included.

LCCA has received increasing attention as a tool to assist transportation agencies in making investment decisions as well as in managing assets (FHWA, 1994).

LCCA of a bridge project can be summarized into the following steps. The first step determines the analysis period or scenarios and the schedules initial and future activities involved in the project design. The second step establishes alternatives for realizing the structural and performance objectives of a project. The third step estimates the agency and user costs of these activities. The best-practice LCCA calls for inclusion of both costs. The fourth step includes the compiling and computation of life cycle cost. Using a discount rate, these costs are converted into dollars and summed for each alternative.

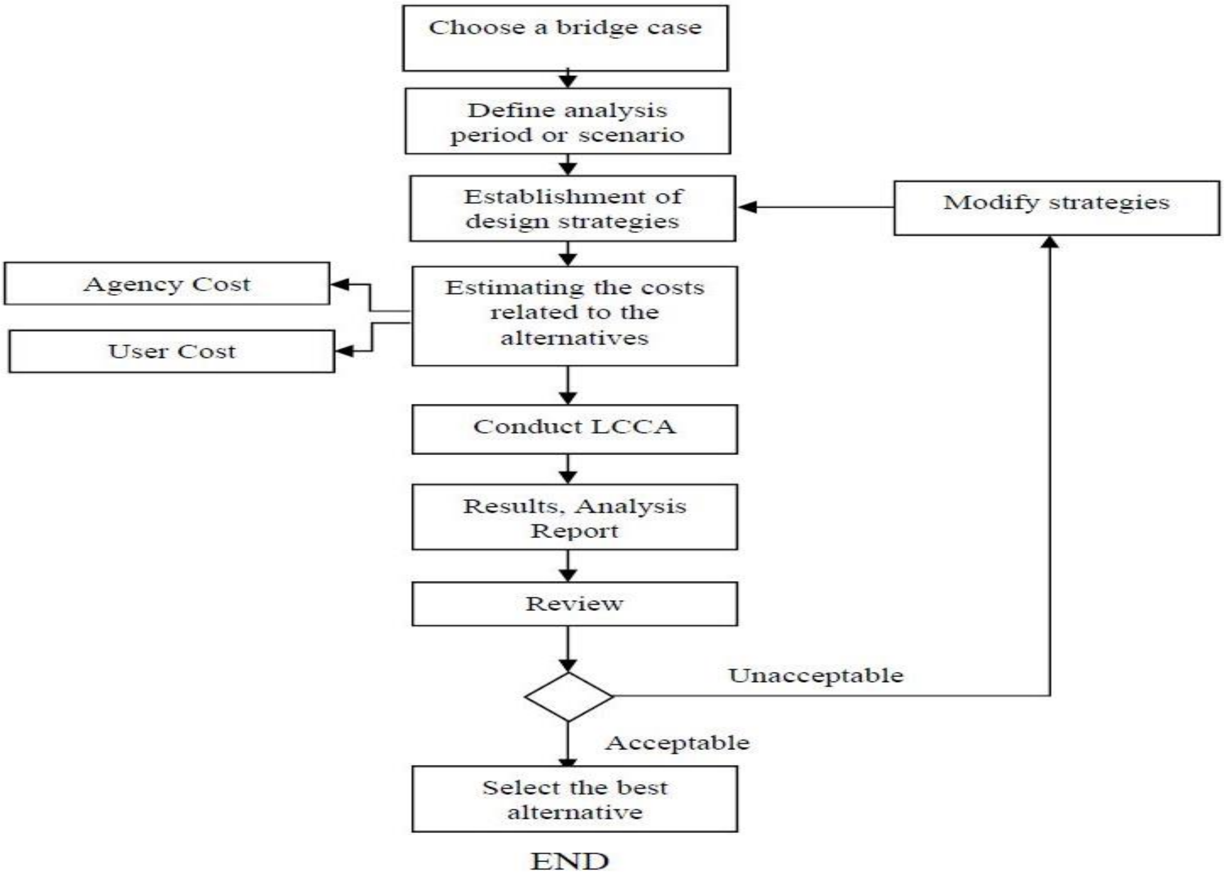


Figure 2.3: LCCA Chart for Bridges.

The final step is analyzing the results and selecting the best and the most cost effective alternative. The flowchart given in Figure 2.3 shows the basic steps involved in conducting LCCA for bridges.

It is particularly vital to set up the alternatives for a bridge project prior to conducting the LCCA. These chosen alternatives should be distinctly different, provide a reasonable, viable, and costeffective solution to the project. A minimum of two different project alternatives should be incorporated into the LCCA. Listed below are some of the possible steps involved in performing the LCCA of bridges. A brief description of every step is also mentioned for guidance.

Choosing a bridge case:

The selected bridge is described in terms of the characteristics relevant to (Hawk, 2003).

- Life Cycle Cost
- National Bridge Inventory (NBI) data
- Traffic Volume
- Inspection Reports
- Design Details.

Define analysis period or scenario:

It is defined as “the time horizon over which future costs are evaluated”. The time period should be selected on the basis of both the physical elements to be analyzed and the type of decision to be made. Generally, the planning horizon should be at least as long as the best-estimate service life of the element. The current service lives of highway bridges in North America may be approximately 30 to 50 years, while AASHTO specifies the service life of new bridges should be 75 years (Hawk, 2003).

Establish alternative bridge design strategies:

A Design Strategy is the combination of initial bridge design and necessary supporting maintenance and rehabilitation activities. It is important to identify the scope, timing, and cost of these activities (FHWA, 1998). Each action have also estimated agency and user costs, also subject to uncertainty; estimation of these costs is a later step.

Estimate costs:

Each of the actions that together compose a design strategy entail agency and user costs. The estimated cost is a crucial component of the bridge LCCA (Hawk, 2003). Construction quantities and costs are directly related to the initial design and subsequent rehabilitation strategy. The first step in estimating agency costs is to determine construction quantities/unit prices. Agency costs include all costs incurred directly by the agency over the life of the project, while user costs are incurred by the highway users over the life of the project. User costs are an aggregation of three separate cost components:

- Vehicle operating costs (VOC), which are costs related to the consumption of fuel and oil, and wear on tires and other vehicle parts.
- User delay costs due to reduced speeds and/or the use of alternate routes.
- Crash costs (also called accident costs), i.e., damage to the user's vehicle and/or other vehicles and/or public or private property, as well as injury to the user and others.

Conduct LCCA:

The analysis focuses on the relationship between costs, timings of costs, and discount rates employed. Once all costs and their timing have been developed, future costs must be discounted to the base year and added to the initial cost to determine the Net Present Value (NPV) for the LCCA alternative.

Review results:

The analyst should review the net present value distributions to ensure they "make sense" in light of expectations and experience.

Select the best alternative:

The main objective of conducting the LCCA is to identify a design strategy with least life cycle cost and the best performance for a project. At the end of analysis, usually the lowest life cycle cost alternative is selected.

3. SUSTAINABILITY PRACTICES

3.1. GHG Emission Calculation Guidelines Based on LCA Methodology

3.1.1. Introduction

The construction sector accounts for 131 Million metric tons of CO_2 equivalents (EPA, 2009). The transportation sector is one of the biggest contributors of Greenhouse Gas (GHG) emissions. According to greenhouse report by Environmental Protection Agency (EPA), transportation sector is responsible for 27% of GHG emissions in 2002 and is the second biggest contributor by sector followed by Industrial sector, which is responsible for 32% of GHG emissions (EPA, 2008) Therefore, significant amount of GHG emissions are associated with the construction and use of transportation infrastructure and this has led State Department of Transportation Agencies to take the challenge of global climate change and investigate strategies that reduce the life cycle GHG emissions associated with transportation infrastructure which involves the design, construction and maintenance of bridges (Mukherjee & and Cass, 2012).

California Environmental Protection Agency has already developed a greenhouse gas emission inventory that provides the estimate of the amount of GHG emissions associated with the various activities. The inventory includes estimated of various gas pollutants such as Carbon-dioxide (CO2), Methane (CH4), Sulphur Hexafluoride (SF6), Nitrous oxide (N2O) etc. (California EPA, 2012). This study propose guidelines to measure GHG emissions for bridge construction projects with the aim to calculate the carbon footprint, defined as a composite measure of all GHG emissions expressed as equivalents of carbon dioxide emissions, and to develop a tool that can be used to estimate and benchmark carbon footprints for bridge construction projects. Cradle to Gate LCA approach is taken into account to estimate the emissions from raw material acquisition, manufacturing and construction phase of different bridges.

3.1.2. Goals and objectives

The goal of this section is to develop an LCA framework and prepare guidelines for determining carbon footprint associated with various items in bridge construction projects to investigate various strategies to reduce GHG emissions thus supporting sustainable decision making. This would allow them to consider such alternatives that reduce GHG emissions considering the requirements developed The framework considers the product and process components of a bridge's life cycle. The LCA framework and the estimation tool developed for highway reconstruction and rehabilitation projects can be used as a guideline for LCA of bridge construction projects as most of the products and processes considered and the methodology used in the LCA framework is directly applicable for the bridge projects also.

3.1.3. Building blocks for ghg emissions calculation guidelines

The research group proposed a project based life cycle assessment framework that can be used to estimate GHG emissions of typical highway reconstruction and rehabilitation projects. The aim of the research study is to calculate the carbon footprint of Hot-Mix Asphalt (HMA) and Portland Cement Concrete (PCC) pavements for both reconstruction and rehabilitation projects.

The objectives stated in the research study are:

a) Report construction inventories for 14 highway reconstruction, rehabilitation and Capital Preventive Maintenance (CPM) projects observed over a period of two summers
b) Report estimated emission factors for construction materials and equipment used
c) Report estimated emission factors for use phase of highways
d) Provide contractors a tool to benchmark construction and rehabilitation projects

State Agencies and contractors can use it to estimate GHG emissions for specific construction operations. These can be used to investigate or identify alternative materials or improvements in construction processes to reduce their emissions. In turn, this will encourage the adoption of low emission products and techniques into practice, thus indirectly including other stakeholders such as material suppliers and equipment manufacturers.

The proposed framework was developed using the following steps (a-l):

a. Data Collection Phase:

In this phase, data were collected from different highway construction and maintenance project sites to develop a comprehensive project inventory of materials and equipment. These projects included HMA and concrete reconstruction, maintenance and rehabilitation projects. The data were collected during the construction phase and use phase of the pavement. The collection of this data was very important to know the materials, equipment and processes involved to develop project inventory. Estimates of GHG emissions from these products were calculated, taking advantage of the existing methods of calculating GHG emissions. It accounts for emissions from the following stages:

a) Extraction of raw materials or mining;
b) Manufacturing and production of the products (materials and equipment used to construct the pavement);
c) Off-road and On-road transportation of the products;
d) Processes involved during the construction and maintenance of the pavement
e) Service life (use-phase of the pavement)

Motor Vehicle Emission simulator (MOVES), which is a traffic simulation environment developed by EPA, is used to estimate the use phase emissions due to on-road vehicular traffic. Excess emissions due to traffic delays and reduced speeds in construction zones are also considered.

Emission factors were collected from existing literature, historical databases to estimate the emissions from these products. EPA defines emission factor as:

"An emissions factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per mega-gram of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category (i.e., a population average)" (EPA, 2011).

Once an emission factor is developed for a product, emissions due to the product in a life cycle can be calculated by multiplying the emission factor by its quantity. For example, if the emission factor is .012 and 100 MT of asphaltic material is used in the project. Then emissions due to asphaltic material will be .012 X 100 MT = 1.2 MT of CO2 i.e. CO2 equivalent emissions of asphaltic materials will be 1.2 MT/100 MT of material. Similarly, emission factor for other products can be developed and emissions can be calculated. Once the emissions from all the products and process are calculated these can be summed up to calculate the total project emissions.

b. Inventory Development

The data that were collected through the fourteen projects were organized into material and equipment categories to develop a project inventory. The inventory would consist of product and processes, their emission factors and other details.

c. Analyzing the inventory and estimating project life cycle GHG emissions

LCA techniques were used to assess the environmental impacts of the products and processes. Economic Input Output Life-cycle Assessment (EIO-LCA) (Hendrickson et al. 1998, Cicas et al. 2007) is one of the many methods used to assess environmental impacts. The principal investigator in this research study uses this method in his previous work to assess the environmental impact associated with the products and processes.

d. Hybrid LCA Methodology:

There are two ways to conduct an LCA a) input-output based LCA, or b) a process based LCA. Economic input-output based LCAs are based on economic transactions and resource interactions between an exhaustive set of economic sectors. The Economic Input Output-Life Cycle Assessment (EIO-LCA) is also used in the hybrid model. It is a model that defines the scope and number of environmental effects quantified in a LCA, developed at Carnegie Mellon University (Hendrickson, 2006). It estimates the economic contribution, resource requirements and environmental emissions for a particular product, service, or activity.

In this study, in order to estimate the GHG for all materials and equipment inputs, an input-output and/or process LCA tool is used to take advantage of the most recent emission factors that have been reported in the process LCA literature, when applicable, as well as maximize the advantages of an input-output LCA. In the model, the GHG emissions are quantified as a function of the construction and vehicle operations in terms of material/fuel usage.

The emission factors used in this study are from process LCAs reported in literature. They have been taken primarily from the Stripple (Stripple, 2011), Athena (ATHENA, 2006) and NREL inventories. These emission factors are usually expressed as Tons of CO2 equivalents per unit weight or volume. Therefore, given a bulk volume or weight of a material use on a particular project, the emissions can be calculated by using the emission factors.

The proposed framework is based on process, product, service (PPS) method which includes different process and product components. This approach uses existing calculation methods of GHG emissions but uses the data collected through fourteen highway construction projects.

e. Product Components:

All the materials that are listed in department of transportation agency specification were accounted for. Both virgin materials and recycled materials were taken into consideration and were accounted for during the mining, manufacturing and transportation of the materials to and from the site phases. All the equipment that are used in highway construction were taken into consideration and accounted for emissions due to manufacturing, transportation, construction and maintenance operations (Mukherjee & and Cass, 2012). For each of these products, emission factors were developed emissions can be calculated depending on the quantity of these products.

f. Process Components:

It includes two components - the processes on site that are directly involved in the highway construction and maintenance operations, e.g., construction schedule and operation design; and the processes that directly influence decisions of long-term pavement behavior, e.g., determination of maintenance schedules (Mukherjee & and Cass, 2012).

g. Service life components:

Since, it can be difficult to estimate, a traffic simulation environment MOVES [35] was used to estimate use phase emissions due to on-road vehicular traffic.

h. Implementation of web based tool to calculate GHG emissions of the products:

The Project estimator tool PE-2 is developed which is an easy to use interface to calculate GHG emission. This tool can be accessed at:

http://www.construction.mtu.edu:8000/cass_reports/webpage/estimator.html

i. Inventory Reporting:

User can query all relevant data collected.

j. Benchmarking and Estimating:

PE-2 tool can be used at the project level to estimate and benchmark emissions. To benchmark expected project emissions, use the bill of materials and estimated material and equipment use in the project. At the end of the project, use PE-2 to generate an emissions report using the actual data collected. Incentive plan can be generated for the contractor's efforts at reducing GHG emissions during the project construction process. This could be through more efficient project site design and schedule planning or using alternative materials during the construction process.

k. Literature and historical databases

arious historical databases are available to calculate the life cycle GHG impacts of products. National Renewable Energy Laboratory (NREL) has developed a life cycle inventory database to assess life cycle impacts. NREL and its partners created the "U.S. Life Cycle Inventory (LCI) database provides individual gate-to-gate, cradle-to-gate and cradle-to-grave accounting of the energy and material flows into and out of the environment that are associated with producing a material, component, or assembly in the U.S" (NREL, 2012).

Various other databases such as Life Cycle Inventory of Portland Concrete, Steel were accessed to determine GHG emissions from those products.

Most of the emission factors are adopted from the research report "Carbon Footprint for HMA and HCC Pavements" developed by Mukherjee and Cass (2012). Emission factors of all the equipment are adopted from this research work.

l. SimaPro

SimaPro is one of the LCA tool is most widely used in the industry. SimaPro is used in this study to develop emission factor of some of the products that can be used on bridge projects. LCA is performed using SimaPro according to International Standard ISO 14040 i.e. it includes all the four phases, which are described before. These are goal and scope definition, life cycle inventory analysis, impact assessment and interpretation. Environmental performance is generally measured in terms of a wide range of potential effects, such as (Carmody & and Trysty, 2005):

- Fossil fuel depletion
- Other non-renewable resource use
- Water use
- Global warming potential
- Stratospheric ozone depletion
- Ground level ozone (smog) creation
- Nutrification (excess nutrients)/eutrophication (oxygen deficiency) of water bodies

- Acidification and acid deposition (dry and wet)
- Toxic releases to air, water, and land.

All of these measures are indicators of the environmental loadings that can result from the manufacture, use, and disposal of a product.

SimaPro is used in this study to calculate total cradle to gate CO_2 equivalent releases of different products. The emission factors taken from the literature, historical databases and calculated using SimaPro. Table shows the list of all the materials, units and the emission factors.

3.1.4. GHG Emissions Calculation Guidelines

In order to develop LCA guidelines for the bridges, the framework described above can directly be used. The following steps can be followed for conducting LCA of bridges and determining the carbon footprint:

a) For a sustainable bridge project, follow the Criteria and determine that which criteria are applicable for LCA as these criteria will be included for determining GHG emissions when considering those criteria on a sustainable bridge project. Some of the criteria may not be applicable for LCA as they are not product based or GHG emissions of those cannot be can be calculated using LCA tool.

b) Use bill of materials to determine all the materials. Also determine all the construction equipment to be used, their number and estimated hours of usage.

c) Use the emissions estimating tool (refer to the format. xlsx) to calculate the emission from the products. This tool is based on Project Estimator Tool PE-2, which can be found at: http://www.construction.mtu.edu:8000/cass_reports/webpage/estimator.html to determine life cycle GHG emissions (Cradle to Gate) associated with the materials and equipment to create benchmark emissions of the project.

   Use material estimator shown in Table 3.1 for calculating GHG emissions from various materials. Input the quantity of materials corresponding the material selected to determine emissions from that material.

Use equipment estimator for calculating GHG emissions from various equipment. It is required to enter the number of equipment and the estimated hours of usage of the equipment corresponding to the equipment of selected to calculate GHG emissions from that equipment.

d) All the emissions will sum up and this will the benchmark emissions.

e) Use emission estimator tool to generate an emissions report using the actual data collected.

f) Investigate strategies to identify alternative products and processes to reduce GHG emissions of products, which have higher GHG emissions.

g) Determine all the recommended solution and alternative products.

h) Calculate the GHG emissions of all the final products that will be used and know the carbon footprint of the sustainable bridge project.

Table 3.1: Steps for Calculating GHG Emissions

Materials	Unit	Emission Factor	Reference
Section 903 (Admixtures and Curing Materials for Concrete)			
White Membrane Curing Compund for Bridge Decks	Gal	0.01255	(Mukherjee & Cass, 2011)
Non-Chloride Accelerator	Cft	NanoMT	(Mukherjee & Cass, 2011)
Latex Admixtures	Ton	2.63	(Mukherjee & Cass, 2011)
Polypropylene Fibers	Ton	2.33	(Mukherjee & Cass, 2011)
			(Mukherjee & Cass, 2011)
Section 904 (Asphaltic Materials)			
Materials	**Unit**	**Emission Factor**	**Reference**
Asphalt Binder PG 58-28	Ton	0.1569	(Mukherjee & Cass, 2011)
Emulsified Asphalt	Gal	0.0071	(Mukherjee & Cass, 2011)
Emulsified Asphalt CSS-1hM	Gal	0.0071	(Mukherjee & Cass, 2011)
Ashpalt emulsion Chip Seal	Gal	0.0071	(Mukherjee & Cass, 2011)
Asphalt Emulsion CSS-1hM	Gal	0.0071	(Mukherjee & Cass, 2011)
Asphalt Emulsion CSS-1mM	Gal	0.0071	(Mukherjee & Cass,

			2011)
Asphalt Emulsion HFRS-2M	Gal	0.0071	(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Asphalt Emulsion RC-250	Gal	0.0071	(Mukherjee & Cass, 2011)
Section 905 (Steel Reinforcement)			
Dowel Bar	Ea	0.001627	(Mukherjee & Cass, 2011)
Dowel Bar Epoxy Coated	Ea	0.001627	(Mukherjee & Cass, 2011)
Steel Reinforcement	Lbs	0.0003	(Mukherjee & Cass, 2011)
Steel Reinforcement Epoxy Coated	Lbs	0.0003	(Mukherjee & Cass, 2011)
			(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Lane Ties Epoxy Coated	Ea	0.01512	(Mukherjee & Cass, 2011)
Load Transfer Device	Ft	0.006	(Mukherjee & Cass, 2011)
Steel Reinforcement Cable Barrier-C Slagter	Lbs	0.003	(Mukherjee & Cass, 2011)
Section 906 (Structural Steel)			
Steel Sections	Ton	0.0016	(Mukherjee & Cass, 2011)
Hot Rolled-Coil Steel	Ton	0.002	(Mukherjee & Cass, 2011)
Hot-Dip Galvanized Steel	Ton	0.0025	(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Steel Sheet Piling	Sft	0.0589	(Mukherjee & Cass, 2011)
Beam Plate Sealant Sherwin Wili 1550A	Tube	0	(Mukherjee & Cass, 2011)
Guardrail Anchorage Bridge	Ea	0	(Mukherjee & Cass, 2011)
Structural Steel	Cft	NanoMT	(Mukherjee & Cass, 2011)
Structural Steel Pin and Hangers	Cft	0	(Mukherjee & Cass, 2011)
Section 907 (Fencing Materials)			
Barbed Wire	Cft	NanoMT	(Mukherjee & Cass, 2011)

Materials	Unit	Emission Factor	Reference
Fence Chain Link (ft)	Ft	0.0092	(Mukherjee & Cass, 2011)
Fence Gate Chain Link	Cft	NanoMT	(Mukherjee & Cass, 2011)
Fence Post Chain Link Corner	Ea	0.0722	(Mukherjee & Cass, 2011)
Fence Post Chain Link Line	Ea	0.0722	(Mukherjee & Cass, 2011)
Fence Post Steel	Ea	0.0722	(Mukherjee & Cass, 2011)
Fence Post Steel Woven Wire	Ea	0.0722	(Mukherjee & Cass, 2011)
Fence Post Wood	Ea	0.0066	(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Protective Fence	Ft	0	(Mukherjee & Cass, 2011)
Fence Woven Wire	Ft	0.0092	(Mukherjee & Cass, 2011)
Section 908 (Miscellaneous Metal Products)			
Anchor Bolts	Cft	NanoMT	(Mukherjee & Cass, 2011)
Bushings	Ea	0	(Mukherjee & Cass, 2011)
Steel Beam Guardrail	Ft	0.0656	(Mukherjee & Cass, 2011)
Gaurdrail Approach Terminal 1 B	Cft	NanoMT	(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Gaurdrail Approach Terminal 1 T	Ea	0	(Mukherjee & Cass, 2011)
Gaurdrail Approach Terminal 2 B	Cft	NanoMT	(Mukherjee & Cass, 2011)
Gaurdrail Approach Terminal 2 T	Cft	NanoMT	(Mukherjee & Cass, 2011)
Gaurdrail Reflectorized Washers	Ea	0	(Mukherjee & Cass, 2011)
Sleeve Steel	Ea	0	(Mukherjee & Cass, 2011)
Section 909 (Drainage Products)			
End Section Concrete	Ea	0.802	(Mukherjee & Cass,

