The Impact and Future Role of Computations and Software in Bridge Modeling, Analysis and Design

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Abstract

Computer application and software have significantly altered the way bridges are designed, constructed and managed. It has made the design process simple for common bridge types and has provided opportunities to explore new concepts and ideas for larger projects. Computer application and software are now an integral part of the bridge lifecycle, right from the conceptual stage to bridge management. This paper particularly focuses on the development and impact of computer applications in bridge modeling analysis and design. It presents an overview of the past developments, the issues involved in the modeling, the current trends, available tools and the future challenges and directions. A hierarchal, multi-scale modeling and design approach is presented to handle various aspects and levels of bridge design process.

1.0 Overview

The history of bridge construction can be traced back to ancient times, when people started using logs and stones to provide a means for crossing streams. After the concept of arch bridge was invented by the Romans, it led to progress in the field of Bridge Engineering, and it has been widely used for the construction of bridges and aqueducts. Today we are able to construct bridges of longer spans, withstanding greater loads, with higher durability, using more advanced construction materials such as steel, pre-stressed concrete, composites and cables, together with more advanced construction methods and techniques [1].

At this time, in Asia region several medium and large-scale infrastructure projects are underway and have been planned for the future. Bridges are important part of the infrastructure projects like highways, elevated expressways, flyovers and water crossings etc. These days, effective and efficient design of bridges requires a good understanding of the bridge engineering principles and usage of the modern computing tools. New theories and computing technologies have evolved so rapidly that engineering community faces difficulty in finding time to absorb them properly or to be educated in them. There is therefore a strong need to provide adequate knowledge, exposure and training to professional engineers in the background theory as well as effective use of computer aided tools.

Bridge engineering is a specialized discipline that deals with various aspects of bridge design right from the conceptual design to its maintenance and rehabilitation. These aspects include: conceptual design, preliminary design, modeling, analysis, detailed design, construction bidding and documentation, bridge management, monitoring and evaluation, maintenance, retrofitting, rehabilitation etc. The overall bridge project is also supported by several information and database sources including local knowledge and practices, organizational standards, designers database, the information on the Internet, library of standardized bridges, historical developments etc. Some of the aspects and information sources are shown in Figure 1. It can be seen from this figure, that any attempt to fully automate the handling of bridge project would make the system too complex and even undesirable; as such a system will preclude the experience and intuitive aspects of engineers' involvement.