Materials	Unit	Emission Factor	Reference
			2011)
Materials	**Unit**	**Emission Factor**	**Reference**
End Section Metal	Ea	1.1995	(Mukherjee & Cass, 2011)
End Section Grate	Lbs	0.0003	(Mukherjee & Cass, 2011)
Pipe Cl A	Ft	0.1464	(Mukherjee & Cass, 2011)
Pipe Cl E	Ft	0.1464	(Mukherjee & Cass, 2011)
Pipe Concrete	Ft	0.0663	(Mukherjee & Cass, 2011)
Pipe Steel	Ft	0.1464	(Mukherjee & Cass, 2011)
Pipe Plastic	Ft	0.0259	(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Pipe RCP	Ft	0.0663	(Mukherjee & Cass, 2011)
Pipe Perforated Underdrain	Ft	0.0004	(Mukherjee & Cass, 2011)
Pipe Non-Perforated Underdrain	Ft	0.0004	(Mukherjee & Cass, 2011)
Pipe Corrugated	Ft	0.0259	(Mukherjee & Cass, 2011)
Expansion Joint Device	Ea	0	(Mukherjee & Cass, 2011)
Section 910 (Geo-synthetics)			
Biaxial Geogrid	Syd	0.0013	(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Geotextile Blanket	Syd	0.0013	(Mukherjee & Cass, 2011)
Geotextile Liner	Syd	0.0013	(Mukherjee & Cass, 2011)
Geotextile Separator	Syd	0.0013	(Mukherjee & Cass, 2011)
Section 912 (Timber and Lumber)			(Mukherjee & Cass, 2011)
Guardrail Block Wood	Ea	0	(Mukherjee & Cass, 2011)
Guardrail Post Wood	Cft	NanoMT	(Mukherjee & Cass, 2011)

Materials	Unit	Emission Factor	Reference
Wood Post	Cft	NanoMT	(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Post Wood Guard	Cft	NanoMT	(Mukherjee & Cass, 2011)
Section 913 (Masonry Units)			
Clay Brick	Ton	0.161	(Pre-Consultants, 2012)
Concrete Brick	Ea	0.0014	(Mukherjee & Cass, 2011)
Concrete Block	Ton	0.121	(Pre-Consultants, 2012)
Sand Lime Brick	Ton	0.13	(Pre-Consultants, 2012)
Materials	Unit	Emission Factor	Reference
Materials	**Unit**	**Emission Factor**	**Reference**
Section 914 (Joint and Waterproofing Materials)			
Fiber Joint Filler	Sft	0.0015	(Mukherjee & Cass, 2011)
Hot Poured Joint Sealant	Lbs	0.0006	(Mukherjee & Cass, 2011)
Foam Backer Road	Ft	0.0001	(Mukherjee & Cass, 2011)
Epoxy Resin Adhesive			(Mukherjee & Cass, 2011)
Waterproofing Membrane Preformed	Syd	0.0094	(Mukherjee & Cass, 2011)
			(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Section 916 (Erosion and Sedimentation Control Materials)			
Cobblestone	Syd	0.0172	(Mukherjee & Cass, 2011)
Fabric	Cft	NanoMT	(Mukherjee & Cass, 2011)
Plain Rip Rap	Syd	0.0172	(Mukherjee & Cass, 2011)
Silt Fence	Ft	0.0008	(Mukherjee & Cass, 2011)
Section 917 (Turf and Landscaping Materials)			
Fertilizer Chemical Nutrient	Lbs	0.0008	(Mukherjee & Cass, 2011)

Materials	Unit	Emission Factor	Reference
Mulch	Ton	0	(Mukherjee & Cass, 2011)
Mulch Blanket	Syd	0.0008	(Mukherjee & Cass, 2011)
Mulch Tackifier	Gal	0	(Mukherjee & Cass, 2011)
Seeding	Lbs	0.001	(Mukherjee & Cass, 2011)
Seeding Mixture	Lbs	0.001	(Mukherjee & Cass, 2011)
Sod	Cft	NanoMT	(Mukherjee & Cass, 2011)
Tack	Gal	0	(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Tackifier	Gal	0	(Mukherjee & Cass, 2011)
Topsoil 4in.	Cft	NanoMT	(Mukherjee & Cass, 2011)
Turf Reinforcement Mat	Syd	0.0008	(Mukherjee & Cass, 2011)
			(Mukherjee & Cass, 2011)
Section 918 (Electrical and Lighting Materials)			
Conduit	Cft	NanoMT	(Mukherjee & Cass, 2011)
High Intensity Light	Ea	0	(Mukherjee & Cass, 2011)
Materials	**Unit**	**Emission Factor**	**Reference**
Section 919 (Permanent Traffic Sign and Support Materials)			
Reflective Sheeting Material	Cft	NanoMT	(Mukherjee & Cass, 2011)
Dileneator Reflector	Cft	NanoMT	(Mukherjee & Cass, 2011)
Temporary sign	Sft	0	(Mukherjee & Cass, 2011)
Sign Cover	Ea	0	(Mukherjee & Cass, 2011)
Section 920 (Permanent Pavement Marking Materials)			
Pavement Marking Glass Beads	Lbs.	0.0004	(Mukherjee & Cass, 2011)

Materials	Unit	Emission Factor	Reference
Pavement Marking Poly Blend-Glass Beads	Lbs.	0.0004	(Mukherjee & Cass, 2011)
Pavement Marking Polyurea	Gal	0.059	(Mukherjee & Cass, 2011)
Pavement Marking Polyurea White	Lbs.	0.0071	(Mukherjee & Cass, 2011)
Pavement Marking Polyurea Yellow	Lbs.	0.0071	(Mukherjee & Cass, 2011)
Reflective Marker	Cft.	NanoMT	(Mukherjee & Cass, 2011)
Thermoplastic	Lbs.	0.0071	(Mukherjee & Cass, 2011)

Materials	Unit	Emission Factor	Reference
Section 922 (Temporary Traffic Control Materials)			
Arrow Board Lighted	Ea	0	(Mukherjee & Cass, 2011)
Barricade	Ea	0	(Mukherjee & Cass, 2011)
Concrete Barrier Reflector	Ea	0	(Mukherjee & Cass, 2011)
Concrete Barrier Temporary	Ea	0	(Mukherjee & Cass, 2011)

Other Products

Materials	Unit	Emission Factor	Reference
Stainless Steel	Ton	3.54	(ISSF, 2010)
Plastic Materials and Resins	USD	0.00168	(Pre-Consultants, 2012)
Portland Slag Cement	Ton	0.776	(Pre-Consultants, 2012)
Precast Concrete (Mix 1)	Ton	0.49	(Marceau et. al., 2007)
Precast Concrete (Mix 2)	Ton	0.43	(Marceau et. al., 2007)
Precast Concrete (Mix 3)	Ton	0.482	(Marceau et. al., 2007)

Cradle to Gate Emissions			
Inventory of Material			
Section 901 (Cement and Lime)	**Unit**	**Quantity**	**Emission Factor**
Portland Cement	Ton	1	0.928
Fly Ash	Ton	1	0.0177
Blast Furnace Slag Cement	Ton	1	0.522
Section 902 (Aggregates)			
Natural Aggregates	Ton	1	0.0061
Aggregates 21A	Ton	1	0.0061
Aggregates 21AA	Ton	1	0.0061
Aggregates 21AA Crushed Concrete	Ton	1	0.0021
Aggregates 22A	Ton	1	0.0061
Aggregates 22A Crushed Concrete	Ton	1	0.0021
Aggregates 22A (For Temp Use Only)	Ton	1	0.0061
Aggregates 23A	Ton	1	0.0061
Aggregates 23A Carol Pit 11-077	Ton	1	0.0061
Aggregates 23A (For Temp Use Only)	Ton	1	0.0061
Aggregates 23A (Reed Pit A 11-085)	Ton	1	0.0061
Aggregates 25A	Ton	1	0.0061
Aggregates 29A	Ton	1	0.0061
Aggregates 2FA	Ton	1	0.0061
Aggregates 34R	Ton	1	0.0061
Aggregates 3FA	Ton	1	0.0061
Aggregates 4G	Ton	1	0.0061
Aggregates 4G Modified Crushed Concrete	Ton	1	0.0021
Aggregates 4G Modified Limestone	Ton	1	0.0061
Aggregate 6A	Ton	1	0.0061
Aggregate Coarse CS-2	Ton	1	0.0061
Fine Aggregate 2fa	Ton	1	0.0061
Fine Aggregate 2FA	Ton	1	0.0061
Flowable Fill	Cyd	1	0.0001
Granular Material	Cyd	1	0.0001
Granular Material CL II	Cyd	1	0.0001
Granular Material CL III	Cyd	1	0.0001
Granular Material CL IIIA	Cyd	1	0.0001
Granular Material CL II Modified	Cyd	1	0.0001
Granular Material CL II Newark	Cyd	1	0.0001
Granular Material CL Tri City	Cyd	1	0.0001
Granular Material CL (Ton)	Ton	1	0.00006
Pulverized HMA	Ton	1	0.0049
Sound Class II (D) for Underdrain	Cyd	1	0.0001
Sound earth	Cyd	1	0.0001
Section 903 (Admixtures and Curing Materials for Concrete)			

Figure 3.1: Created GHG Calculation Tool.

Limitations/Assumptions

a) The focus of the guidelines is calculation of GHG emissions and does not include other impact categories.
b) GHG emissions are calculated based on Cradle to Gate LCA i.e. emissions are calculated up-to the products manufacturing stage.
c) The inventory may not include all the products used in bridge projects.

3.2. LCCA Guidelines For Bridges

Life-Cycle Cost Analysis (LCCA) is "an engineering economic analysis tool useful in comparing the relative merit of competing implementation alternatives" (FHWA, 2002). It helps the transportation agencies to consider the different alternative's cost incurred during the service life of a project and opt for the best performance option with the lowest cost. For example, LCCA will help finding out whether the use of high-performance concrete in a bridge project, which may add to the initial cost but result in reduced maintenance cost, is cost-effective or not.

These guidelines for conducting LCCA of sustainable bridges will educate to consider not only the initial costs in planning, design and construction of a bridge but also long-term costs, including operation, repair and maintenance etc. This section includes defining LCCA for bridges, estimating the accurate input parameters, generic approach for conducting LCCA. A review of the available and significant LCCA models is presented as well. Towards the end, the section discusses the case studies on the application of LCCA in deciding the best alternative for a project.

3.2.1. LCCA methodologies and procedure

a life-cycle cost analysis (LCCA) include:

1. Determine performance periods and activity timing.
2. Establish alternative bridge design strategies for the analysis period.
3. Estimate agency costs.
4. Estimate user costs.
5. Develop expenditure stream diagrams.
6. Compute net present value and analyze the results.

While the steps are generally sequential, the sequence can be altered to meet specific LCCA needs. The following sections discuss each step.

1. Determine performance periods and activity timing.

The initial bridge design and subsequent rehabilitation/replacement activities has a major impact on LCCA results. It directly affects the frequency of agency intervention on the project, which in turn affects the agency cost as well as user costs during periods of construction and maintenance activities.

The planning horizon or analysis period is a key variable. The time period should be selected on the basis of both the physical elements to be analyzed and the type of decision to be made. Generally the planning horizon should be at least as long as the best-estimate service life of the element (under normal maintenance) that is the primary focus of analysis; this element will then have a very low expected residual value in the base case at the end of the analysis period. The current service lives of highway bridges may be approximately 30 to 50 years, while AASHTO specifies the service life of new bridges should be 75 years.(Hawk, 2003)

Table 3.2. provides a useful information for bridge preservation activities. For example, a relatively short period may be adequate for determining when a deck overlay should be scheduled, while a longer period of two to three decades is more likely to be appropriate for deck replacement for a bridge.

Table 3.2: Bridge Preservation Activities

Preservation Action	Bridge Selection Criteria	Expected Service Life
Total Replacement	NBI Rating of 3 or less, or when cost of rehabilitation exceeds cost of replacement, or when bridge is scour critical with no countermeasures available	70 yrs
Superstructure Replacement	NBI Rating for Superstructure of 4 or less, or when cost of rehabilitating superstructure & deck exceeds replacement cost.	40 yrs
Deck Replacement	Use guidelines in MDOT's *Bridge Deck Preservation Matrix.*	
Epoxy Coated Steel	NBI Rating of 4 or less for deck surface and deck bottom, or when deck replacement cost is competitive with rehabilitation.	70 yrs
Black Steel		40 yrs
Substructure Replacement **(Full or Partial)**	NBI Rating of 4 or less for abutments, piers, or pier cap, or there is existence of open vertical cracks, signs of differential settlement. Presence of active movement, or bridge is scour critical with no countermeasures available.	40 yrs

Table 3.2 (cont.): Bridge Preservation Activities

Concrete Deck Overlays	Guidelines in MDOT's Bridge Deck Preservation Matrix	
Deep	NBI Deck Rating < 5 for surface and > 5 for bottom	25 yrs
Shallow	NBI Deck Rating < 5 for surface and > 4 for bottom	12 yrs
HMA /Membrane	NBI Deck Rating < 5 for surface and > 4 for bottom	8 yrs
HMA Cap	NBI Deck Rating < 5 for surface and < 4 for bottom	3 yrs
Complete Painting	NBI Rating for paint condition is 3 or lower, or in response to Inspector's work recommendation for complete painting	15 yrs
Zone Painting	NBI Rating for paint condition is 5 or 4, or less than 15% of existing paint area has failed and remainder of paint system is in good or fair condition.	10 yrs
HMA Overlay Cap without Membrane	NBI Rating of 3 or less for deck surface and deck bottom. Temporary holdover to improve rideability for a bridge in the 5 year plan.	3 yrs

2. Establish alternative bridge design strategies for the analysis period.

The second step in conducting the LCCA of bridges is to define the alternative design for the analysis period under consideration and evaluate the alternative against the base case. The alternatives must be developed in adequate detail to derive good cost estimates, which are required to run the life cycle cost calculations and to capture the incremental cost differences of the options. Any number of alternatives can be developed for a project. The goal should be to develop roughly two to three alternatives for a project.

Typically, each design alternative will have an expected initial design life, periodic maintenance treatments, and possibly a series of rehabilitation activities. It is important to identify the scope, timing, and cost of these activities (FHWA, 1998).

3. Estimate Agency Cost

The agency costs are defined as “all those costs associated with the alternatives, incurred by the agency during the analysis period”(Hall, 2003). According to Bridge LCCA, guidance manual (Hawk, 2003), the key agency costs typically include:

- Design, engineering and regulatory,
- Acquisitions, takings and other compensation,
- Construction,
- Maintenance and repair,
- Contract incentives and disincentives,
- Demolition, removal and remediation,
- Inspections,
- Site and administration services,
- Replacement and rehabilitation and
- Miscellaneous agency actions.

The additional detailed discussions of agency costs are provided in the Bridge LCCA Guidance Manual. The primary step in estimating agency costs is to determine construction quantities/unit prices. Unit prices can be determined from historical data on previously bid jobs of comparable scale. Only those agency costs that are significantly different for the different alternatives need to be considered in the life-cycle cost analysis (Hall, 2003). Engineering and administration costs, for example, may be excluded if they are the same for all alternatives. Rehabilitation and maintenance costs depend not only on the types and quantities of materials and work items, but also on the traffic control plan (detours, lane closures, work hours, etc.) selected for each alternative. Different traffic control plans may have different risks of accident costs, including costs to the agency.

4. Estimate User Cost

User costs are defined as "*the costs incurred by the user over the life of the project*". User costs are an aggregation of the following cost components (Hawk, 2003)

- Traffic congestion delays,
- Traffic detours and delay-induced diversions,
- Highway vehicle damage,
- Environmental damage,
- Business effect and
- Miscellaneous routine user actions.

More precise discussion of user costs is provided in Bridge LCCA Guidance Manual. Furthermore, computer programs such as NCHRP's Bridge Life Cycle Cost Analysis (BLCCA) software are also available for use in analyzing user costs for bridge highway projects.

5. Develop expenditure stream diagram

These diagrams are graphical representations of expenditures over time and are commonly developed for each design strategy in visualizing the extent and timing of expenditures.

Figure 3.2. shows a typical expenditure stream diagram. The expenses associated with each project alternative are sketched along the vertical axis while the horizontal axis represents the related time. Under these conditions, the LCCA objective becomes finding the alternative design strategy that meets the best performance requirements at the lowest life-cycle cost.

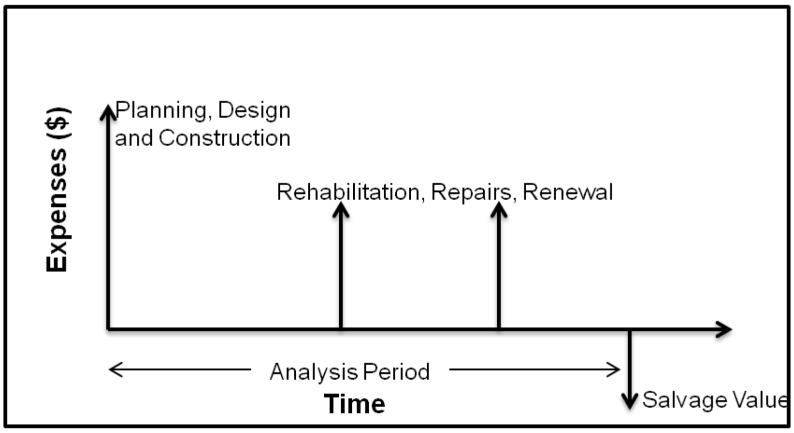


Figure 3.2: Expenditure Stream Diagram

6. Compute Net Present Value (NPV)

All the alternatives considered in a life-cycle cost analysis needs to be compared using a common measure of economic worth. The economic worth of an investment may be measured using NPV:

Net Present Value: the conversion of all cash flows, using a discount rate, to an equivalent single sum at time zero in Eqution 3.1.

$$NPV = FV / (1 + DR)^{N} \qquad \textbf{3.1}$$

where, NPV = Net Present Value

FV = Future Value of an expenditure made at time N

DR = Discount Rate

N = Number of periods between NPV and FV

Discount Rate: The rate used to discount future cash flows to the present value is a key variable of this process. The discount rates are used to determine discount factors. A discount factor is the present value of $1 received at a stated future date. To calculate a discount factor, the following formula may be used:

$$\text{Discount Factor} = [\ 1 / (1+DR)^{N})\ ] \qquad \textbf{3.2}$$

From Equation 3.2, the value of $1 two years from now at a discount rate of 4% yields a discount factor of 0.9246. All modules of the LCC used discount factors to determine present values.

Once completed, all LCCA should, at a minimum, be subjected to a sensitivity analysis. Sensitivity analysis is a technique used to determine the influence of major LCCA input assumptions, projections, and estimates on LCCA results. In a sensitivity analysis, major input values are varied (either within some percentage of the initial value or over a range of values) while all other input values remain constant and the amount of change in results is noted. The input variables may then be ranked according to their effect on results. Sensitivity analysis allows the analyst to subjectively get a feel for the impact of the variability of individual inputs on overall LCCA results.

Many times a sensitivity analysis will focus on best case/worst case scenarios in an attempt to bracket outcomes. Most LCC sensitivity analysis, as a minimum, evaluates the influence of the discount rate used on LCCA results.

3.2.2. Key Steps

An in-depth discussion was provided here on the step-by-step procedure to conduct LCCA for bridges. The key steps in LCCA of bridges include establishment of bridge alternatives, defining a suitable analysis period, selection of an appropriate discount rate, precise estimation of agency and user costs and the different economic measures by which alternatives may be compared.

The LCCA of bridge alternatives allows the identification of economical approach that results the best decision, by providing the maximum performance at the lowest cost over the analysis period. Ideally, a comprehensive LCCA would consider quantitatively all of the costs incurred by both the agency and the users over the analysis period. However, some of these costs are difficult to quantify, necessitating some simplifications to the LCCA.

4. BRIDGE TYPES IN TURKEY

4.1. Introduction

Bridges have great importance for transportation network. The starting point of bridge project is to select the most appropriate bridge form for the site. Probably, the main goal about the selecting suitable structure type is to design a cost-effective bridge.

Bridges can classify into several groups which can state as according to form, material of construction, inter-span relationships, length of the bridge and according to function. The material that constituent of bridges have different types leads up to this classification and bridges are seperated into timber, concrete, stone, RCC, steel, PCC, aluminum and composite. The development process of load-bearing systems change their ways from based on compression systems to based on compression systems. From this reason timber was started to use and the other types of materials go after that progression. The earliest form of materials used for construction of bridges was first stone and later brick. The masonry bridges are used for short spans and according to availability of material and skilled labour. They are mainly of arch type of bridges. The next form of construction was Timber Bridge in which timber was used for spanning the gap and also for supporting the beams. Timber bridges are used for short spans, light loads and for use as temporary and unimportant bridges. With the invention and development of concrete, bridges are being built entirely with concrete, either reinforced or prestressed or a combination of both for superstructure.

Different types of bridge superstructures provide effective solution for different span adjustments. There are many possible reasons for choosing spesific span lengths. Owner desires, hard requirements (i.e. water crossings), location of existing constraints, site access, the desired consruction schedule may control span arrangements. Many bridge types are available for current construction. The various types are ideally suited to different span lengths. However, multiple bridge types are generally viable at most span ranges. The bridge types that globally used are listed below:

1. Rolled Beam Bridges
2. Welded Plate Girder Bridges
3. Trusses
4. Arches
5. Cable Stayed
6. Suspension Bridges

The other factor is economics which can affect the structure type selecting. Welded plate girders are currently the most common type of steel bridge in order to applicable in span lengths and provide the most cost-effective design because of lower fabrication and erection costs trusses and arches need. Trusses are not generally economic for span lengths under 150 meters arches used for the shorter span ranges are generally used mor efor aesthetic than cost-effectiveness. Cable-stayed bridges become very cost competetive for main span lengths over 250 meters. With the development of cable-stayed bridge technology, suspension bridges do not become economical until the main span length approaches 1000 meters (FHWA, 2012).

Besides cost-effectiveness, constructability is the factor that has large majority for bridge applications. Rolled beam and plate girder bridges are generally easily constructed. Stability of the girders during erection also becomes increasingly critical as the span lengths exceed 75 meters. Compared to deck girder structures, truss construction has a much more labor intensive process. Arches are more complex to erect than trusses or plate girders. The concern of this type may be the height of the arch. Cable-stayed bridges are becoming more common worldwide. One significant reason for this is that the erection methods required for cable-stayed bridges have become better understood over the recent years.

4.2. Bridge Types in Turkey

Bridges have major functions over the years both as transportation of people from one side to another and cross-continental parts. The first bridge that merges two continent in Istanbul, Asia and Europe, was completed in 1973 is Bosphorus Bridge also called the First Bosphorus Bridge which one of two suspension bidges spanning the Bosphorus strait. The Fatih Sultan Mehmet Bridge, also known as the Second Bosphorus bridge was completed in 1988 and at this time it was the 5th longest suspension bridge span in the world; today it is the 19th.

Besides new constructed bridges, Turkey has greatest historical bridges that stand for many centuries. The two of important illustrations of this are Taskopru and Malabadi Bridges. The Malabadi Bridge is an arch bridge spanning the Batman River. Construction began in the year 1146 during Artuqid period, and appears to have been completed in 1154 (Hillenbrand, 1979). It was once the only bridge across the river in this area, and was in continuous use until the 1950s, when a new road bridge was opened upstream. Taskopru is a Roman bridge spanning the Seyhan River. Throughout ancient Anatolia and Persia, the bridge was a vital contribution to the trade routes and until 2007, it was one of the oldest bridges in the world to be open to motorized vehicles.

The bridge types that frequently used in Turkey differ greatly. The main ones of which classified according to structural systems are girder bridges, truss, rigid frame bridges, arch bridges, cable-stayed bridges, suspension bridges.

4.2.1. Girder bridge

A girder bridge, in general, is a bridge built of girders placed on bridge abutments and foundation piers. (AINIIT, 2012) A girder bridge is the most common and most basic bridge. In modern girder steel bridges, the two most common girders are I-beam girders and box-girders. A girder bridge only requires a rigid beam, and two supports at each end to rest upon it. These components are what allows the downward weight of the bridge and any traffic to travel across it. Many girder bridges utilize concrete or steel beams to fortify the structure and properly handle the load. Both the size and height of the beam controls the distance that the beam can span. By increasing the height of the beam, the beam has more material and thus more easily able to dissipate any tension exerted on the foundation.

There are several types of girder bridges which are rolled steel girder bridge, plate girder bridge, concrete girder bridge, box girder bridge, I-beam bridge. In modern steel girder bridges, the most common girders are I-beam girders and box-girders. Girder bridges have existed for millennia in a variety of forms depending on resources available. The oldest types of bridges are the beam, arch and swing bridges, and they are still built today. Torbalı Ismetpasa Railway Overpass, Izmir; Muradiye Bridge, Rize; Oltu Bridge, Erzurum are the examples of this type of bridges from Turkey.

Flexure or bending between vertical supports is the main structural action in this type. Plate girder bridges are adopted for simply supported spans less than 50 m and box girders for continuous spans upto 250 m.

4.2.2. Truss bridge

A truss bridge is a bridge whose load-bearing superstructure is composed of a truss, a structure of connected elements forming triangular units. The connected elements (typically straight) may be stressed from tension, compression, or sometimes both in response to dynamic loads. Truss bridges are one of the oldest types of modern bridges. A truss bridge is economical to construct because it uses materials efficiently. The nature of a truss allows the analysis of the structure using a few assumptions according to statics. For purposes of analysis, trusses are assumed to be pin jointed where the straight components meet. This assumption means that member of the truss will act only in tension or compression.

Like the girder bridges, there are both simple and continuous trusses. The small size of individual parts of a truss make it the ideal bridge for places where large parts or sections cannot be shipped or where large cranes and heavy equipment cannot be used during erection. Because the truss is a hollow skeletal structure, the roadway may pass over or even though the structure allowing clearance below the bridge often not possible with other bridge types. Adana Demirkopru is an example for this type of bridges from Turkey.

4.2.3. Rigid frame bridge

Rigid-frame bridges (also known Rahmen bridges) are a bridge type made up of groups of rigidly connected members on which bending moment, axial force, and shear force work at the same time. Rigid frame bridges are suitable in the span range of 25m to 200m.

The cross sections of the beams in a rigid frame bridge are usually I shaped or box shaped. Design calculations for rigid frame bridges are more difficult than those of simple girder bridges. The junction of the pier and the girder can be difficult to fabricate and requires accuracy and attention to detail. Though there are many possible shapes, the styles used almost exclusively these days are the pi-shaped frame, the batter post frame, and the V shaped frame.

In the selection of a bridge type, especially for a crossing over an intersecting railroad, street or highway, an important factor to consider is the approach fills at the ends of the bridge. Although not true in every case, the approaches can usually be constructed more economically if the grade is as low as possible. The limitting factor is in most cases the clearance required under the bridge. By using a rigid frame bridge the required clearance can be obtained with very economical approaches. (Palmer, 1930)

4.2.4. Arch bridges

After girders, arches are the second oldest bridge type and a classic structure. Unlike simple girder bridges, arches are well suited to the use of stone. Many ancient and well know examples of stone arches still stand to this day. Arches are good choices for crossing valleys and rivers since the arch doesn't require piers in the center. Arches can be one of the more beautiful bridge types.

An arch bridge is a bridge with abutments at each end shaped as a curved arch. Arch bridges work by transferring the weight of the bridge and its loads partially into a horizontal thrust restrained by the abutments at either side. The loads are transferred to the foundations by arches acting as the main structural element. Axial compression in arch rib is the main force, combined with some bending. Arch bridges are competitive in span range of 200 m to 500 m.

Like the truss, the roadway may pass over or through an arch or in some cases both. Structurally there are four basic arch types: hinge-less, two-hinged, three-hinged and tied arches. Akkopru, Ankara; Talazan Bridge, Tokat are historical example of this type bridges from Turkey.

4.2.5. Cable stayed bridges

Cable-Stayed bridges rely on high strength steel cables as major structural elements. The stay cables are inclined from the supporting towers to edge girders at or below the deck elevation. These bridges are generally signature structures with excellent aesthetics characterized by very slender superstructures and tall towers (FHWA, 2012).

A typical cable-stayed bridge is a continuous girder with one or more towers erected above piers in the middle of the span. From these towers, cables strecth down diagonally(usually to both sides) and support the girder. Steel cables are extremely strong but very flexible. Steel cables are extremely strong but very flexible. Cables are very economical as they allow a slender and lighter structure which is still able to span great distances. Though only a few cables are strong enough to support the entire bridge, their flexibility makes them weak to a force we rarely consider: the wind. For longer span cable-stayed bridges, careful studies must be made to guarantee the stability of the cables and the bridge in the wind.

There are no distinct classifications for cable-stayed bridges. However, they can distinguished by the number of spans, number of towers, girder type, number of cables, etc. There are many variations in the number and type of towers, as well as the number and arrangement of cables. Typical towers used are single, double, portal, or even A-shaped towers. Cable arrangements also vary greatly. Some typical varieties are mono, harp, fan, and star arrangements. In some cases, only the cables on one side of the tower are attached to the girder, the other side being anchored to a foundation or other counterweight. Nissibi Bridge, Adıyaman; Zeynel Senol Bridge, Antalya can be shown as examples.

4.2.6. Suspension bridge

Of all the bridge types in use today, the suspension bridge allows for the longest spans. At first glance the suspension and cable-stayed bridges may look similar, but they are quite different. Suspension bridges are leading long span technology today. The development of metals brought the use of linked iron bars and chains. But it was the introduction of steel wire ropes that allowed spans of over 500m to become a reality. Today the Akashi Kaikyo bridge boasts the world's longest center span of any bridge at 1,991 meters.

A suspension bridge is a type of bridge in which the deck (the load-bearing portion) is hung below suspension cables on vertical suspenders. This type of bridge has cables suspended between towers, plus vertical suspender cables that carry the weight of the deck below, upon which traffic crosses. This arrangement allows the deck to be level or to arc upward for additional clearance. The suspension cables must be anchored at each end of the bridge, since any load applied to the bridge is transformed into a tension in these main cables. The main cables continue beyond the pillars to deck-level supports, and further continue to connections with anchors in the ground.

The main forces in a suspension bridge of any type are tension in the cables and compression in the pillars. Since almost all the force on the pillars is vertically downwards and they are also stabilized by the main cables, the pillars can be made quite slender. The remarkable examples of suspension bridges in Turkey are the Bosphorus Bridge and the Fatih Sultan Mehmet Bridge.

5. REPRESENTATIVE BRIDGE MODELS

In this Chapter, Bridge models are presented. Representative bridges are modeled with SAP2000. Modeled bridges are analyzed and evaluated. 2, 4, and 5 span bridges are considered in the analyses. Structural analyses were carried out with different material properties of the bridges.

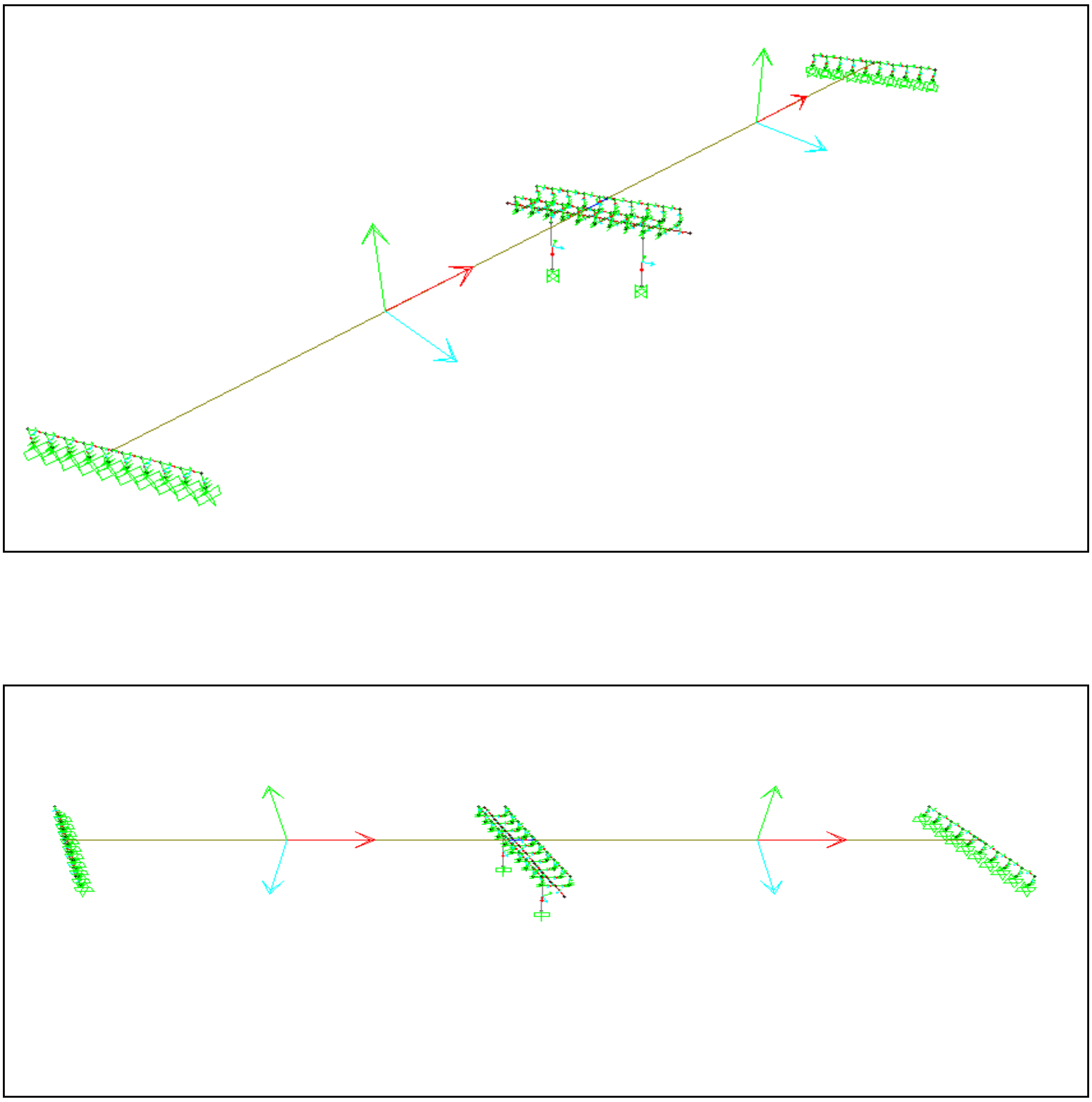
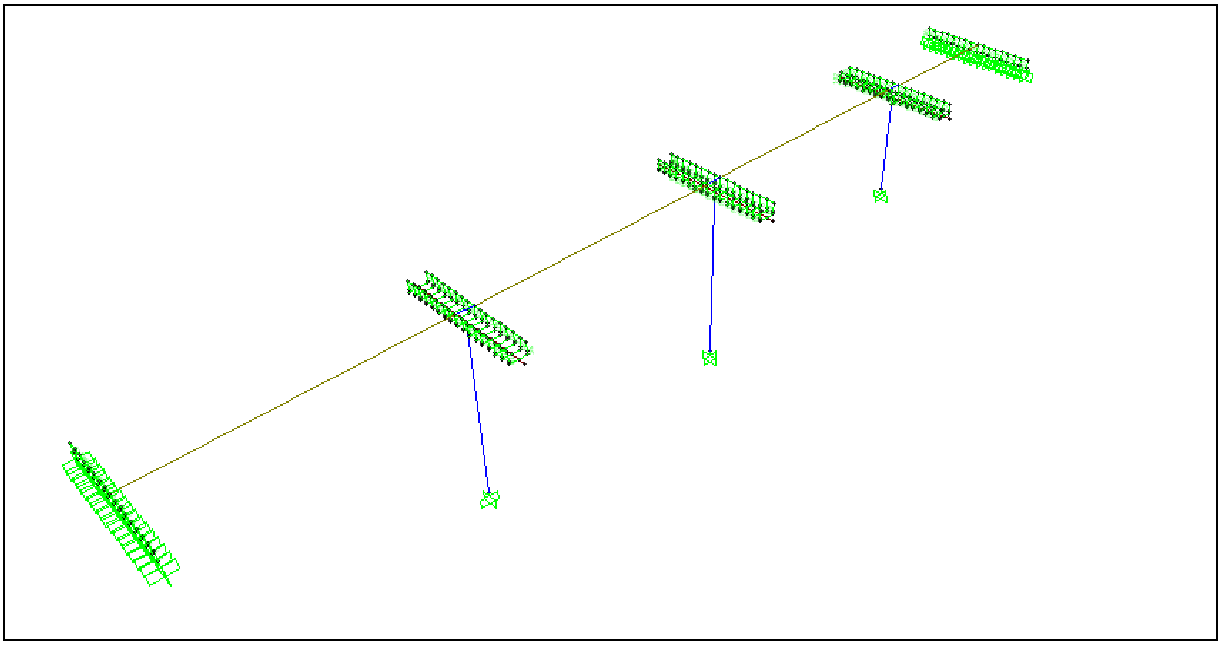


Figure 5.1: Two Span Bridge Model.



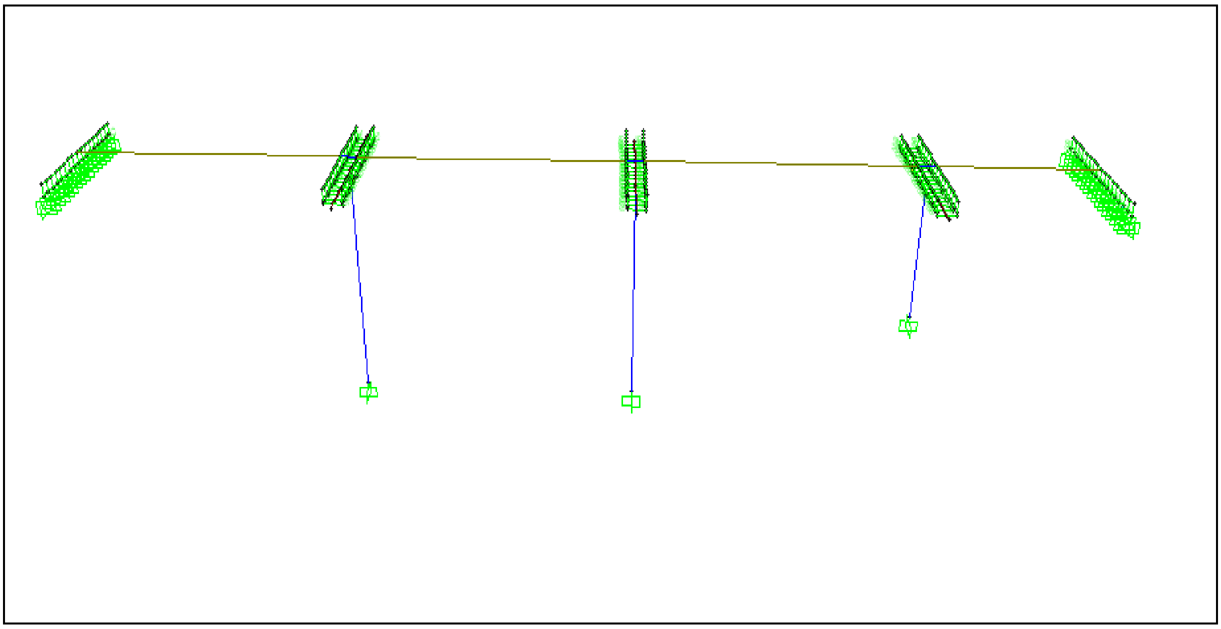


Figure 5.2: Four Span Bridge Model.

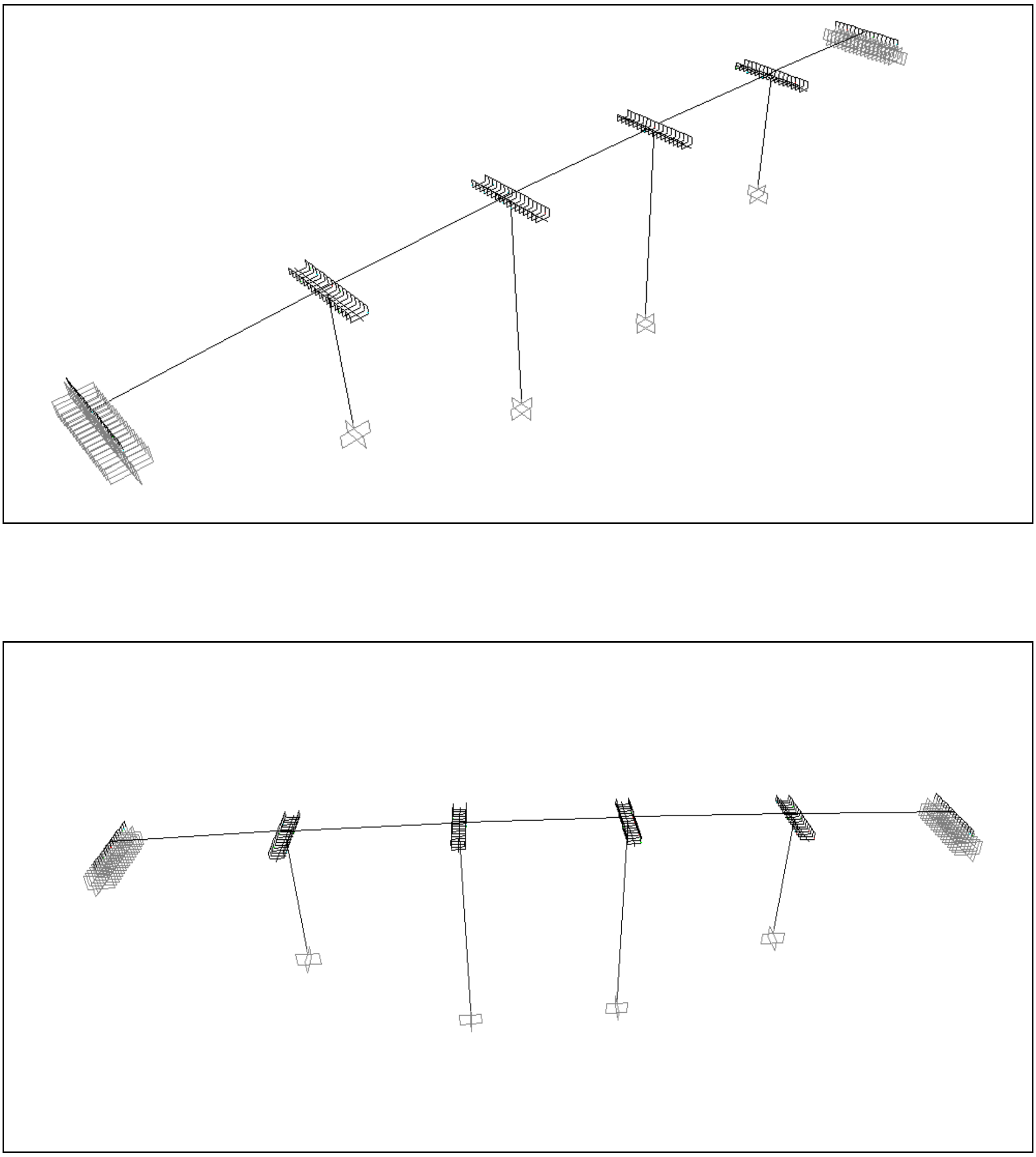


Figure 5.3: Five Span Bridge Model.

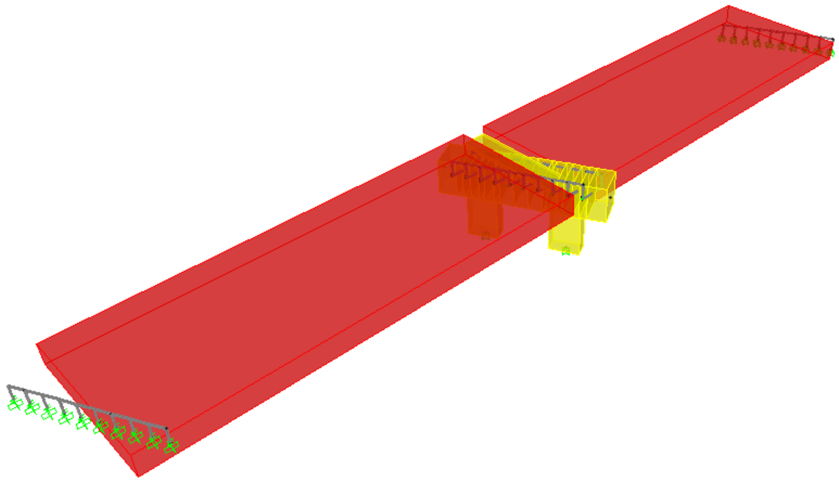


Figure 5.4: Two Span Bridge Model 3D View.