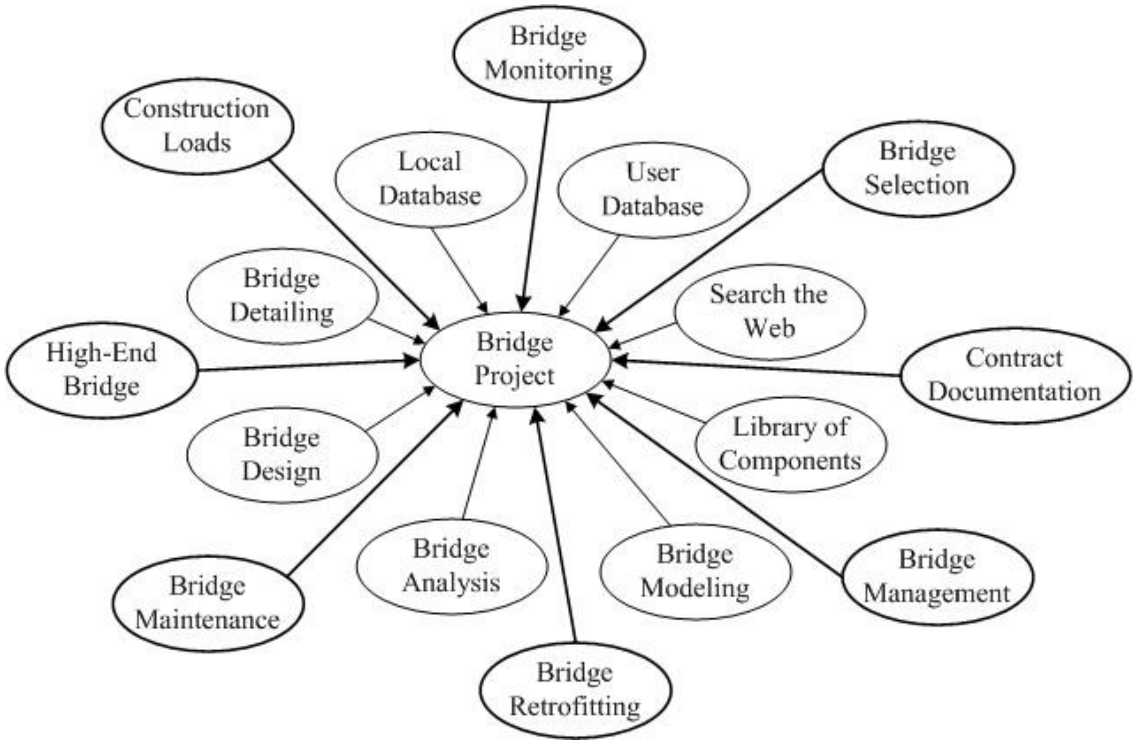


Figure 1: The Overall Bridge Project Scope

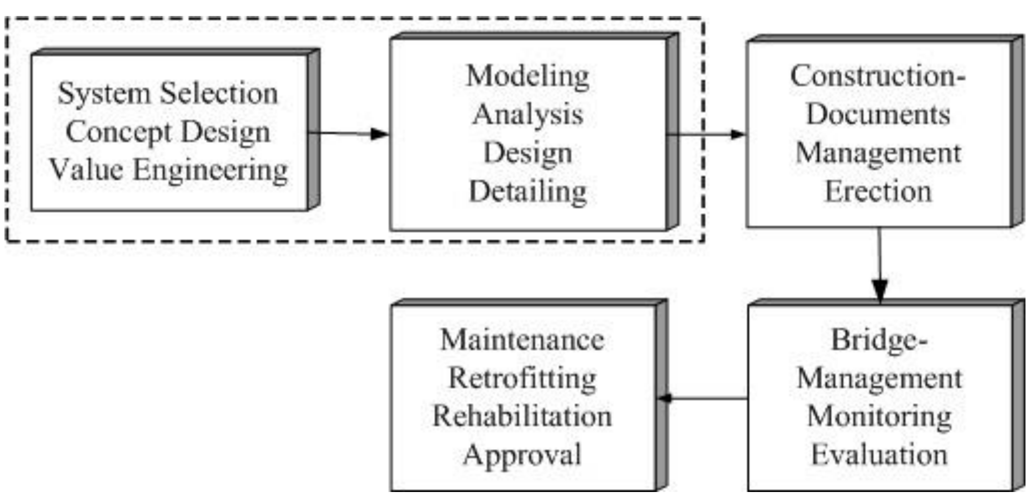


Figure 2: The Bridge Project Subsystems

However, it is possible and desirable to develop automation tools and computer applications for specific sets or groups out of these aspects and activities, as shown in Figure 2. Although some sort of software or some level of computer aided systems are available and are being used for most of these sub-systems, our focus is the Modeling-Analysis-Design-Detailing sub system, collectively called as Bridge Design system.

2.0 The Bridge Design Problem and its Computer Aided Solution

The bridge design problem can be classified in a number of ways: based on bridge size, bridge type, bridge location, primary material, structural system, construction methodology and so on. For the purpose of this paper, we will sub-divide the bridge design problem into two main categories;

a) Category-1: Small to medium size roadway and waterway bridges. These include the bridges over canals, small rivers, flyovers, elevated urban roads, bridges over railway crossings etc.

b) Category-2: Large span bridges and mega projects. These include bridges crossing over wide rivers, valley crossings, bridges over ocean straits, highly elevated roadway bridges passing through open landscape and mountains.

Considering by numbers, Category-1 bridges account for almost 90% or more of all the bridges built. However, by scale, cost, complexity, significance, importance and visibility, Category-2 bridges carry far more impact. The demands and range of computer application and software are quite different for the two categories. Although most of the discussion in this paper is applicable, both categories of bridges, where ever appropriate, specific reference will be made to these categories.

Another classification of the bridge design problem is in terms of the steps or stages in the design cycle, such as conceptual design preliminary design, geometric design, modeling, analysis, detailed component design, detailing, drafting and documentation. The range and extent of computer applications for each of these steps is varied, both for Category-1 and Category-2 bridges and in various countries. A typical and symbolic extent of computer application for various design stages is shown in Figure 3.