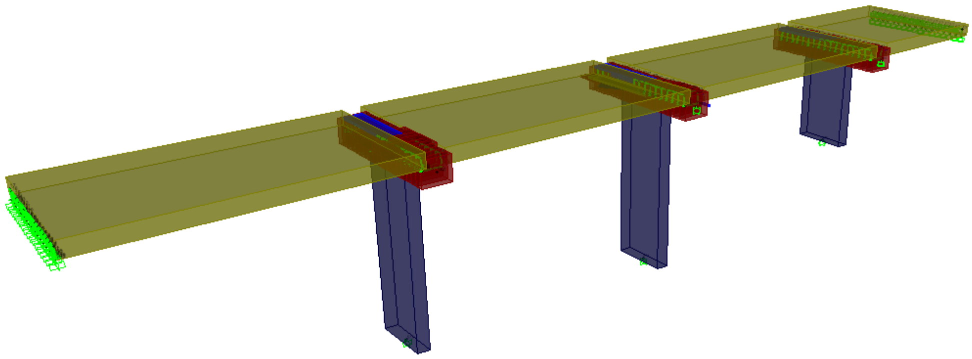


Figure 5.5: Four Span Bridge Model 3D View.

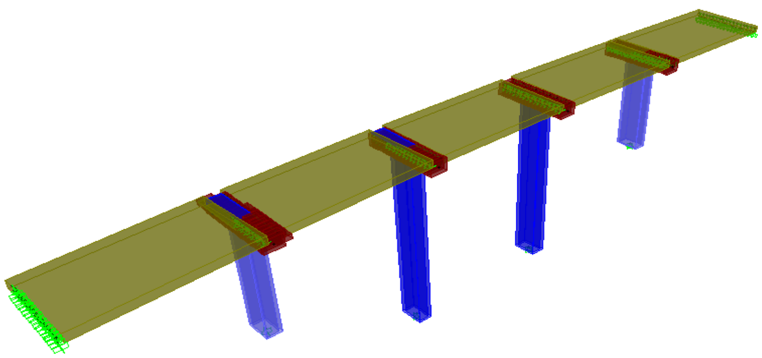


Figure 5.6: Five Span Bridge Model 3D View.

6. SAP2000 MODELLING OF BRIDGES

6.1. Brief Introduction on SAP2000

SAP 2000 is software that enables the analysis and design of bridge structures. Complex bridge structures can be modeled effortlessly, which makes SAP 2000 one of the most popular computer programs in the construction business. Complex bridge parameters can be defined directly: such as geometry, boundary conditions, load cases, spans, bearings, abutments, bents, hinges and they are updated automatically as the bridge parameters alter. Loads, lanes and vehicles can be defined swiftly and include width effects.

The design of the bridge starts with the analysis, followed by the design check and finally, the optimization. This sequence is repeated until a fulfilling design is achieved.

6.2. Design Parameters

The example that was considered has these properties:

Spans: two-span 27.432m – 27.432m continuous bridge

Plate girders: 4 plate girders spaced at 3.048m and 1.0668m overhangs

Roadway width: concrete deck of 10.3632m and is centered over the girders

Reinforced concrete deck thickness: 21.59cm of normal weight with a compressive strength of 27.58 MPa. It is reinforced with nominal S420 reinforcing steel.

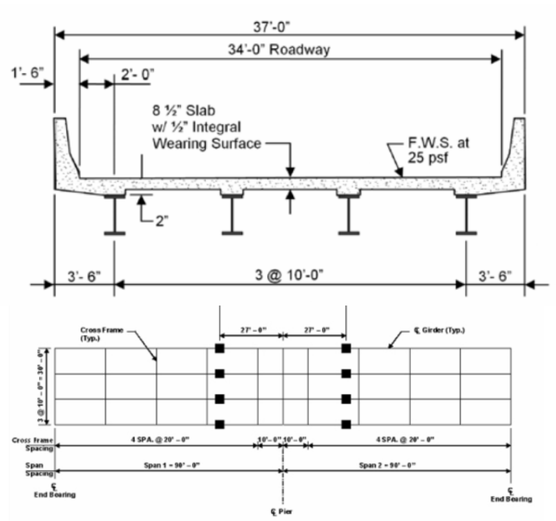
Integral wearing surface: 1.27cm thick

Haunch thickness: 5.08cm thick

Structural steel: ASTM A615, S420

Design specifications: AASHTO LRFD 2007

Assumptions: the girders are designed assuming composite action with the concrete slab.



Bridge Cross Section　　　　　　　　Framing plan

Figure 6.1: Bridge Section and Framing Plan.

To complete a bridge analysis in SAP2000, the following process is in general adopted:

- Start by creating the model using the bridge modeler, it can be accessed from the menu bridge commands or from the bridge wizard.
- Define the layout lanes.
- Define the lanes.
- Define the materials.
- Define the section and assign the materials.
- Define the bridge components: diaphragms, bearings, restrainers, foundations springs, abutments, bents.
- Define the vehicle classes.
- Define the load combinations.
- To analyze the results, use the **Display menu> Show forces/Stress** command to review the bridge response after an analysis and design have been performed.

The framework in which the bridge is performed is as follow:

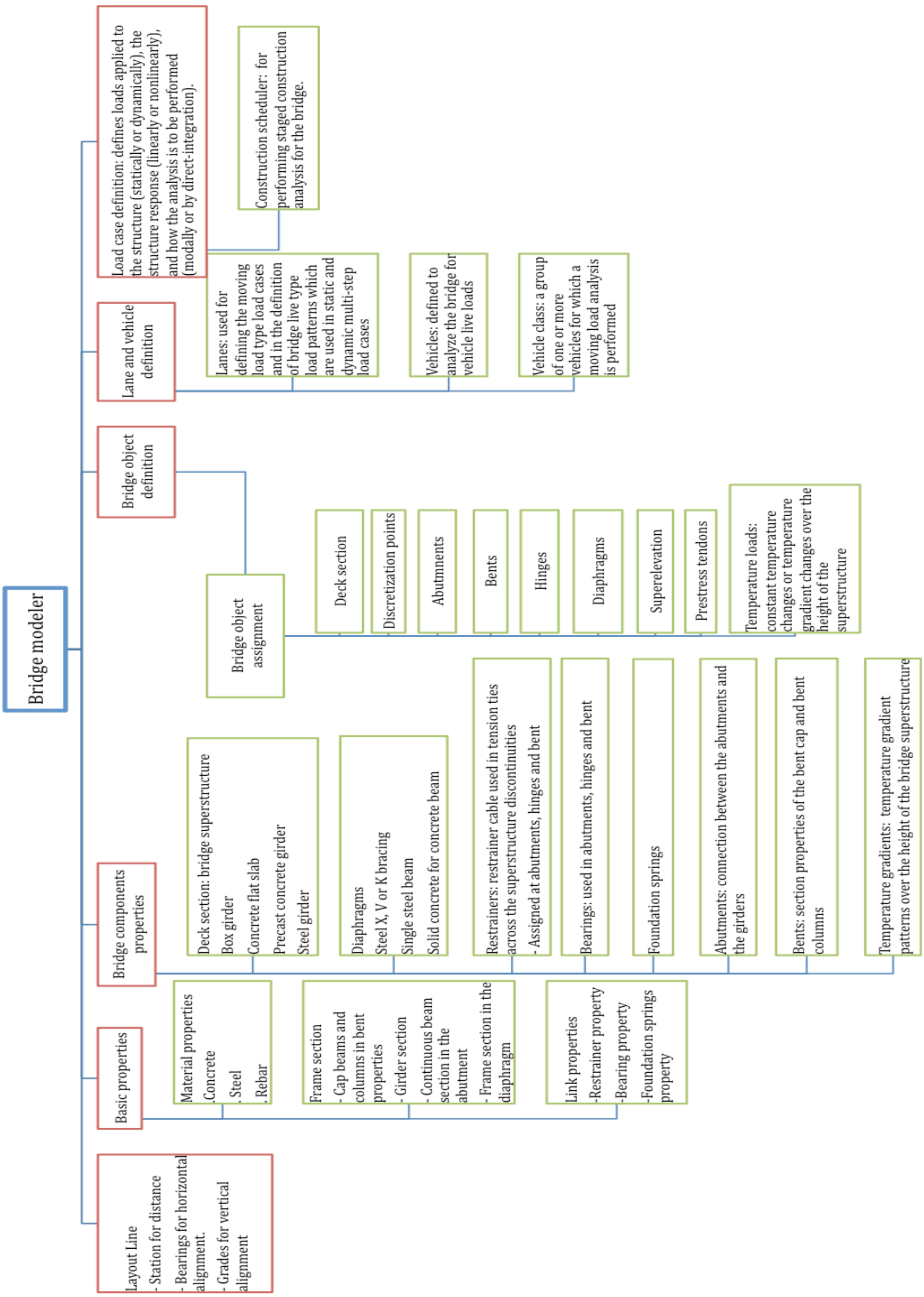


Figure 6.2: Bridge Model Definition with SAP2000.

6.3. New Model

This part shows the steps that are necessary to create the bridge model. The formation of the bridge initiate with using the **Quick Bridge** template.

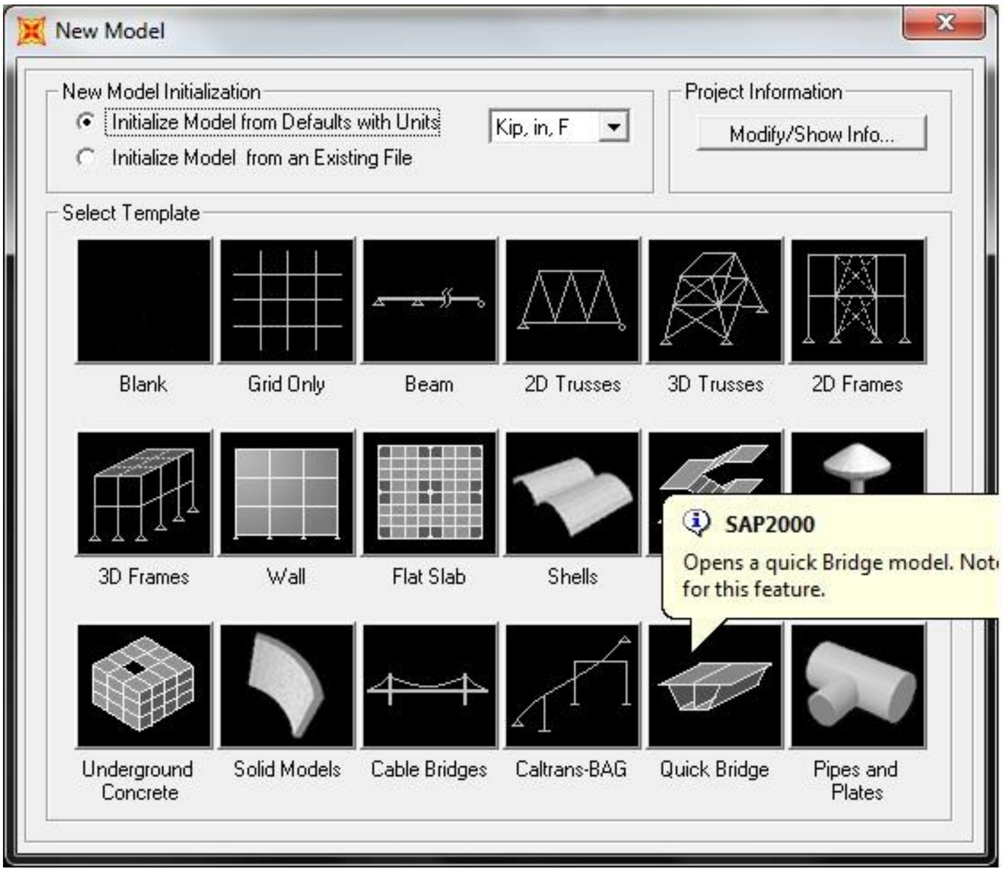


Figure 6.3: New Model Form.

From the Quick Bridge Template, we choose the steel girder option.

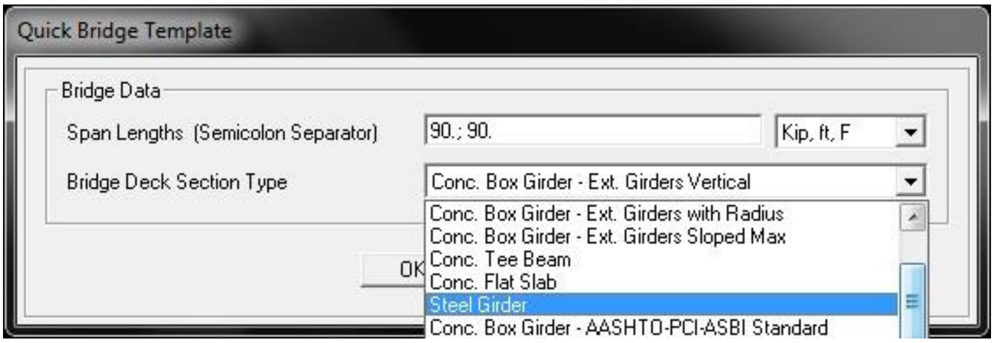


Figure 6.4: Quick Bridge Template.

6.3.1. Layout definition

The first process in creating a bridge object is to define the layout line. At least one layout line and one deck section must be defined before a bridge object can be defined. Also, a layout line (or frame objects) must exist in the model before lanes can be defined. Layout lines are reference lines used for defining the horizontal and vertical alignment of the bridge and the vehicle lanes.

From the Bridge **Menu>Layout Lines** command, the Bridge Layout Line can be defined. They are used for defining the horizontal and vertical alignment of the bridge and the vehicle lanes. Layout lines are defined using stations for distance, bearings for horizontal alignment, and grades for vertical alignment.

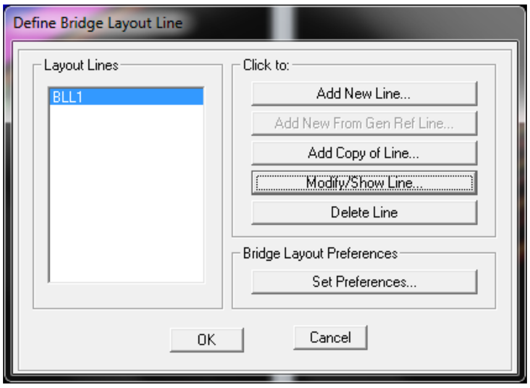


Figure 6.5: Definition of Bridge Layout Line

The **Modify/Show Line** command displays the Bridge Layout Line Data. It is recommended to define the axis of the bridge in the West/East direction. This way, the bridge is oriented from left to right. For this example, the layout line is straight.

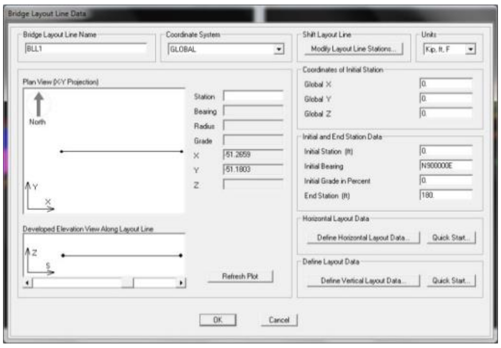


Figure 6.6: Specify Layout Line Data

6.3.2. Lanes definition

Lanes must be defined if you want to analyze the bridge for vehicle live loads.

The **Bridge menu>Lanes** command displays the Lanes definition. The traffic lane is defined with respect to a reference line. The program has created two lanes; the lane data includes two lines that define the start and end stations, centerline offset and lane width.

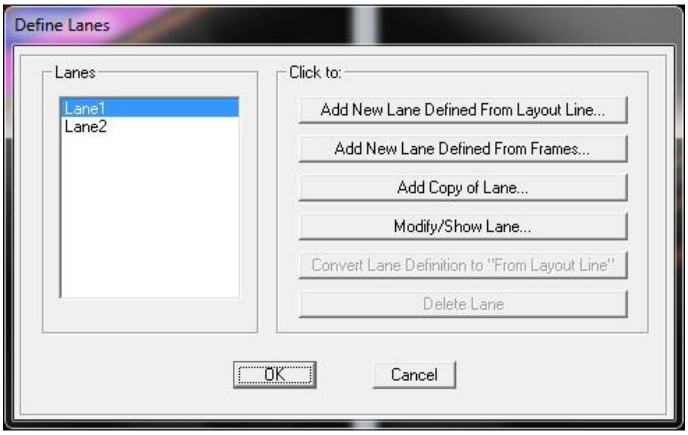


Figure 6.7: Lane Definition.

The **Modify/Show Lane** command displays the bridge Lane data. In this example, two 12 foot-wide lanes are added as follow:

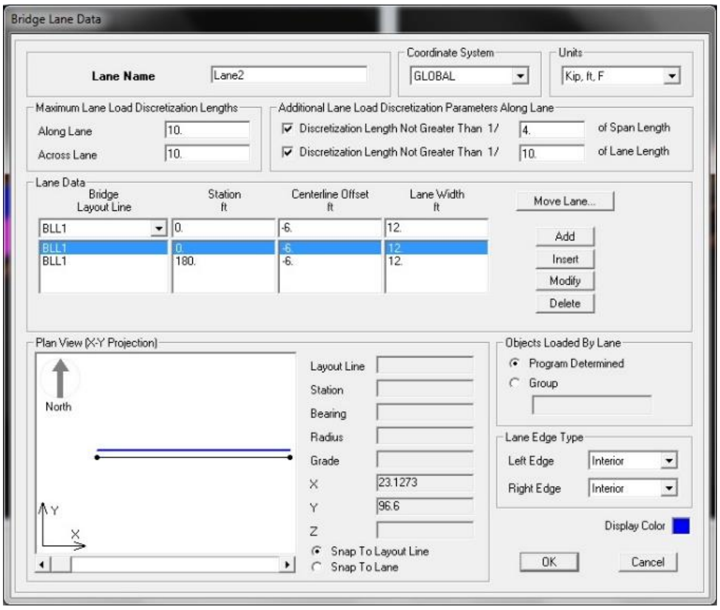


Figure 6.8: Bridge Lane Data form.

6.3.3. Deck section definition

Deck sections are used to define the bridge superstructure. Many deck sections can be chosen from depending on the design.

The **Bridge Menu>Deck sections** command displays the bridge deck section definition. A new section is added by clicking on the “Add new section” button”.

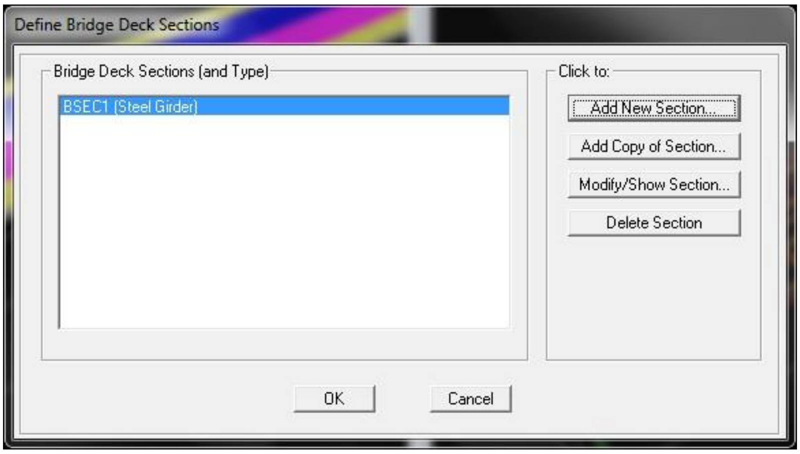


Figure 6.9: Deck Selection

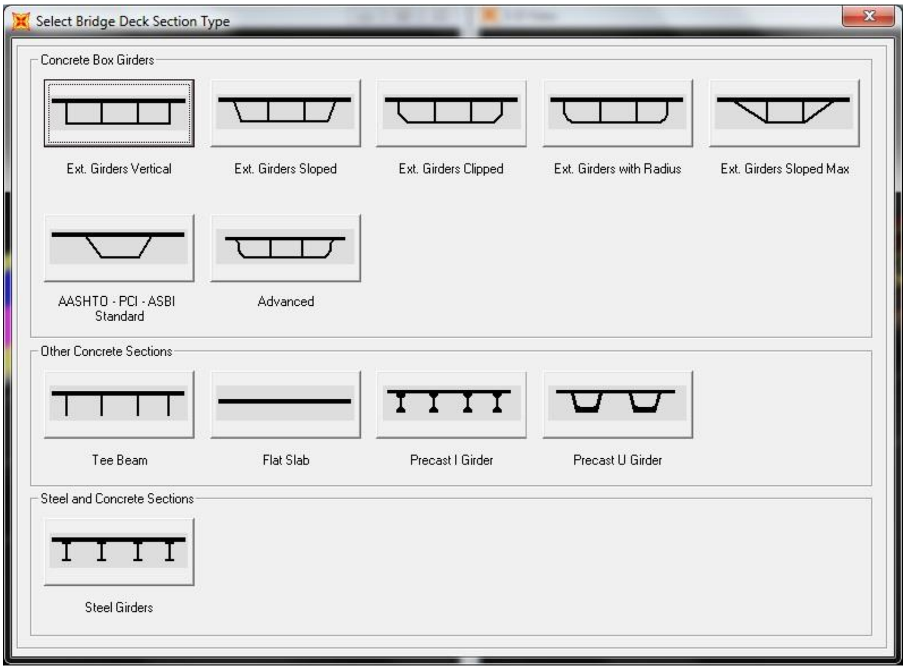


Figure 6.10: Select a Bridge Deck Section.

6.4. Lanes Definition

Lanes must be defined if it is desirable to analyze the bridge for vehicle live loads.

The **Bridge menu>Lanes** command exhibits the Lanes definition. The traffic lane is defined with respect to a reference line. The program has created two lanes; the lane data includes two lines that define the start and end stations, centerline offset and lane width.

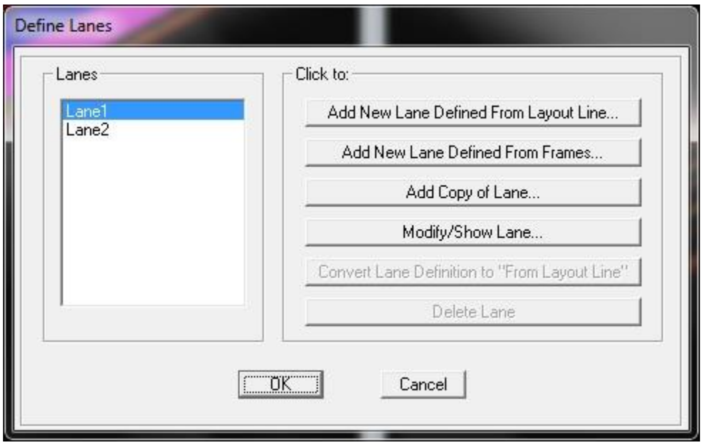


Figure 6.11: Lanes Definition Form.