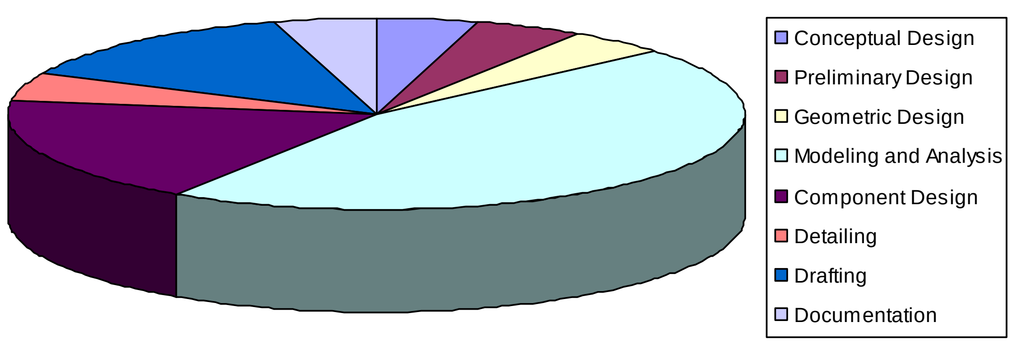


Figure 3: Approximate Extent of Computer Applications in Bridge Design Steps

The type of computer application and computing tool used for each design step is summarized in Table-1. We will briefly discuss these applications and tools, with more focus on the Modeling-Analysis-Design steps as that has the widest application.

Table-1: Computer Applications in Design Steps

Design Step	**Computer Application Type**	**Sample Software**
Conceptual Design	Expert Systems, Artificial Analysis Systems, Value Engineering,	ANSYS/Civil FEM Bridges
Preliminary Design	Standard Database and Libraries, Expert Systems	ANSYS/Civil FEM Bridges
Geometric Design	Alignment and functional design	SAP 2000 Bridge Modular, ANSYS/Civil FEM Bridges, Bridgade, LEAP Bridge, QConBridge, SAM, MIDAS-WinBDS
Modeling and Analysis	Finite Element Analysis	SAP 2000 Bridge Modular, ANSYS/Civil FEM Bridges, Bridgade, LUSAS Bridge, LEAP Bridge, QConBridge, SAM, STRAP AutoBridge, ACES, MIDAS-WinBDS
Component Design	RC Design, Steel Design, PSC Design, Footing Design…	SAP 2000 Bridge Modular, ANSYS/Civil FEM Bridges, Bridgade, LUSAS Bridge, LEAP Bridge, QConBridge, SAM, STRAP AutoBridge, ACES, MIDAS-WinBDS
Detailing	Automated Detailing, Computer Aided Drafting	SAP 2000 Bridge Modular, ANSYS/Civil FEM Bridges, Bridgade
Drafting	Computer Aided Drafting	SAP2000-Bridge Modular, LEAP-Bridge, MIDAS-WinBDS
Documentation	Analysis and Design Programs, Word Processing, Spread Sheets, Database	MSWord. Excel, Access, SAP 2000 Bridge Modular, Bridgade, LEAP Bridge, QConBridge, ACES, MIDAS-WinBDS

3.0 Developments in Computer Applications

We will now review the major developments in computing tools and techniques and their overall application and relevance to bridge project design stage. Later, more specific and detailed discussion of the issues involved in the bridge modeling and analysis will be discussed together with developments in bridge modeling.

3.1 Developments and Application of Expert Systems

The Expert system capture the experience and expertise of the established experts in set of rules and attempts to provide solution to the problem by successive decision making following a decision tree and corresponding logic. The early developments in Expert Systems and Artificial Intelligence showed a lot of promise and potential and were trumpeted as the future of computer applications and automations. However, this promise has not lived up to the hope, especially in the realm of structural and bridge engineering. The application of Expert Systems in bridge design has been limited and has been used primarily for conceptual design and preliminary design stage or for evaluation and rating [2]. At this time expert and knowledge based system are being used for bridge rating, bridge system selection, damage assessment, bridge planning, bridge evaluation, bridge management etc. Some of the conceptual and preliminary design tools use a database of previously completed bridge projects and suggest the solution to a new problem by simple information search and matching or by using more elaborate methods such as Linear Programming (LP), Fuzzy Logic (FL), Artificial Neural Networks (ANN), Genetic Algorithms (GA), or Analytical Hierarchy Approach etc [2]. The current research and application of expert systems seems to be on the decline.

3.2 Developments in Finite Element Modeling and Analysis

The most significant application of computers in the field of computing has been the development of Finite Element Method (FEM) and the Finite Element Analysis (FEA). Finite Element Method can be used to determine the response of any continuum problem governed by total or partial differential equations. The main link between the use of the FEM and the real world problem is the Finite Element Model. The structure is of a finite size and it made up of an assemblage of substructures, which can be divided into structural components, one at continuum level, and other at global structure level. Structure can be considered as an assemblage of "Physical Components" called Members such as Slabs, Girders, Beams, Piers, Columns, Footings, Piles etc. These physical members can be modeled by using one or more "Conceptual Components" called Elements such as 1D elements, 2D element, 3D elements or frame element, plate element, shell element, solid element, etc.

The key to proper use of FEA is the ability to represent the real structure and its behavior in most appropriate finite element model. The approach to the generation of FE model has undergone several phases. In Phase 1, mostly developed and in use before the 1980s, the Nodes are defined first by coordinates and then Elements are defined that connect the nodes. This was mostly done through data files and text base scripts that were interpreted by the programs to generate the model. The loads and other assignments, such as materials, supports etc were directly applied to the nodes and elements. During Phase 2, starting somewhere in the 1980s and 1990s, the Elements are defined directly, either numerically or graphically and the Nodes are created automatically at the intersections. Alternatively, the nodes are generated graphically and elements are drawn in between. During this phase, several mesh generation tools were also developed. In Phase-3, which is in current development stage, the structure is represented by generic objects and the elements and nodes are created automatically by the program as needed. Another aspect of this Phase is also the greater use and popularity of Parametric Models. More details about the object based and parametric models in context of the bridge modeling and analysis will be discussed latter in this paper.

Significant developments have taken place on the solution aspects of the finite element models. Models can now be analyzed for linear static response with elastic material assumptions to determination of fully non-linear response of dynamic systems with inelastic materials. Specific solutions have been developed to handle non-linear Pushover Analysis, sequential construction analysis, buckling analysis, P-Delta analysis, large displacement analysis, incorporation of time depended material models and so on. Several specialized elements have been developed to handle tension only behavior, compression only behavior, contact problems, friction problems, non-linear hinges, dynamic isolators, area and volumetric springs etc. Again, the relevance and application of these analysis techniques and elements will be discussed in the following sections.

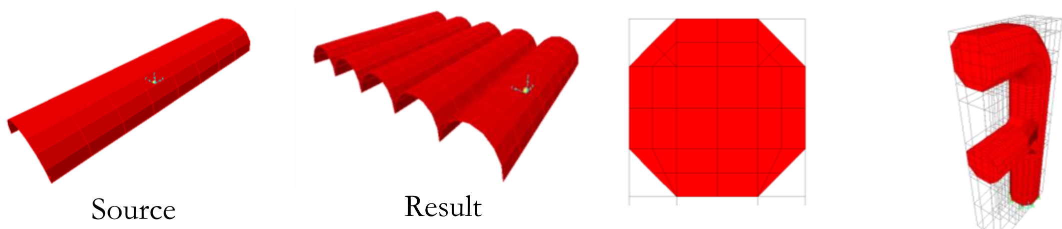
3.3 Developments in Component Design and Detailing

Unlike structural analysis that can be consistently carried out for structures made of different types of materials, the component or member design and detailing heavily depends on the type of material as well as the design codes being used. The development in design of steel members is fairly mature and several software carryout the design extensively. The aspects sometimes not considered may be fatigue, local buckling, locked in stress, certain type of stability issues etc. The design of reinforced concrete, pre-stressed concrete and composite materials is often not fully integrated with the analysis programs and many designers find it more appropriate to carry out the design separately either using specialized software or programs developed in-house following local and organizational standards and practices. Although are a large number of software for isolated member design, most of these are for columns, beams, slabs, footings and walls in residential, industrial and multistory buildings.