The **Modify/Show Lane** command displays the bridge Lane data. In this example, two 12 foot-wide lanes are added as follows:

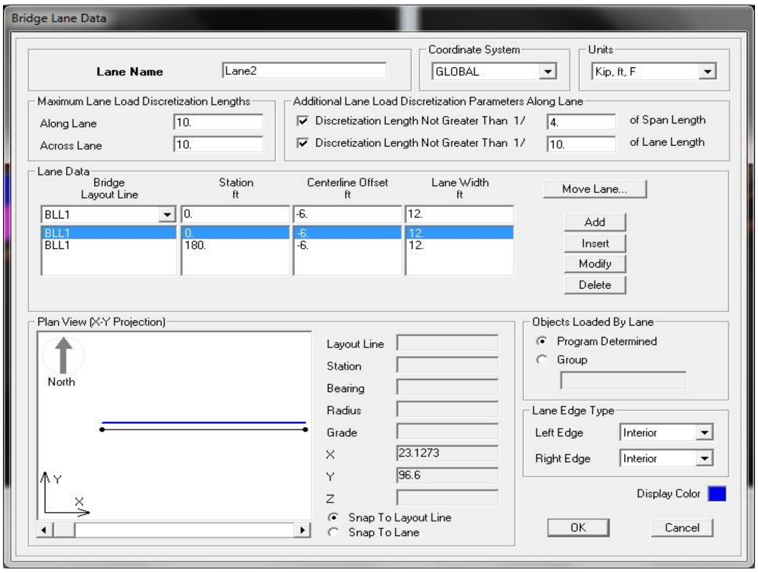


Figure 6.12: Lane Modification.

6.5. Deck Section Definition

Deck sections are used to define the bridge superstructure. Many different deck sections can be chosen, depending on the type of the design.

The **Bridge Menu>Deck sections** command displays the bridge deck section definition. A new section is added by clicking on the "Add new section" button".

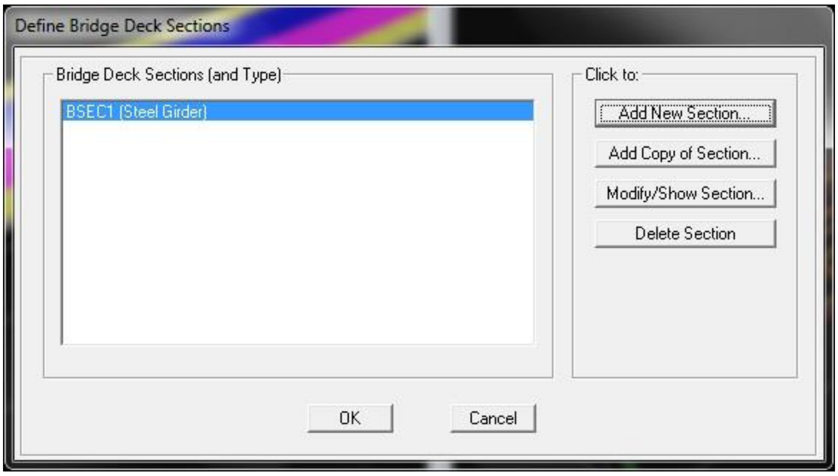


Figure 6.13: Bridge Deck Section.

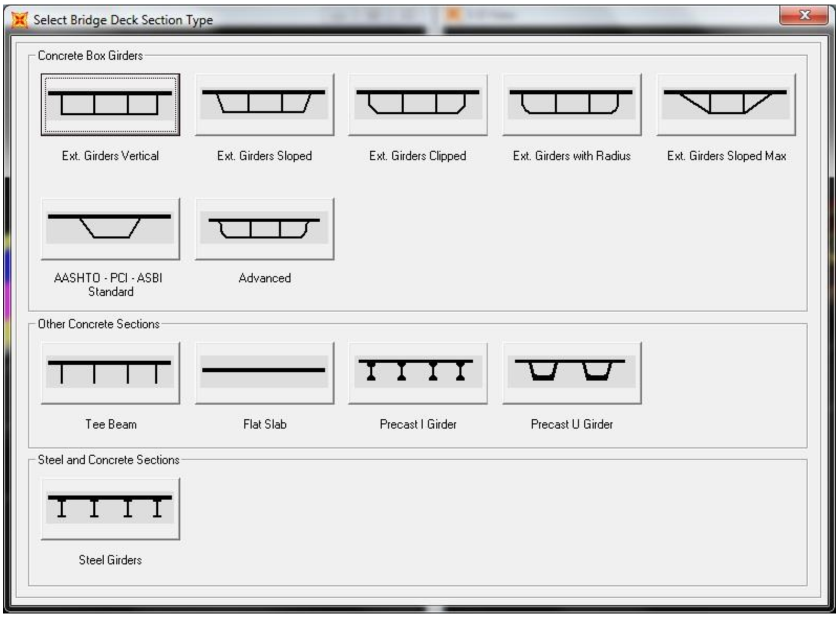


Figure 6.14: Select a Bridge Deck Section.

The **Define Bridge Section Data** form is used to define the specific material properties and geometries that represent the superstructure deck section. After the defining process, it can be assigned to a Bridge Object.

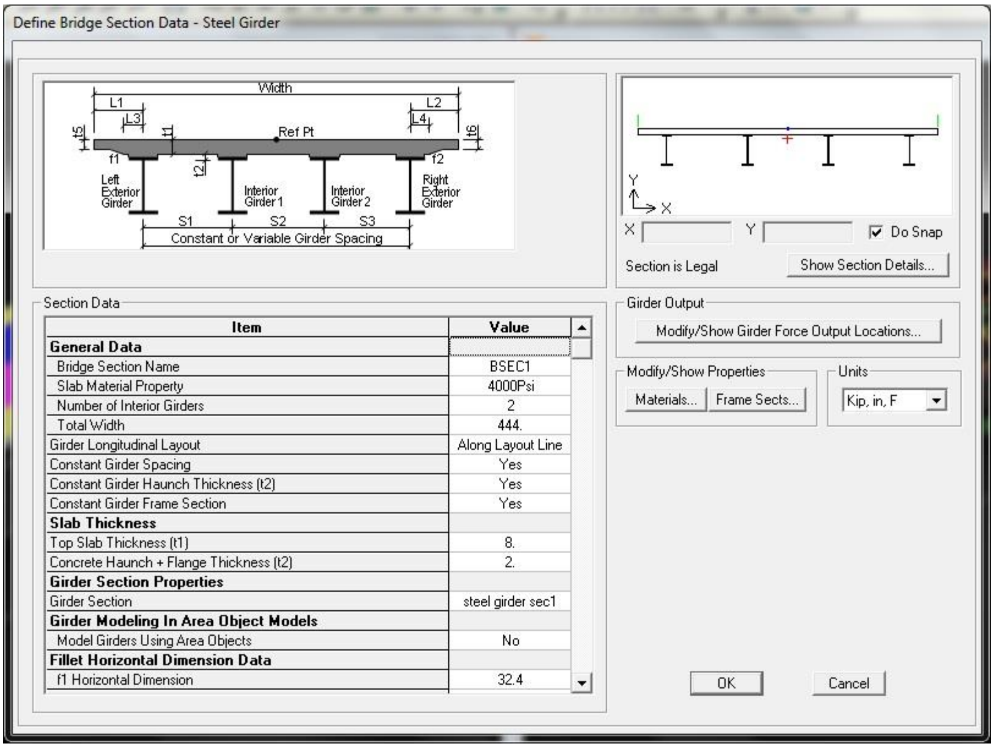


Figure 6.15: Specify The Deck Section Properties.

6.6. Material Definition

The **Define Menu>Materials** command displays the materials definition, one for concrete and one for the steel.

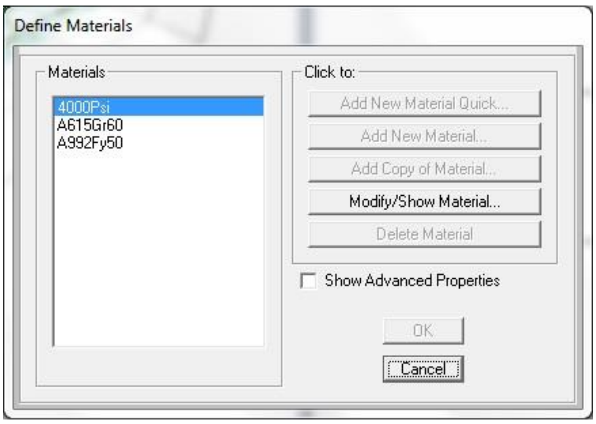


Figure 6.16: Specify The Type of Material Used.

The **Modify/Show material** button shows the material properties and permits to change the data. To add new material, the **Add New Material Quick** allows to choose from different types of materials.

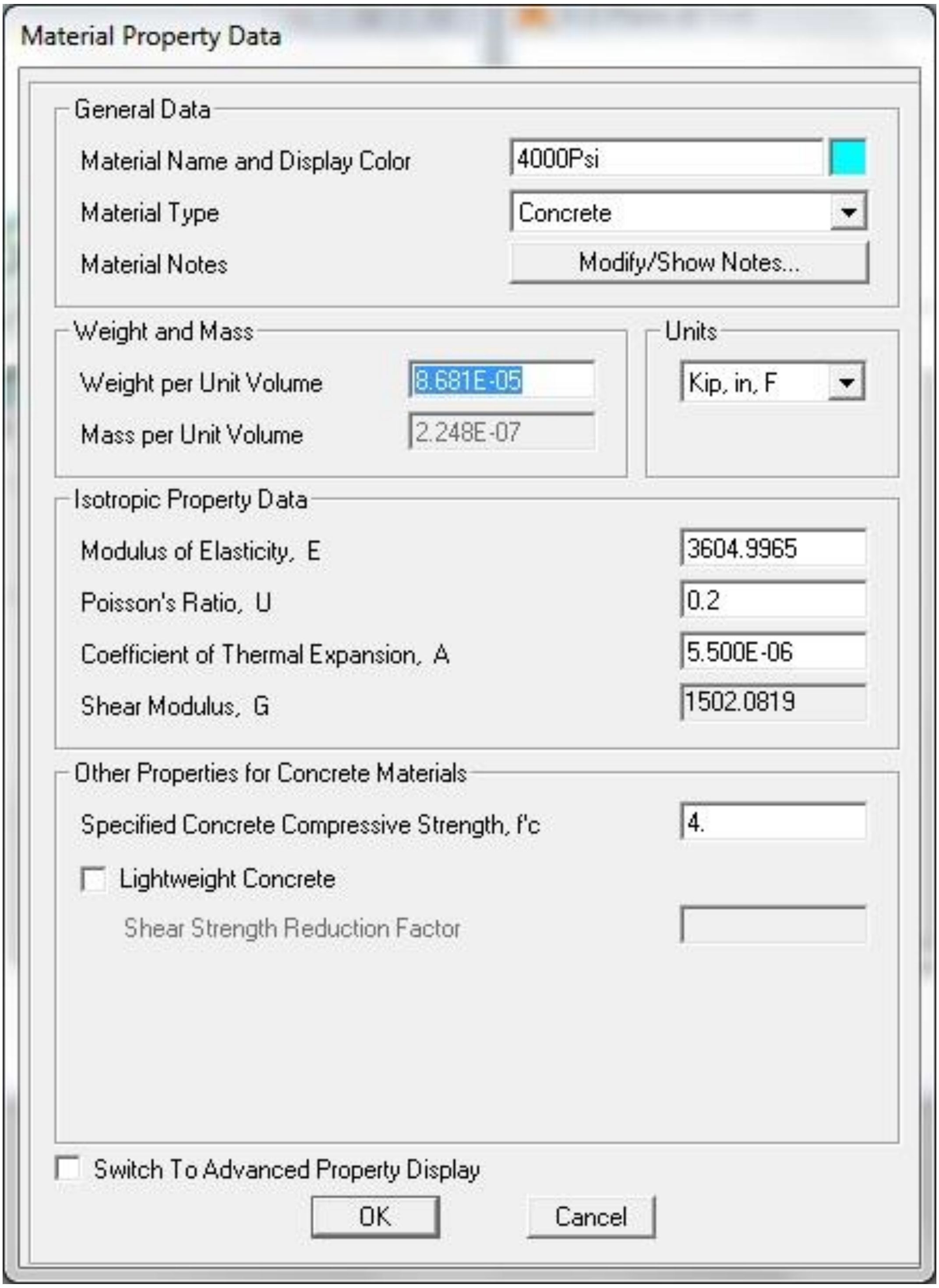


Figure 6.17: Concrete Properties Definition.

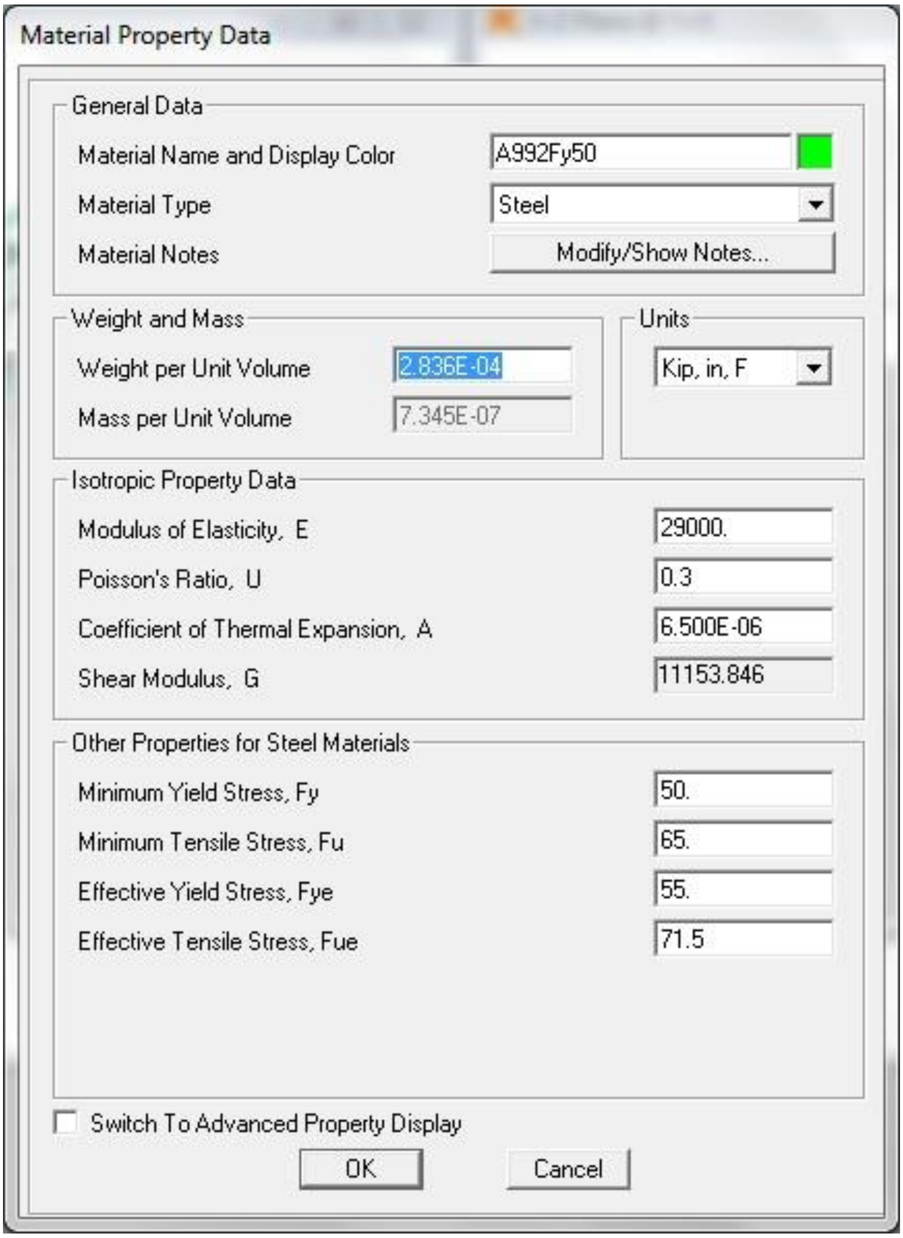


Figure 6.18: Steel Properties Definition.

6.7. Diaphragms

A diaphragm assignment includes a location, property, and orientation. In-span diaphragms are assigned as part of the Bridge Object definition. Diaphragms that take place at abutments, bents and hinges are assigned as part of the bridge object abutment, bent and hinge assignments, respectively.

From **Bridge menu>Diaphragm**, the Bridge diaphragm could be defined. **Add new diaphragm** button creates a new one. The **Modify/Show diaphragm** button allows the modification of its properties and parameters.

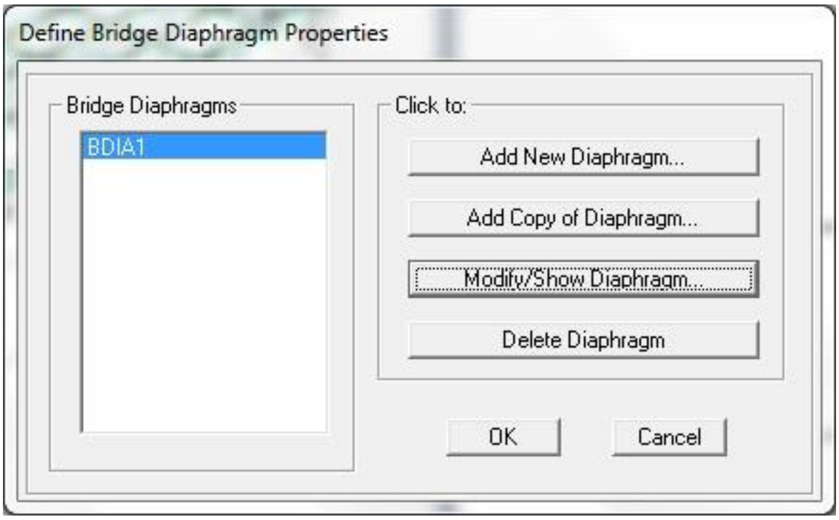


Figure 6.19: Bridge Diaphragm.

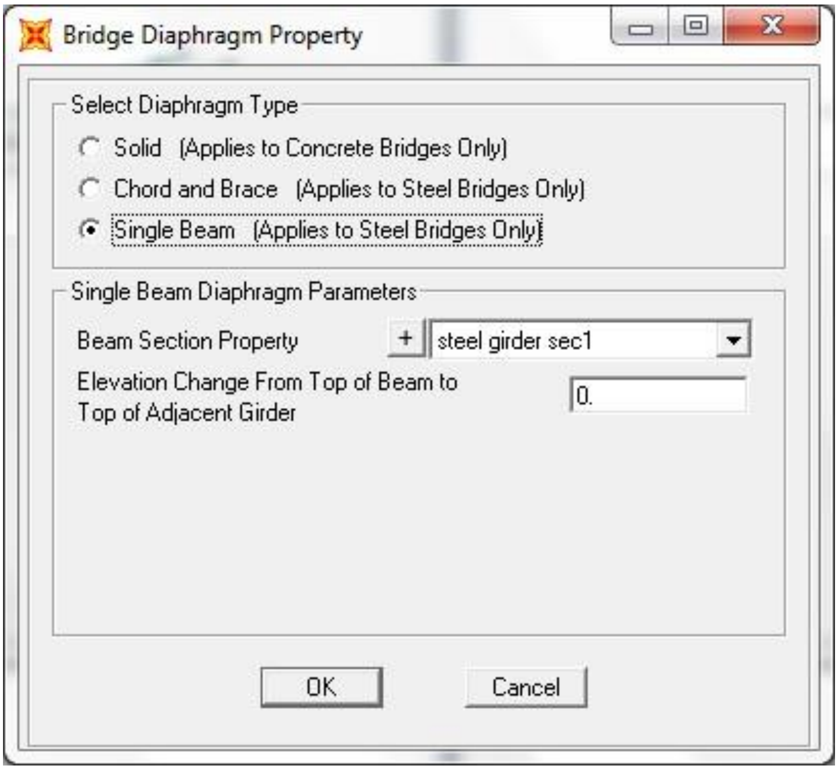


Figure 6.20: Diaphragm Property Definition.

6.8. Foundation Springs

Foundation spring properties specify data for the connection of the substructure to the ground. When defining the foundation springs, they could be given each of the six degrees of freedom as fixed, free or partially restrained with a specified spring constant. The Foundation Spring Data form is accessed from the **Bridge menu** > **Foundation Springs** command.

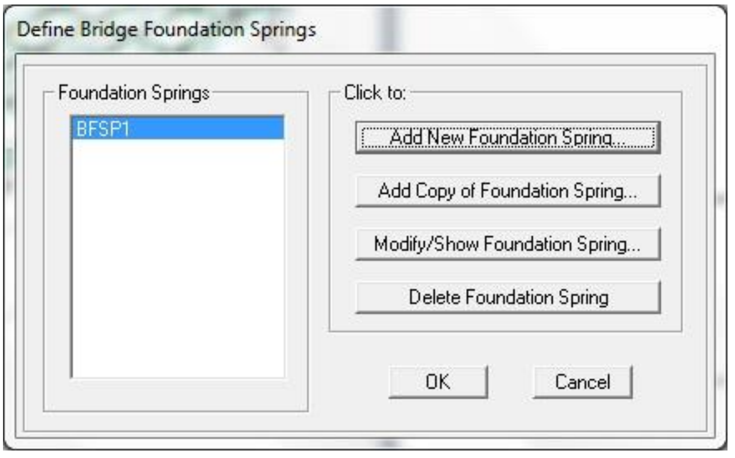


Figure 6.2: Foundation Springs.

The **Modify/Show Foundation Springs** button is used to display the Define Bridge Foundation Springs form.

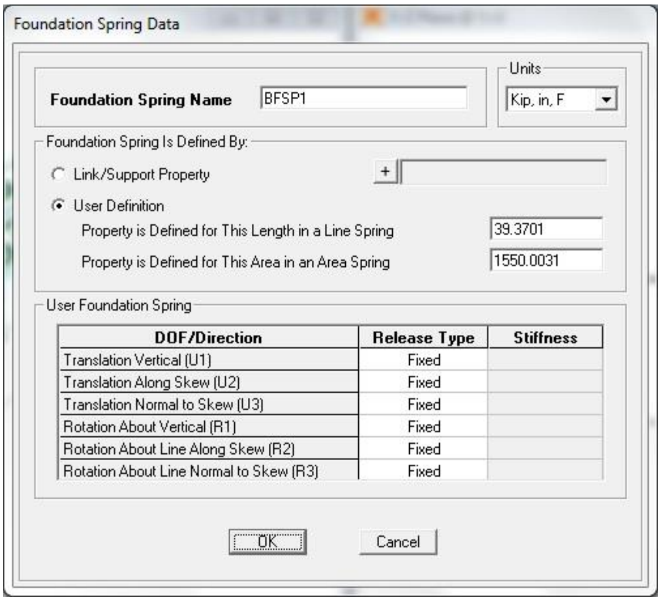


Figure 6.22: Foundation Spring Data Form.