3.4 Advanced Modeling Technique in FEM

There has been quite a lot of development in the modeling tools and technique with advanced features that expedites the process of model generation. Some of these modeling features are: geometric transformations, replication, extrusion, auto meshing, parametric structures, mesh subdivision, mesh clipping, nonlinear links, rigid offsets, constraints, restraints, etc. These features can be classified into two groups. The first group is to create the model property and the second group is to modify the model to capture the particular behavior or particular response. So, transformations, replication, extrusion, auto meshing, parametric structures expedites the creation of model while constraints, restraints and all links are in second group.

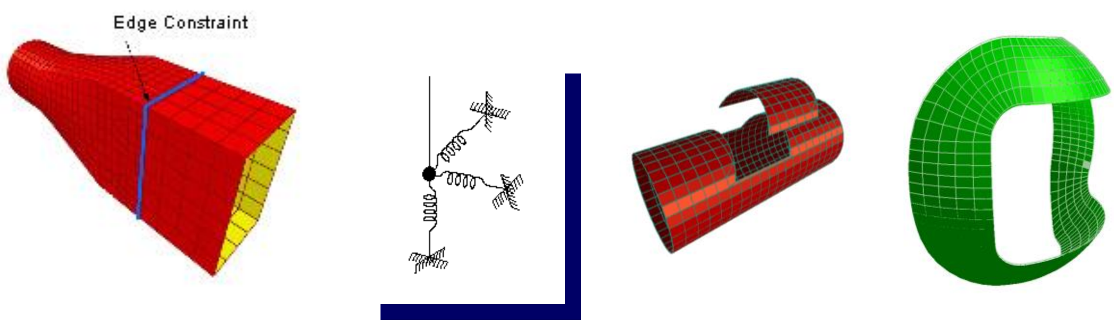
The geometric transformation allows a parametric object drawn in local coordinate system can be transferred to global coordinate system or vice versa. A parametric structure can be scaled in X or Y-directions or can be rotated in different axes. So, for any selected object eight composite transformations can be applied along local and global for scaling, mirroring, rotation, and translation. The Replicate feature produces replicas of selected object. Replication command replicates section and material, meshing, constraints and restraints, masses, stiffness modifiers and local axis properties. Replication could be linear or at equal interval or at non-equal interval. Similarly, the extrusion features creates new objects of higher dimension for a selected objects. The process of extrusion increases the dimensional space of an existing object by one. For example: Line objects are of one dimension that can be generated from a dimensionless point object. Two-dimensional area or plate/shell can be generated from a one-dimensional line object. This feature is especially suited to creating solid elements from plate/shells, plate/shell elements from beams and beams/columns from point/nodes. The Parametric Structures is very powerful technique that enables to add objects or structures from template files or parametrically defined entities which ease in constructing models and saves time while generating complex structural models. The next useful technique is to subdivide the mesh appropriately. Object based model would require that the object is converted to elements automatically. Automated meshing bridges the gap between modeling objects and finite elements. Automated meshing also helps in automated load calculation and application. For automated meshing first draw or define overall structure geometry in terms of Physical Objects. Then the program uses specified rules to convert Objects to valid Finite Element Mesh. Analysis is carried out using elements and results presented in terms of Objects without changing the number of objects in the model. Some examples of the model creation by using these advanced modeling techniques are shown in Figure 4.



(a) (b)

Figure 4: (a) Replication of similar object, (b) Extrusion of solid model from shell element

A constraint, restraints, and non-linear links model the particular behavior of the joint or element in the model. The displacements of each pair of joints in the constraint are related by constraint equations. The types of behavior that can be enforced by constraints are: rigid-body behavior, equal-displacement behavior, and symmetry and anti-symmetry conditions. Different types of constraints can be used in model depending on type of behavior. For example: Body Constraints, Diaphragm Constraints, Plate Constraint, Rod Constraint, Beam Constraint, Equal Constraint, Local Constraint, and Weld. Similarly, if a displacement along any one of its available degrees of freedom, such as at a support point, is known then that degree of freedom can be restrained. The known value of the displacement may be zero or non-zero, and may be different in different Load Cases. The restraint reaction is determined by the analysis and the unavailable degrees of freedom are essentially restrained. The restraint forces and moments are required to enforce the restraints and these reactions are computed as the sum of the applied loads, stiffness forces, spring forces, and NL Link forces acting on the restrained degrees of freedom and results are given only for joints that possess restrained degrees of freedom. When one or two elements are combined together that are passing through or intersecting or overlapping, then there is possible to either intersect the mesh or remove the unnecessary mesh, but the boundary nodes may not match. With the introduction of line constraints and area constraints, even if joints are not matching at the boundary the connection can still be established. This mesh clipping can be defined by Plane, by Cylinder, by Tube, by Cone, by Sphere, by Surface, or by Parametric Objects. Mapping is selected to mesh on to a specified surface which can be Plane Area, Cylinder, Sphere, Cone, or Surface. Some examples of the model modification by using these advanced modeling techniques are shown in Figure 5.