6.9. Bearings

Fixed, free or partially restrained bearings can now be defined. At abutments, they are used to connect the girders to the substructure. At bents, they are used in the connection between the girders and the bent cap beam. Finally, at hinges, bearings are used in the connection between the girders on the two sides of the hinge. The bearing definition can be accessed from the **Bridge menu > Bearings** command and **the Define/Show Bearings** button to access the Define Bridge Bearings form.

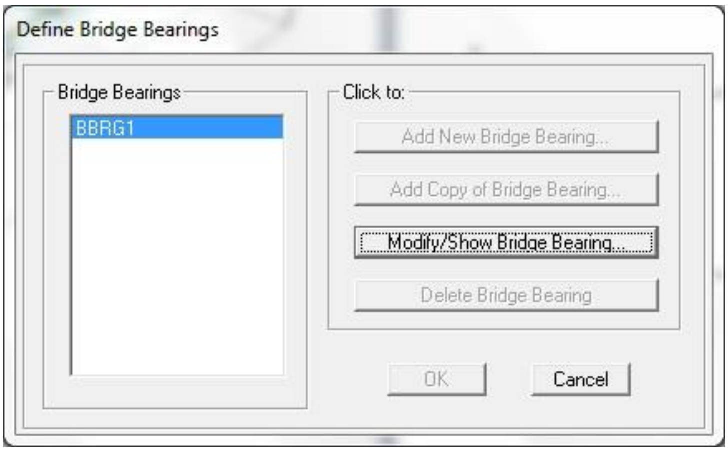


Figure 6.23: Bearing Definition.

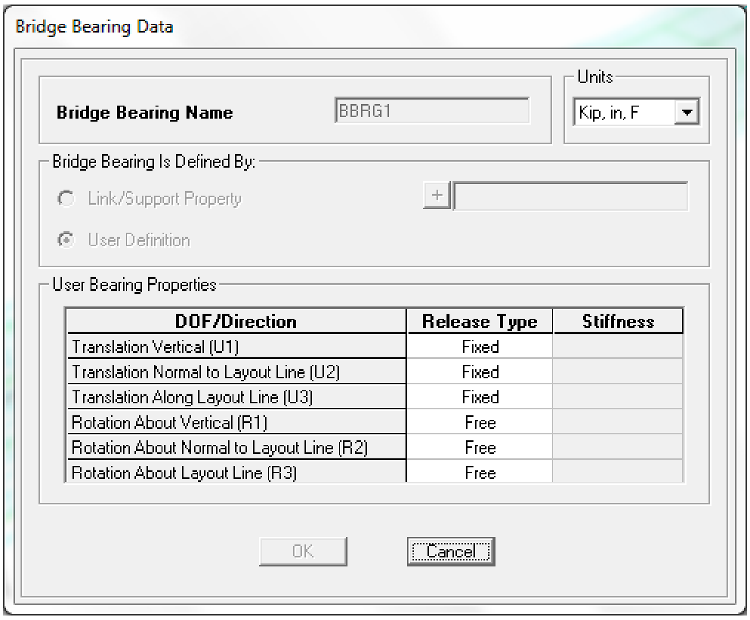


Figure 6.24: Bridge Bearing Data Form.

Here is how the model looks like after all the parameters are defined.

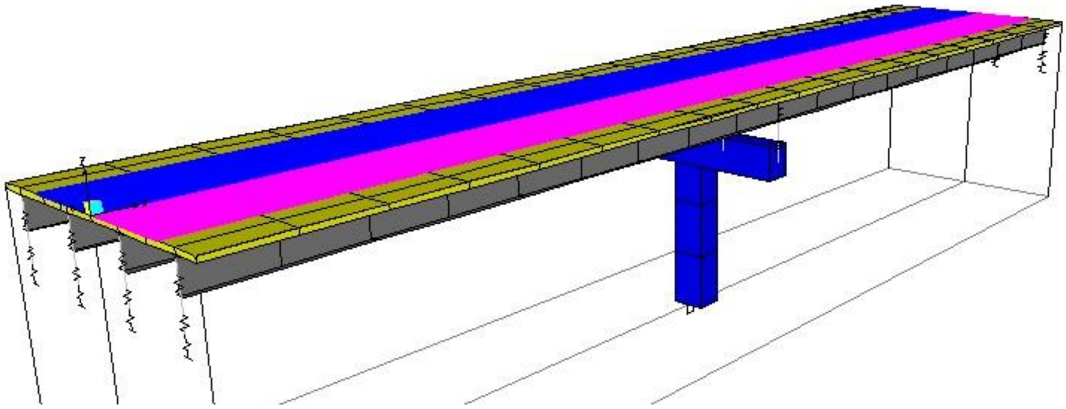


Figure 6.25: 3D view of the Two-Span Continuous Straight Composite I Girder.

The bridge analysis can be used to compute influence lines for traffic on bridge structures and to analyze these structures for the response resulting from vehicle live loads. The vehicle live loads can be combined with static and dynamic loads, and envelopes of the response can be computed. Now, the bridge model geometry, load patterns, and load cases have been defined, the bridge model is ready for analysis. Here is how the bridge deforms after the analysis is run.

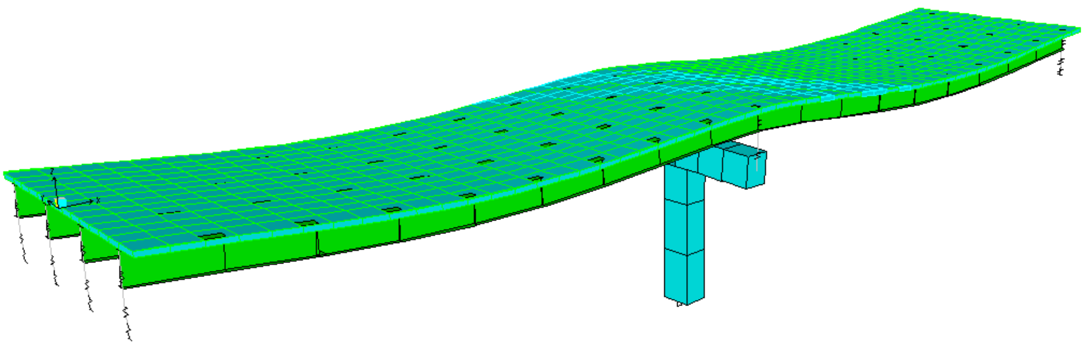


Figure 6.26: Deformed Shape of the Bridge.

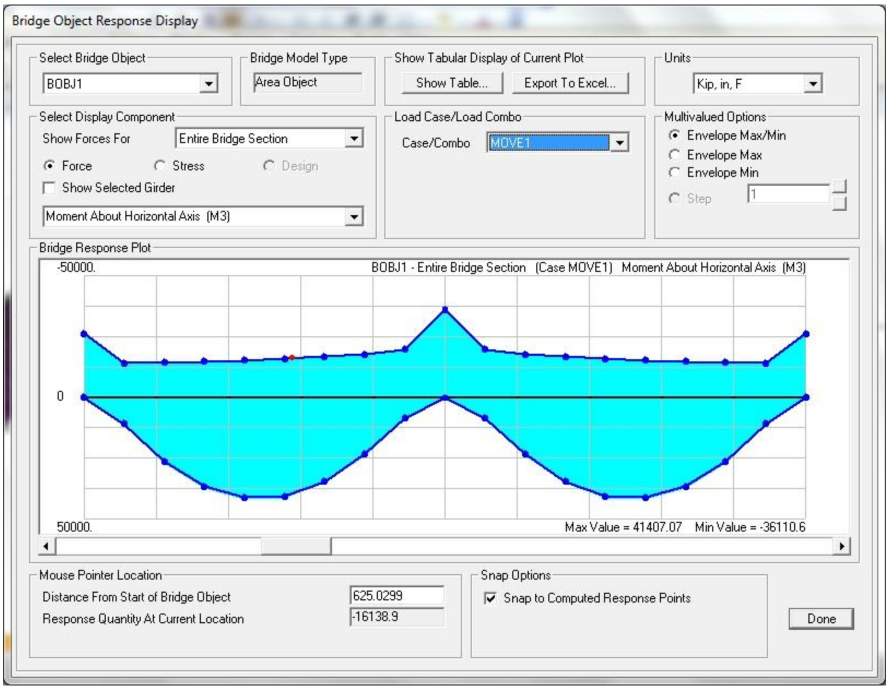


Figure 6.27: Moment Diagram of the Analyzed Bridge.

6.10. Selected Earthquake Records in This Study

The most common way to describe a ground motion is with a time history record. The motion parameters may be acceleration, velocity, or displacement, or all the three combined together. Generally, the directly measured quantity is the acceleration and the other parameters are the derived quantities. However displacement and velocity can also be measured directly. The measured time histories of records include errors resulting from many sources, such as noises at high and low frequencies, base line error, and instrumental error. These errors are removed from the data before they are used. Further, measured data are in an analogue form, which are digitized before they are used as seismic inputs. In recent years, digital seismographs are more commonly used but the various errors mentioned above are equally present in the analogue and digital forms. Time histories of ground motions are used directly for the time domain analysis of structures subjected to deterministic seismic inputs. At any measuring station, ground motions are recorded in three orthogonal directions; two of them are in horizontal directions and the third is in the vertical direction. Thus, three components of ground motions are available from any measuring station. For structural analysis, these three components of ground motions are transformed into those corresponding to the principal directions. It has been observed that the major direction of ground motion lies in the direction of the line joining the measuring station and the epicenter. The other two components of the ground motion are decided accordingly.

Eartthquake strong ground motions are taken in to account in numerical analysis are given in Table 6.1. Acccelation between time relationships are given in Figure 6.27 to Figure 6.33 for considered eartquakes.

Table 6.1: Strong Ground Motion Characteristics

Eartquake	Magnitude	Mechanism	Station	Direction (H1)	Direction (H2)	Epicentrical Depth (km)	Rupture Depth (km)	Soil Class (NEHRP)
Hector Mine	7.1	Strike Slip	Hector	HEC000 .AT2	HEC090 .AT2	26.5	11.7	C
Manjil, Iran	7.4	Strike Slip	Abbar	ABBAR --L.AT2	ABBAR --T.AT2	40.4	12.6	C
Duzce 12.11.199	7.1	Strike Slip	Lamont 362	362-N.AT2	362-E.AT2	43.5	23.4	C
Duzce 12.11.199	7.1	Strike Slip	Lamont 1060	1060-N.AT2	1060-E.AT2	44.4	25.9	B
Duzce 12.11.199	7.1	Strike Slip	Lamont 1061	1061-N.AT2	1061-E.AT2	31.6	11.5	C
Kocaeli 17.8.1999	7.5	Strike Slip	Arcelik	ARC000 .AT2	ARC090 .AT2	53.6	13.5	C
Kocaeli 17.8.1999	7.5	Strike Slip	Goynuk	GYN000 .AT2	GYN090 .AT2	77.6	31.7	C

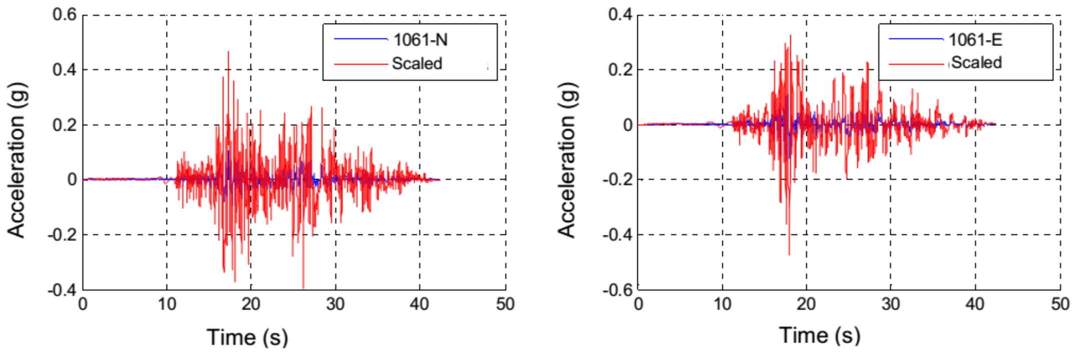


Figure 6.27: Accelation –Time relationship for Lamont 1061 Strong Ground Motion.

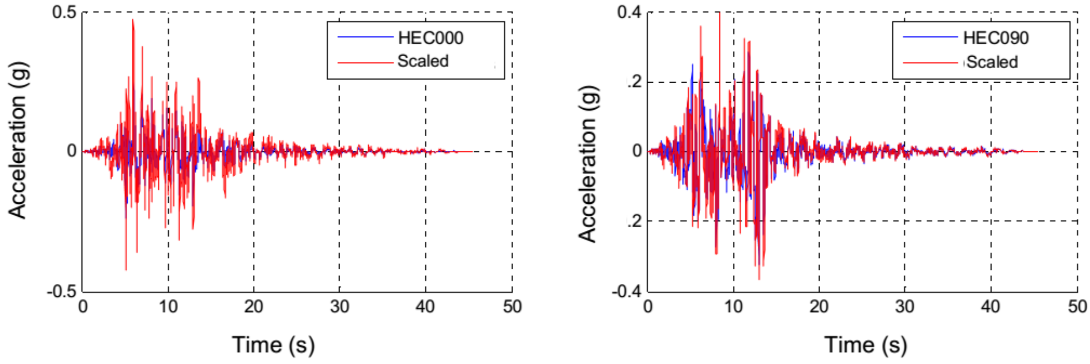


Figure 6.28: Accelation –Time relationship for Hector Mine Strong Ground Motion.

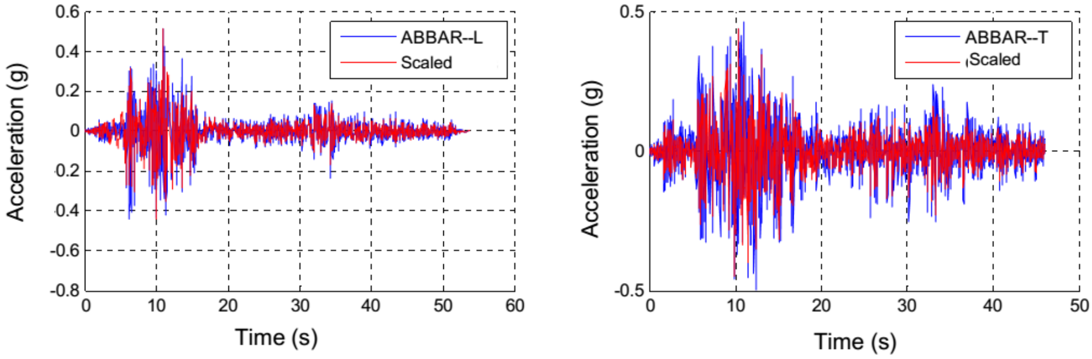


Figure 6.29: Accelation –Time relationship for Abbar Strong Ground Motion.

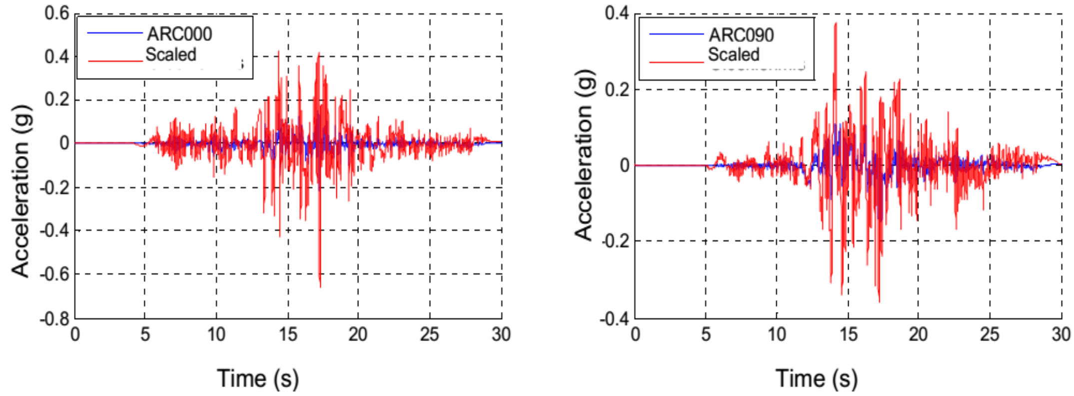


Figure 6.30: Accelation –Time relationship for Arcelik Strong Ground Motion.

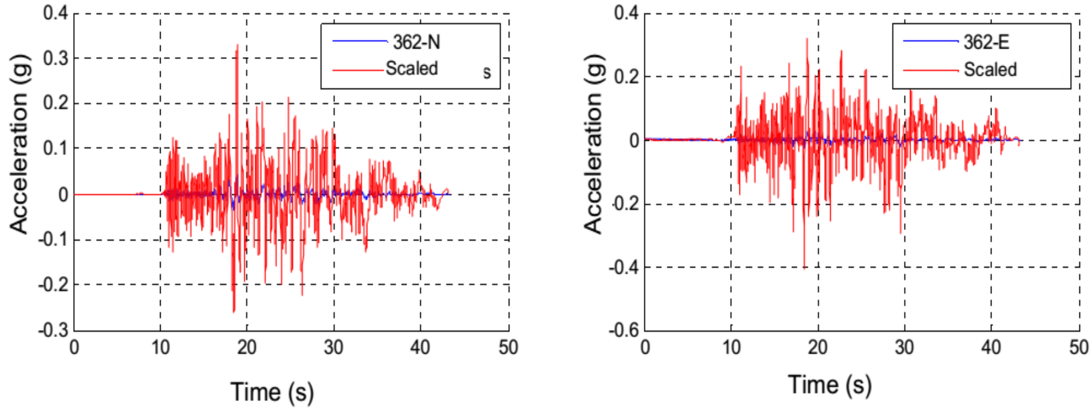


Figure 6.31: Accelation –Time relationship Lamont 362 Strong Ground Motion.

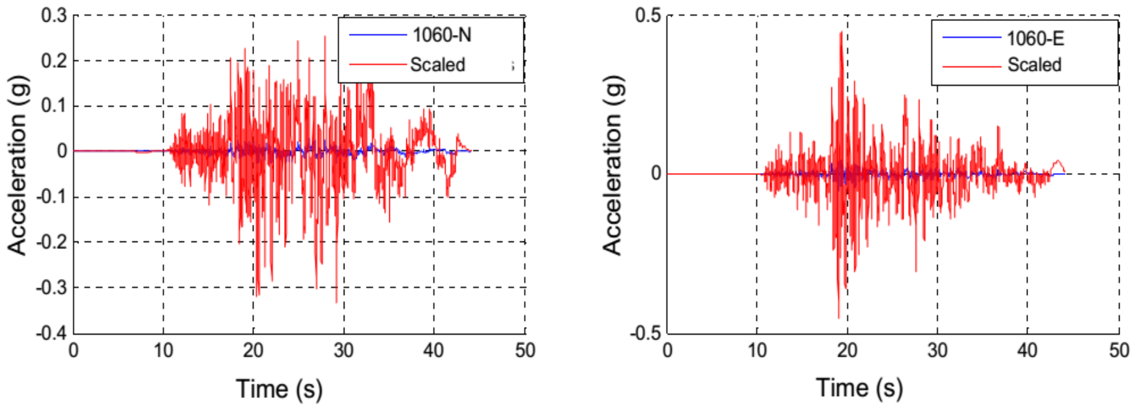


Figure 6.32: Accelation –Time relationship Lamont 1060 Strong Ground Motion.

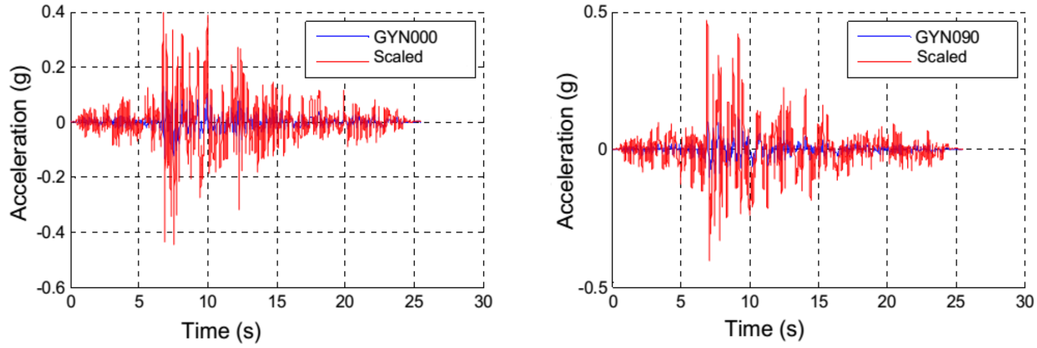


Figure 6.33: Accelation –Time relationship Göynük Strong Ground Motion.

6.11. Basic Concepts of Static Pushover Analysis

The use of inelastic static analysis in earthquake engineering is traced to the work of Gulkan and Sozen (1974) or earlier, where a single degree of freedomsystemis derived to represent the multi-degree offreedomstructure via an equivalent or 'substitute' structure. The load-displacement curve of this substitute to the real structure is evaluated by either finite element analysis or hand calculation to obtain the initial and post-yield stiffness, the yield strength and the ultimate strength. Simplified inelastic analysis procedures for multi-degree of freedomsystems have also been proposed by Saiidi and Sozen (1981) and Fajfar and Fischinger (1988). Therefore, pushover analysis per se is not a recent development. However, this review isconcerned with multi-degree offreedominelasticanalysis ofcomplex structures, which is relatively recent. There are several publications that review the advantages and disadvantages of pushover analysis, with varying degrees of success. Theyall, however, utilize global response parameters, namely top displacement versus base shear. Lawson et al. (1994) discuss in somedetail the range ofapplicability, the expected realismfor various structural systems and highlight the difficulties encountered. The latter study is both conceptual and applied, rendering it specifically valuable. In the course of describing recent trends in seismic design, Krawinkler (1995) discusses pushover analysis as a prelude to capacity spectrumapplications. The author mentions a contentious point, which is that 'in most casesthe normalized displacement profile at a first estimate of the target displacement level is utilized for these (defining the shape vector) purposes'. Another important issue raised in the latter review is that 'it must be emphasized that the pushover analysis cannot disclose performance problems caused by changes in the inelastic dynamic characteristics due to higher mode effects'. This is true if the current (as in 1995) techniques are assessed, but is not an insurmountable problem, as discussed in the current report and the earlier work of Bracci et al. (1995) and the authors of this report. Several cases of success of the pushover method were reported by Faella (1996), who also pointed towardsdifficulties with static-dynamic comparisons when the strong-motion input is rich in long period amplifications.