(a) (b) (c) (d)

Figure 5: (a) Edge Constraint, (b) Joint Restraint, (c) Mesh Clipping, (d) Mesh Mapping

Most of these developments are extremely important for generating models for bridges. For example extrusion can be used to generate mesh for box girders for a complicated alignment. Also, replication and transformations can be used effectively to generate complex bridges on local coordinate systems.

4.0 Developments in Bridge Modeling and Analysis

In the earlier stages of development in finite element analysis different types of structures or modeling problems needed to be defined directly in terms of nodes and elements and the solver program were unaware of the type of problems being solved. However in the later stages more specialized software started to emerge providing higher level of problem abstraction. For example, programs like ETABS specifically focusing on modeling and analysis of tall buildings were introduced almost 30 years ago. There were several specialized software for bridge modeling and analysis but they were typically developed and used in-house by bridge designers and related departments. These days the developments in the core finite element solutions has almost been standardized and the focus has turned to development of software that works more closely and directly in the problem domain often hiding the underline solutions. Several software are now available that have been developed customized or specialized to handle various aspects of bridge design such as LUSAS, SAP2000 Bridge Module, ANSYS/Civil FEM Bridges, BRIGADE, BD3, LEAP Bridge, MC3D, QConBridge, MIDAS-WinBDS, SAM, STRAP, etc.

These programs handle varying levels of the bridge design problem such as: modeling and analysis, integrated design, component design, substructure design, and some handle integrated geometric and structural design. Rather than discussing specific program and their features, we will focus on idealized software that would handle the entire bridge design process in the unified and integrated manner. This idealized software may be considered as model for future computer application in bridge engineering.

4.1 Special Issues and Specific Modeling Problems

Before we present the future approach lets review the current state of the art as well as the basic issues involved in modeling and analysis of bridge structures and how they are being handled or may be handled. The modeling and analysis of bridge structure present some unique problem not found in other structures such as tall buildings and industrial structures, as discussed in Table-2.

Tabe-2: Some of the General Issues involved in Modeling and Analysis

Modeling Issues	Solution
The problem of the moving loads	Traditionally this problem has been handled by influence lines and influence surfaces. However, in computer aided analysis, this may be handled by automatic generation of multiple load cases representing moving loads. Many programs generate vehicles, traffic lanes following the road alignment compute the corresponding post processing of results. Some programs also generate animated display of deformations and stresses.
The joints that must allow movement while transferring loads and forces	Unlike in building, where the expansion joints separate parts of the structure completely, in bridges, the joints are often required to transfer heavy loads, while allowing movement. This presents special modeling issues for selecting appropriate connection elements and introduces non-linearity. Even a simple elastomeric bearing is difficult to model properly if right tools are not available. This issue is discussed further in greater detail.
The interaction between the post tensioning design and the basic behavior	Generally post tensioning is designed to counter the actions obtained from analysis. However, as many bridges are indeterminate structures, the secondary effects of pos-tensioning affect the basic response, hence complicating the analysis and design cycle.
The large proportion and scale of the structure and its components	Most of the structural components in buildings are of such proportions that they can be modeled as line or frame elements. However, in bridges often members are of massive proportions requiring more refined models using shell or solid elements. Also the