Attempts at improving the procedure have been made, with varying degrees of rigor and success. The simplest and most pragmatic of which is the work of Sasaki et al.

(1998). This comprises running several pushover analyses under forcing vectors representing the various modes deemed to be excited in the dynamic response. If the individual pushover curves, converted to spectral displacement-spectral acceleration space using the dynamic characteristics of the individual modes are plotted alongside the composite spectra, it becomes apparent which mode would be the cause ofmore damage and where is the damage likely to occur. The procedure is intuitive, and does indeed identify potential problems thatconventional single mode pushover analysis fails to point out. It, however, falls short of the work of Bracci et al. (1997), which is the most recent in-depth study of pushover analysis.

The pros and cons of the procedure were alsodiscussed by Krawinkler and Seneviratna (1998). Amongst many other interesting comments, the authors stress that the most important shortcoming of the procedure is the definition and invariance of the applied load vector. The significance of defining the target displacement (required for evaluating structural adequacy under a specific earthquake) is considered secondary to the load vector definition and control. Whereas the authors report on successful pushover cases, they emphasize problemareas by discussing the response of a tall (20 story) structure, and a structure with a full-height wall. In he former case, the errors are due to the omission of higher mode effects, whilst the latter demonstrates the difficulties encountered with effect of concentrated local demand (base of the wall) on force distribution. A short review by Tso and Moghadam(1998) concluded that fixed load patterns in pushover analysis are limiting, but newly proposed variable load patterns are not sufficiently verified as a superior option.

Kim and D'Amore (1999) set out to assess pushover analysis in comparison with inelastic timehistory procedures. They concluded that not all analyses of the samestructure under a set of distinct earthquake records are predicted by pushover analysis, a rather obvious conclusion that did not require inelastic dynamic analysis to prove. The interaction between the continuouslychanging dynamic characteristics of the inelasticmulti-degree of freedom structure with the various frequencies of a set of natural records cannot possibly be duplicated by a single pushover analysis under a predefined and fixed transverse load or displacement vector.

Pushover analysis is the nonlinear incremental-iterative solution of the equilibrium equation **KU = P** in a finite element formulation, where **K** is the nonlinear stiffness matrix, **U** is the displacement vector and **P** is a predefined load vector applied laterally over the height of the structure in relatively small load increments. This lateral load can be a set of forces or displacements that have a necessarily constant ratio throughout the analysis (fixed pattern). The out-of-balance forces are iteratively re-applied until convergence to a specified tolerance is reached (Bathe, 1982):

The procedure continues either until a predefined limit state is reached or until structural collapse is detected. This target limit state may be the deformation expected for the design earthquake in case of designing a new structure, or the drift corresponding to structural collapse for assessment purposes. Furthermore, it is presumed that the finite element code has been sufficiently verified, so that numerical collapse, as opposed to structural, is not operative. Generally, this procedure allows tracing the sequence of yielding and failure on the member and structure level, as well as the progress of the overall capacity curve of the structure (Figure 6.34).

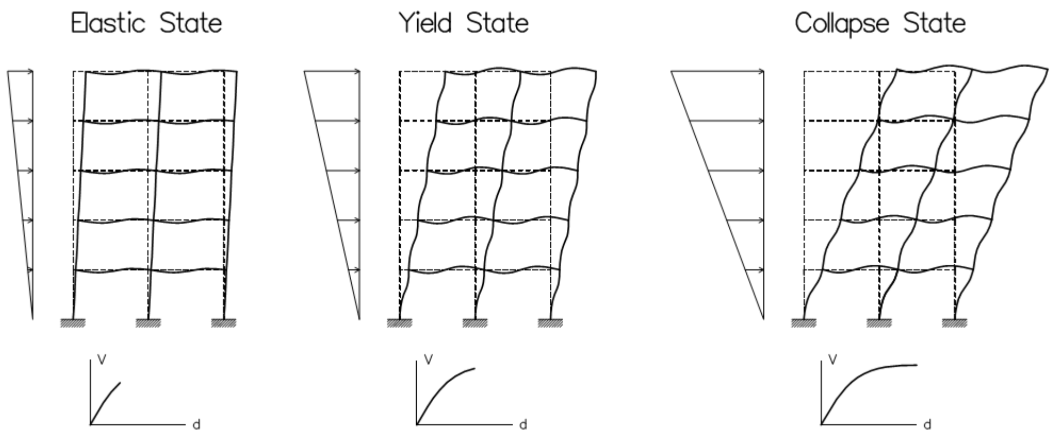


Figure 6.34: Yielding sequence through conventional pushover analysis.

The critical parameters to define the characteristics of the conventional pushover analysis are the lateral load nature (forces or displacements), its distribution pattern along the height of the structure (triangular, uniform etc) and its magnitude. The number of load steps, the convergence criteria and the iterative strategy also play a significant role in the effectiveness and reliability of the analysis.

7. ANALYSIS RESULTS

In this chapter, earthquake analysis results for representative bridges are given. The analyses were repeated with C30, C50 and C80 material classes for concrete and S420 for reinforcement. In this perspective, the results are compared and evaluated.

Table 7.1: Two Span Bridge C30.

Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	m	m	m	Radians	Radians	Radians
50	DEPX	Combination	Max	0,0031	0,001458	-0,000381	0,000343	0,00063	0,00003
50	DEPX	Combination	Min	-0,0031	-0,001483	-0,000388	-0,000313	-0,000645	0,000021
50	DEP_G_TH_ENV	Combination	Max	0,0023	0,001004	-0,000377	0,000226	0,000462	0,000029
50	DEP_G_TH_ENV	Combination	Min	-0,0020	-0,001091	-0,000391	-0,000225	-0,000411	0,000023

Table 7.2: Two Span Bridge C50.

Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	m	m	m	Radians	Radians	Radians
50	DEP_G_RSX	Combination	Max	0,0027	0,0013	-0,0003	0,000303	0,000558	0,000026
50	DEP_G_RSX	Combination	Min	-0,0028	-0,0013	-0,0003	-0,000277	-0,000571	0,000018
50	DEP_G_TH_ENV	Combination	Max	0,0021	0,0009	-0,0003	0,000194	0,000423	0,000025
50	DEP_G_TH_ENV	Combination	Min	-0,0017	-0,0010	-0,0003	-0,000206	-0,000352	0,00002

Table 7.3: Two Span Bridge C80.

TABLE: Joint Displacements									
Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	m	m	m	Radians	Radians	Radians
50	DEP_G_RSX	Combination	Max	0,0024	0,0011	-0,0003	0,000267	0,000493	0,000023
50	DEP_G_RSX	Combination	Min	-0,0024	-0,0011	-0,0003	-0,000245	-0,000504	0,000016
50	DEP_G_TH_ENV	Combination	Max	0,0019	0,0008	-0,0003	0,000169	0,000384	0,000022
50	DEP_G_TH_ENV	Combination	Min	-0,0015	-0,0008	-0,0003	-0,000188	-0,000309	0,000017

Table 7.4: Four Span Bridge C30.

Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	m	m	m	Radians	Radians	Radians
575	DEP_G_RSX	Combination	Max	0,000463	-6,552E-07	-0,000342	-8,906E-07	0,00018	7,485E-07
575	DEP_G_RSX	Combination	Min	-0,000448	-8,572E-07	-0,000345	-9,407E-07	-0,000196	-7,475E-07
575	DEP_G_TH_ENV	Combination	Max	0,001266	0,000032	-0,000343	0,000008327	0,000357	0,000001037
575	DEP_G_TH_ENV	Combination	Min	-0,000926	-0,000043	-0,000344	-0,000013	-0,000477	-0,000001156

Table 7.5: Four Span Bridge C50.

Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	m	m	m	Radians	Radians	Radians
575	DEP_G_RSX	Combination	Max	0,000436	-4,709E-07	-0,000302	-7,962E-07	0,000157	7,262E-07
575	DEP_G_RSX	Combination	Min	-0,000423	-7,534E-07	-0,000305	-8,402E-07	-0,000171	-7,253E-07
575	DEP_G_TH_ENV	Combination	Max	0,000403	0,000012	-0,000303	0,000002396	0,000128	4,126E-07
575	DEP_G_TH_ENV	Combination	Min	-0,000378	-0,000017	-0,000304	-0,000005037	-0,000157	-4,452E-07

Table 7.6: Four Span Bridge C80.

TABLE: Joint Displacements									
Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	m	m	m	Radians	Radians	Radians
575	DEP_G_RSX	Combination	Max	0,000415	-3,094E-07	-0,000266	-7,097E-07	0,000138	7,126E-07
575	DEP_G_RSX	Combination	Min	-0,000405	-6,528E-07	-0,000269	-0,000000749	-0,00015	-7,116E-07
575	DEP_G_TH_ENV	Combination	Max	0,00034	0,000012	-0,000267	0,000001958	0,000091	4,046E-07
575	DEP_G_TH_ENV	Combination	Min	-0,000333	-0,000017	-0,000268	-0,000004253	-0,000117	-4,278E-07

Table 7.7: Fıve Span Bridge C30.

TABLE: Joint Displacements									
Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	m	m	m	Radians	Radians	Radians
675	DEP_G_RSX	Combination	Max	0,025754	-0,000008581	-0,001298	0,000001519	0,000539	0,0000061
675	DEP_G_RSX	Combination	Min	-0,025723	-0,000036	-0,001302	7,593E-07	-0,000537	-0,000006091
675	DEP_G_TH_ENV	Combination	Max	0,055967	0,043858	-0,001293	0,000662	0,001112	0,000018
675	DEP_G_TH_ENV	Combination	Min	-0,055069	-0,0402	-0,001306	-0,000703	-0,001097	-0,000013

Table 7.8: Fıve Span Bridge C50.

TABLE: Joint Displacements									
Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	m	m	m	Radians	Radians	Radians
675	DEP_G_RSX	Combination	Max	0,025278	-0,00000784	-0,00116	0,000001413	0,000548	0,000005185
675	DEP_G_RSX	Combination	Min	-0,02525	-0,000035	-0,001163	6,626E-07	-0,000546	-0,000005176
675	DEP_G_TH_ENV	Combination	Max	0,054417	0,03724	-0,001156	0,000626	0,001291	0,000014
675	DEP_G_TH_ENV	Combination	Min	-0,053641	-0,038921	-0,001167	-0,00063	-0,00114	-0,000011

Table 7.9: Five Span Bridge C80.

TABLE: Joint Displacements									
Joint	OutputCase	CaseType	StepType	U1	U2	U3	R1	R2	R3
Text	Text	Text	Text	m	m	m	Radians	Radians	Radians
675	DEP_G_RSX	Combination	Max	0,024753	-0,000007211	-0,001034	0,000001311	0,000552	0,000004401
675	DEP_G_RSX	Combination	Min	-0,024728	-0,000033	-0,001036	5,794E-07	-0,00055	-0,000004393
675	DEP_G_TH_ENV	Combination	Max	0,057398	0,034069	-0,00103	0,000621	0,00142	0,000012
675	DEP_G_TH_ENV	Combination	Min	-0,051717	-0,035108	-0,001039	-0,000603	-0,001161	-0,000009583

Pushover analysis are carried out according to the material models and rules given in chapter 7 of TERDC (2007).

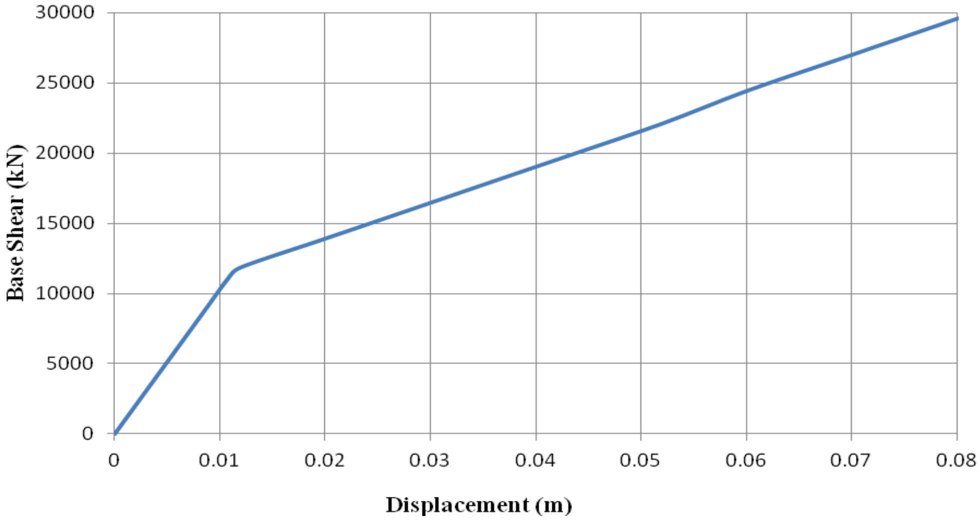


Figure 7.1: Two Span Bridge Pushover Curve along x (transverse) direction (C30, S420).

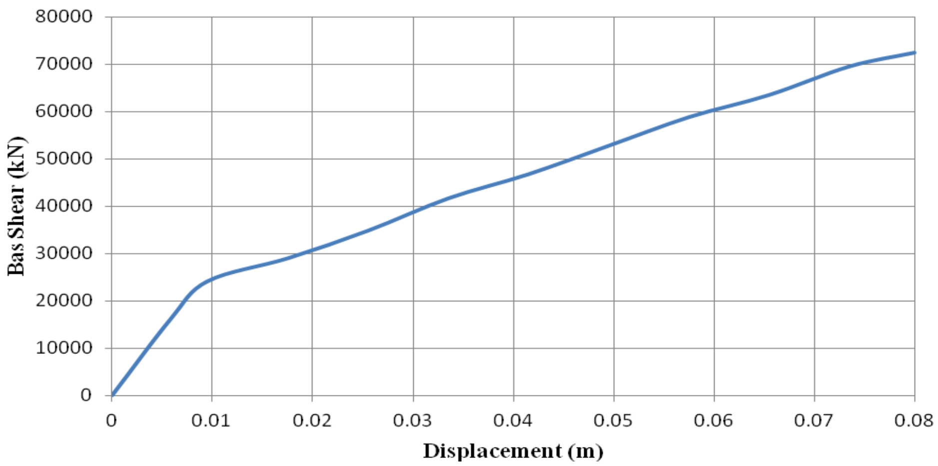


Figure 7.2: Two Span Bridge Pushover Curve along y (longitudinal) direction (C30, S420).

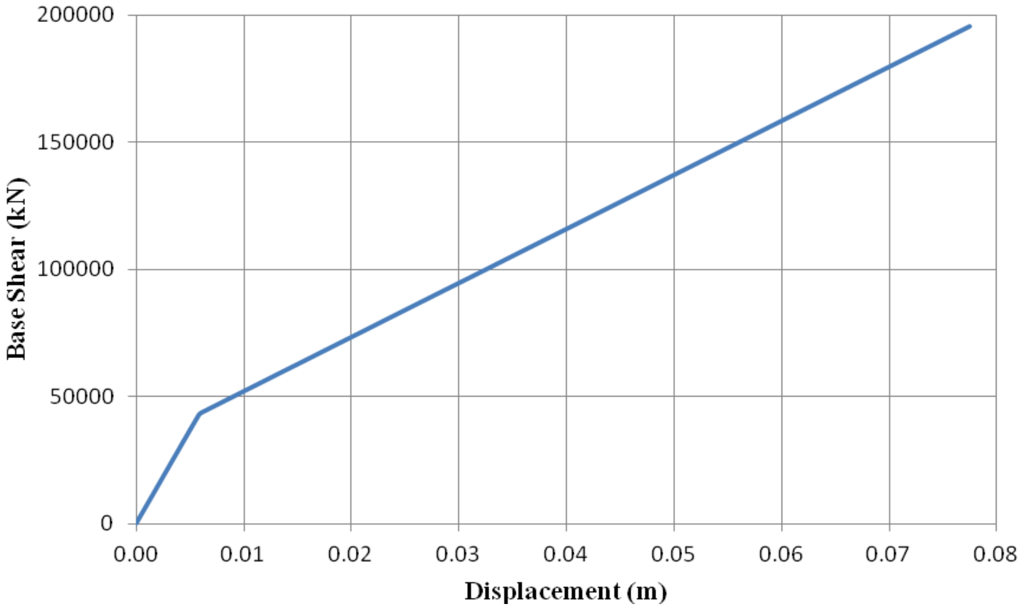


Figure 7.3: Four Span Bridge Pushover Curve along x direction (C30, S420).

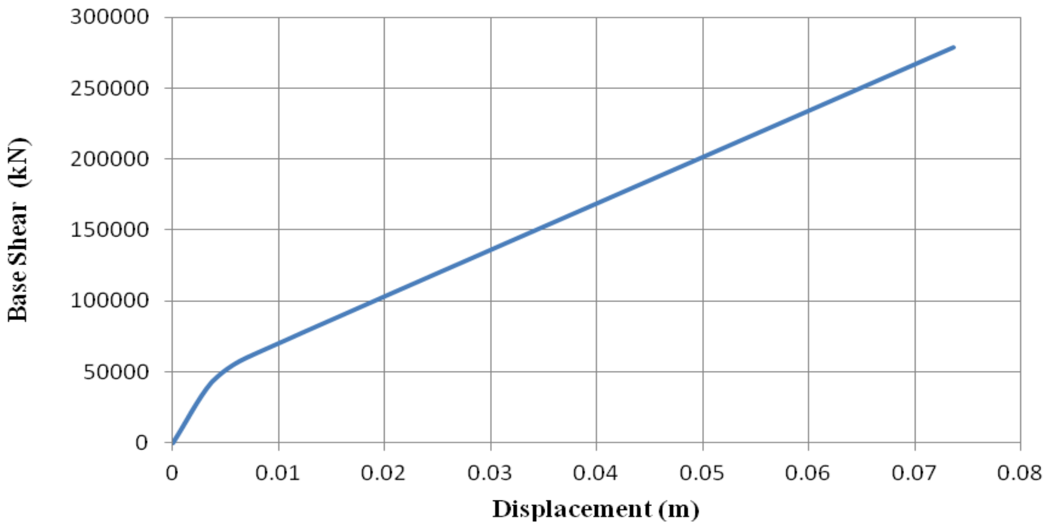


Figure 7.4: Four Span Bridge Pushover Curve along y direction (C30, S420).

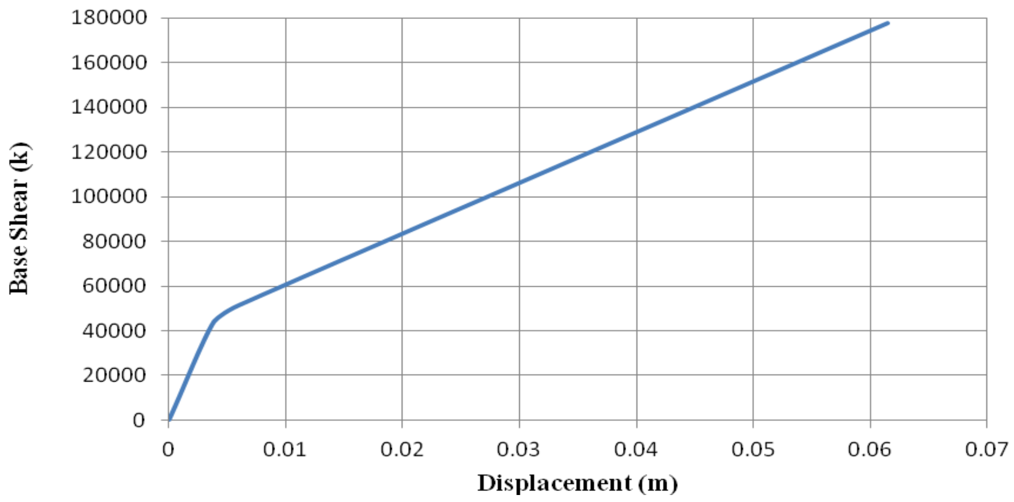


Figure 7.5: Five Span Bridge Pushover Curve along x direction (C30, S420).

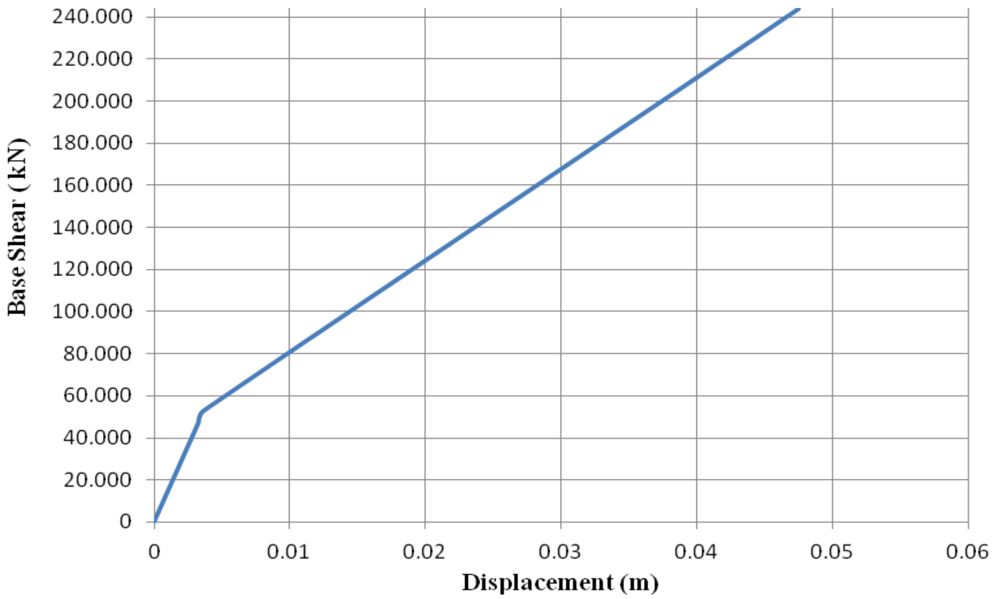


Figure 7.6: Five Span Bridge Pushover Curve along y direction (C30, S420).

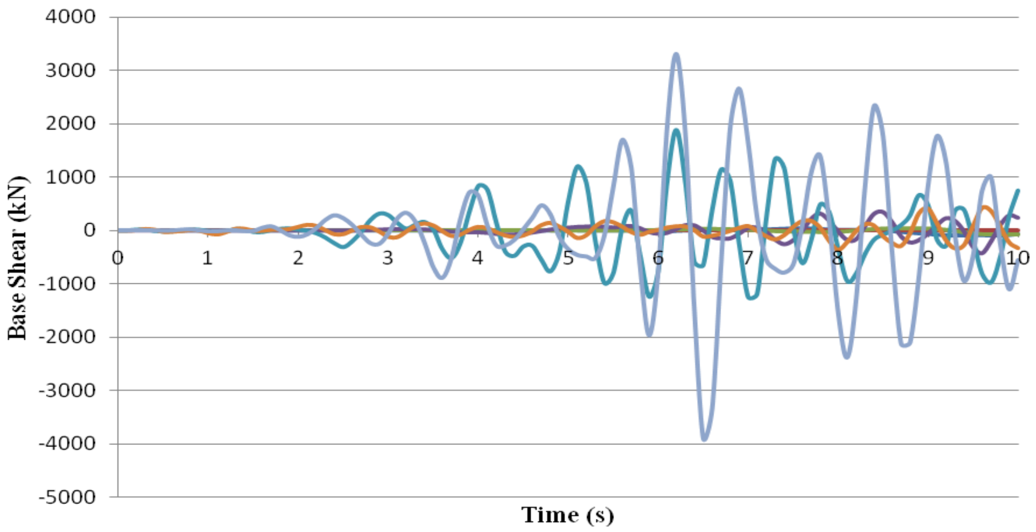


Figure 7.7: Two Span Bridge Time- Base Shear Relationship along x direction (C30, S420).

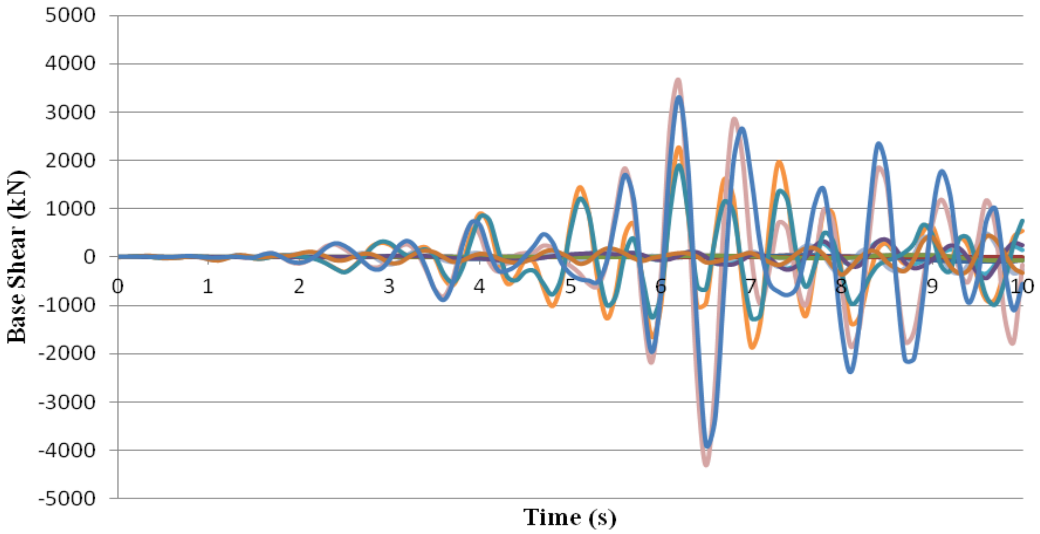


Figure 7.8. Two Span Bridge Time- Base Shear Relationship along y direction (C30, S420).

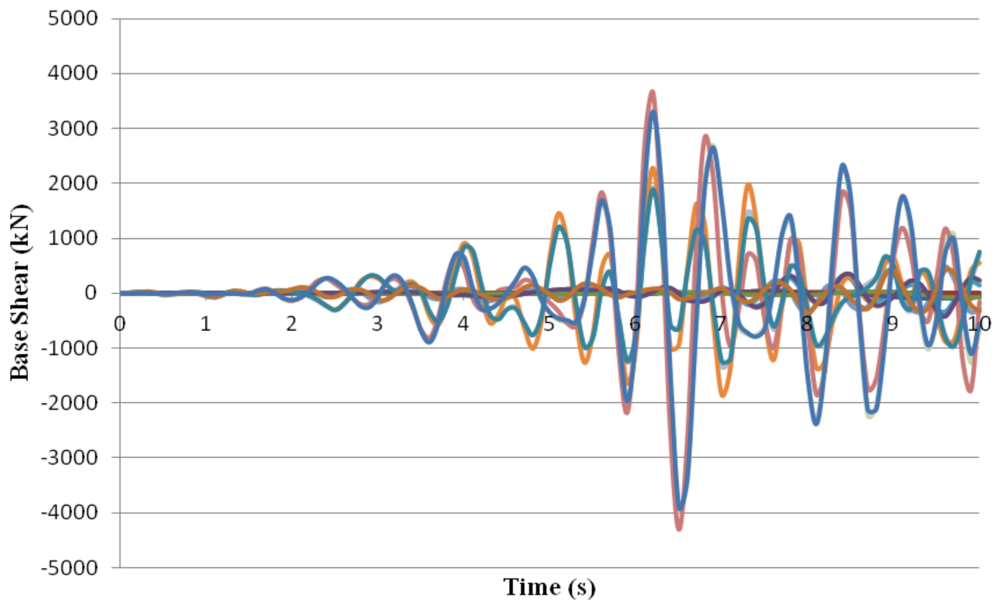


Figure 7.9: Four Span Bridge Time- Base Shear Relationship along x direction (C30, S420).

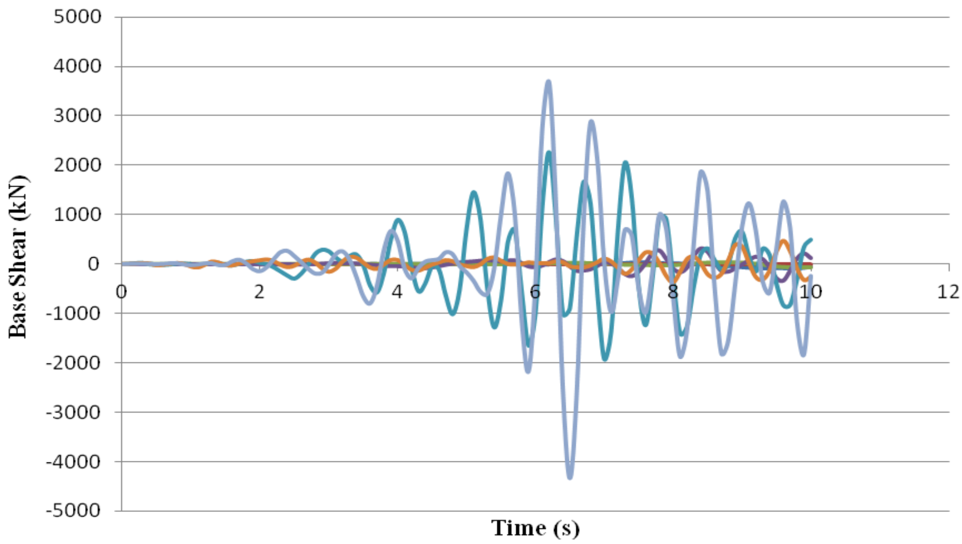


Figure 7.10: Four Span Bridge Time- Base Shear Relationship along y direction (C30, S420).

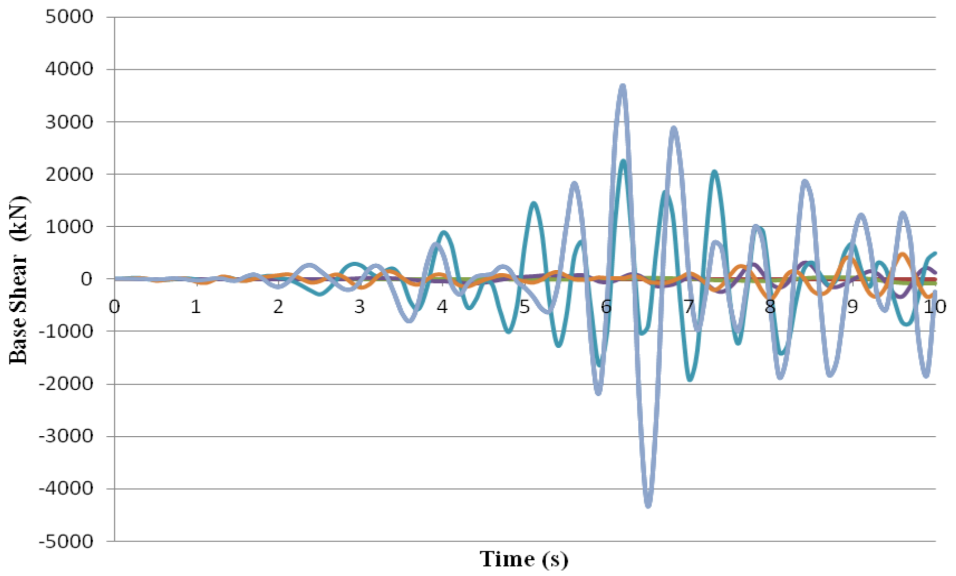


Figure 7.11: Five Span Bridge Time- Base Shear Relationship along x direction (C30, S420).

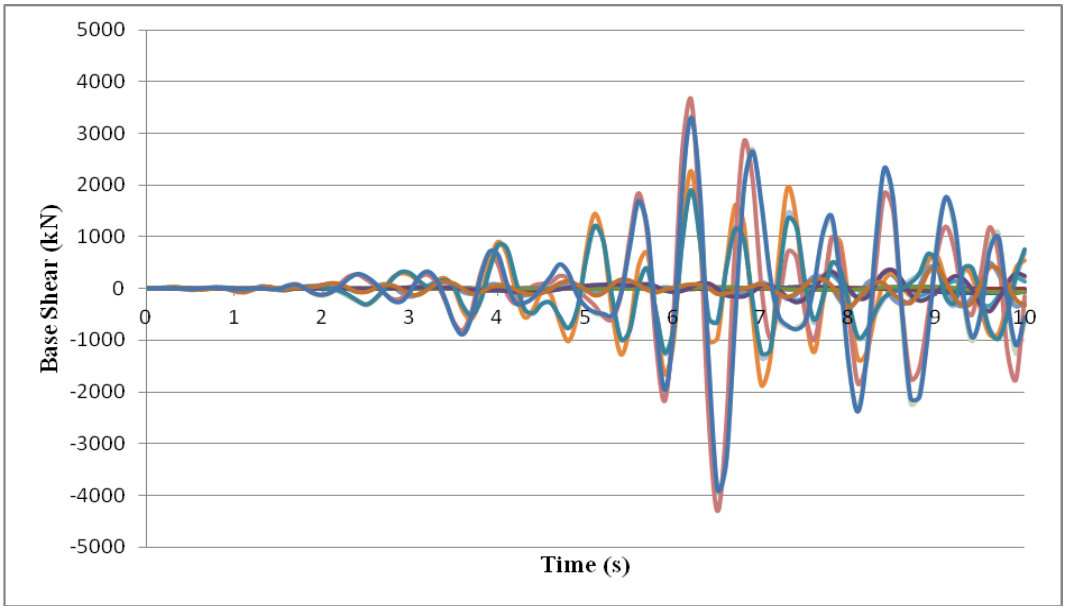


Figure 7.12: Five Span Bridge Time- Base Shear Relationship along y direction (C30, S420).

8. CONCLUSIONS

In the presented MS thesis, a detailed investigation on sustainability and behavior of bridges are given. Thesis has two main parts as one is for sustainability development, the other is for the seismic assesment. These two parts work together in such a manner to understand the different material usage in the structural capacity change and environmental effects. As a result of Chapter 7, it is understood that bridges are vulnereable for stronger earthquakes from analyses conducted, vulnerability increases with the bridge span increment, on the other hand, bridge sustainability decrease with higher strength concrete due to its cement amount used during the production and carbon emmission released. If the long run behavior is investigated, a structural behavior has a correlative results with sustainability. Gained results from the analyses conducted in the thesis have been listed below:

a) The focus of this thesis is to develop a framework that assists transportation engineers and managers to develop more sustainable design and construction processes for new bridges, and sustainable maintenance practices for existing bridges.

b) Sustainable practices were synthesized that can be used in bridge construction projects.

c) Guidelines were developed to estimate cradle to gate GHG emissions from materials and GHG emissions from construction equipment in the use phase and can be used to evaluate the framework.

d) LCCA Guidelines were developed to estimate life cycle cost of the alternatives.

e) Erthquake loads are reduced as 2/5 for central bridge piers in horizantal direction that provides frame behavior, hence economical sections would be available that provides environmental benefits with less material use.

f) For bridge piers, concrete compression strength has been increased from 30MPa to 80MPa that results with 20-25% decrease in displacement. On the other hand, economically, 80MPa concrete unit is double times higher than 30MPa. While column hight increases, concrete strength effect decreases.

Herein the results on sustainability and seismic risk assessment are given for bridges. As a further step, the study can be extended for other kinds of structures, such as buildings. The parameters those affect the seismic behavior of bridges such as bearings and prestressed precast beams are not studied. Their effects can also be considered.

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Appendix

1. Live Load

In the LRFD specifications, live load consist of

- the gravity loads (vehicular live loads, rail transit loads, pedestrian loads);
- dynamic load allowance;
- centrifugal forces;
- braking forces;
- Vehicular collision forces.

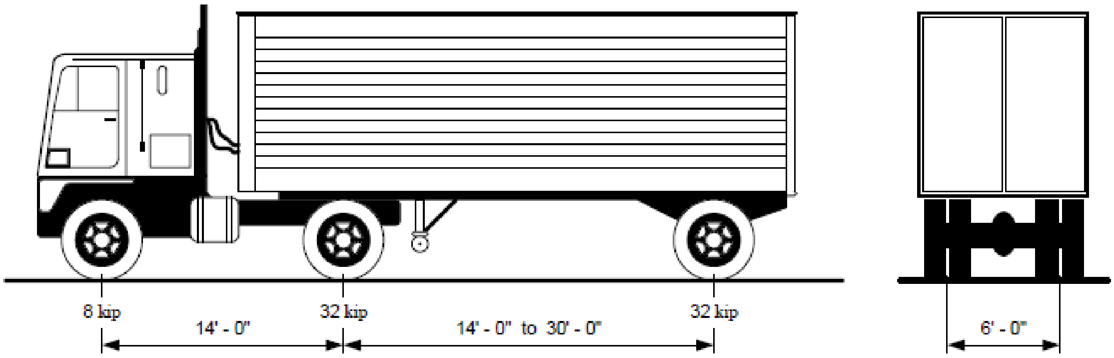
The live load considered in here are the basic design vehicular live load, a specified loading for optional live-load deflection evaluation, and a fatigue load. Live loads are considered to be transient loads that are assumed applied to the short term composite section.

2. Design vehicular live load (Article 3.6.1.2)

In the LRFD specifications, it is designed as HL93 which consist of the combination of the following placed within each design lane:

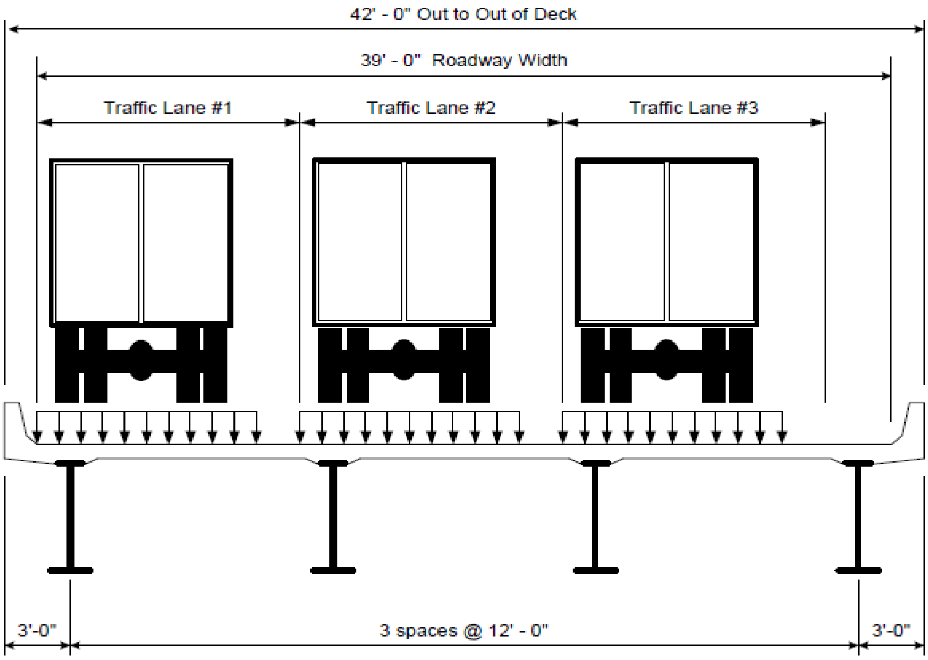
- A design truck or design tandem;
- A design lane load.

The design truck (art. 3.6.1.2.2) is equivalent to the current AASHTO HS20 truck with the spacing between the 32 kip rear-axle loads varied between 14 and 30 ft to produce extreme force effects. The 8 kip front axle is located at a constant distance of 14 ft from the closest rear axle. The transverse spacing of the wheels is 6 ft.



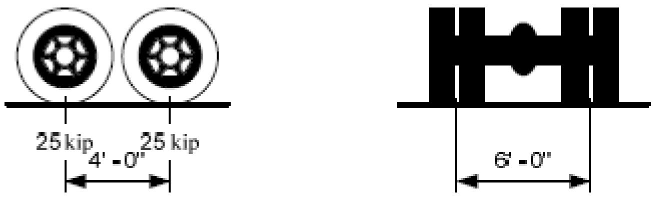
- Design truck configuration

The truck is assumed to occupy a design lane 12 ft in width with only one truck to be placed within each design lane. The truck is to be positioned transversely within a lane to produce extreme force effects; however, the truck is to be positioned no closer than 2 ft from the edge of the design lane.



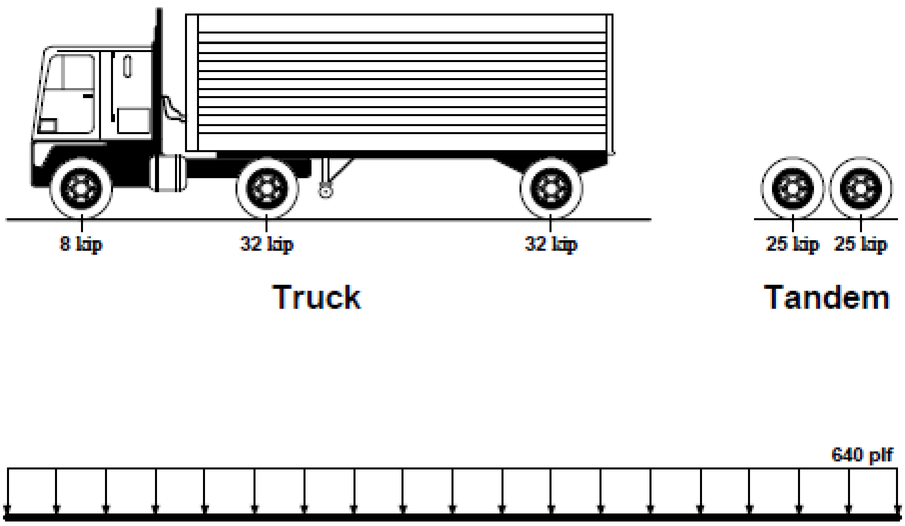
- Truck design lane placement

The design tandem (art 3.6.2.3) consists of a pair of 25 kip axles spaced 4 ft apart with a transverse spacing of wheels equal to 6 ft.



- Design tandem configuration

The design lane load (art 3.6.1.2.4) consists of a 0.64 kips/ft uniformly distributed load occupying a 10 ft lane width positioned to produce extreme force effects. The uniform load may be continuous of discontinuous as necessary to produce the maximum force effect.



- Lane load configuration

3. Loading for optional live-load deflection evaluation (Article 3.6.1.3.2)

The vehicular live load for checking the optional live-load deflection criterion is taken as the larger of:

- The design truck alone;
- 25% of the design truck along with the design lane load.

4. Fatigue load (Article 3.6.1.4)

the vehicular live load for checking fatigue in steel structures in the LRFD specifications consists of a single design truck (without the lane load) with a constant rear-axle spacing of 30 ft (art 3.6.1.4.1). The fatigue load is used to represent the variety of trucks of different types and weights in actual traffic. The constant rear-axle spacing approximates that for the 4- and 5-axle semi-trailers that do most of the fatigue damage to bridge.

5. Load combinations

Four limit states are defined in the LRFD specifications to satisfy the basic design objectives of LRFD; that is, to achieve safety, serviceability, and constructability.

According to the AASHTO-LRFD 2007:

- Strength:

Intended to ensure that strength and stability are provided to resist statistically significant load combinations that a bridge will experience during its design life.

Extensive distress and structural damage may occur at strength limit state conditions, but overall structural integrity is expected to be maintained.

- Service:

Deals with restrictions on stress, deformation, and crack width under regular service conditions.

Intended to ensure that the bridge performs acceptably during its design life.

- Extreme Event:

Intended to ensure structural survival of a bridge during an earthquake, vehicle collision, ice flow, or foundation scour.

- Fatigue:

Deals with restrictions on stress range under regular service conditions reflecting the number of expected cycles.

STRENGTH I is the load combination to be used for checking the strength of a member or component under normal use in the absence of wind.

STRENGTH I: 1.25DC + 1.5DW + 1.75(LL+IM)

STRENGTH II Is the load combination used to check the strength of a member or component under special permit loadings in the absence of wind.

STRENGTH II:

STRENGTH III is to be used for checking strength of a member or component assuming the bridge is exposed to a wind velocity exceeding 55 miles/hr in the absence of live load.

STRENTGH III: 1.25DC + 1.5DW + 1.4WS

In the STRENTGH IV load combination, all permanent-load effects (for both the construction and final conditions), relates to very high dead-to-live load force effect ratios.

STRENTGH IV: 1.5(DC+DW)

STRENGTH V load combination is to be used to check the strength of a member or a component assuming the bridge is exposed to a wind velocity equal to 55 miles/hr under normal use.

STRENGTH V: 1.25DC + 1.5DW + 1.35(LL+IM) + 0.4WS + 1.0WL

EXTREME EVENT I is the load combination including earthquake loading.

EXTREME EVENT I

EXTREME EVENT II is the load combination relating to vehicle and ship collisions and ice loads.

EXTREME EVENT II

SERVICE I relates to normal operational use of the bridge and would be used primarily for crack control in reinforced concrete structures.

SERVICE I

SERVICE II load combination is used only for steel structures and corresponds to the Overload level in standard specifications.

SERVICE II

SERVICE III is used for crack control in prestressed concrete structures

SERVICE III

Where:

DC = Dead load: components and attachments

DW = Dead load: wearing surface and utilities

LL = Vehicular live load

IM = Vehicular dynamic load allowance

CE = Vehicular centrifugal force

WS = Wind load on structure

WL = Wind on live load

TU = Uniform temperature

BR = Vehicular braking force

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