	assumptions of linear strain distribution may not hold true in many cases, specially at junctions and joints. Often several types models may be needed to complete the analysis of some parts.
The inter dependency of construction methods, construction sequence, modeling and design	The construction sequence and construction methodology greatly effect the modeling as well as analysis, specially for segmental construction, cantilever construction, incremental launching and construction of cable stayed bridges. Not many software are equipped to handle the aspects
Large number of different load cases and combinations	Bridges are subjected to or must be analyzed for a large number of load types and cases arising from environmental factors, construction sequence, vehicle movement, time dependent effects, post-tensioning etc. This also leads to a very large number of load combinations to be considered in member design. Many programs are capable of generating most of the code specified load combinations, but may not be able to handle some of the loads such as vessel or vehicle impact.
Extensive nonlinearity inherently present in the structure itself	Several of the major bridge systems , such as cable stayed, suspension, tied arch, cantilever, stressed ribbon etc. posses high degree of non linearity due to presence of cables, coupled effect of creep, differential movements, relaxation etc. Again, not all programs can carry out the desired non-linear analysis.
Complexities due to wind induced forces and motion	The collapse of the Tacoma bridge due to wind induced oscillation is well known. Many long span bridges with flexible decks are susceptible to flutter, vortex shedding and even hyper elasticity with significant interaction between structure and wind. Not may software are capable to handle wind analysis properly, and often wind tunnel tests are carried out to supplement the analysis.
Complexities in dynamic response	Due to large dimensions and often different types and scale of members, the local dynamic response of such model may affect the global dynamic response, specialty when determining primary time period, mass participation and mode extraction. Also, sometime multiple but independent support excitation may be needed for seismic analysis of long span bridges, with possibly different response spectrum or time history functions. Much software may not be equipped to handle such scenarios.
Special modeling needs for	The proper modeling of joints, bearings and

handling bearing, joints and connections	connections is very important for the determination of bridge response, specially for lateral; and longitudinal faces. The assumptions of simple, pin, roller or fixed supports are often inaccurate. Most of the joints and bearings behave in a highly non linear manner. Only software that has the capability of handling non-linear links and connections can be used effectively.
Special problems involved in the modeling of abutments and foundation	Modeling of abutments can be significantly difficult. Active-passive response, the soil structure interaction combined with the non-linearity of the bearings, anchor blocks, restraining blocks etc. complicate the behavior and hence modeling and analysis. This aspect is further discussed in this paper in greater detail.
Complexities in generating finite element models to account for geometric design.	The geometric design requirement such as curved decks, super elevation, vertical curves, skewed supports, merging and diverging bridge decks, very tall piers and towers, variable depth and width multicell box girders, etc make the generation of models a very difficult problem. However, several tools are now available in many programs to assist in this modeling task. This is further discussed in the next sections.

There may be other specialized issues to be considered in some bridges, such as:

- The temperature effect caused by heat of hydration in hollow thin pier
- Vibration of bridge due to vehicular high-speed movement such as high speed train
- High water level during construction period
- Performance of bridge under blast loading

The issues involved in the modeling and analysis of Category-2 bridges such as cable stayed and suspension bridges are listed below separately because of their greater popularity and significance.

- Modeling of Cables and Hangers
  - Consider the nonlinearity due to cable profile and material
  - Consider the pre-tensioning and multiple stressing cases
  - Consider the partial fixity at anchors and local anchor forces
  - Consider the dynamic response, flutter, resonance etc
  - Local modeling and design of saddles and anchors, including fatigue

- Modeling of Deck
  - The extent of deck model and level of detail. Several models may be needed
  - Composite action, transverse load transfer, tensional stiffness and modeling
  - Axial forces in the entire deck, stiffening and softening

- Modeling of Pylons
  - Modeling the Flexibility and Stability

- Partial construction loading and unbalanced conditions
    - Interaction of pylons and cables
    - Stability, P-Delta, Buckling, Verticality etc.

- Modeling of Expansion Joint systems
    - Accommodating Large movements (as much as 0.5 m or more)
    - Transfer of large forces

- Modeling of Foundations
    - Very large loads and moments from pylons
    - Modeling of Water waves, collision etc
    - Soil-structure-water interaction
    - Anchors and dead-man modeling and design

5.0 Modeling of Bridge Components

We have seen above that there are several issues involved in the modeling and analysis of bridges. We will now consider the modeling of specific parts or components of the bridge structure in more detail. The bridge structure is divided into two parts: superstructure and substructure. The superstructure consists of bridge deck and the substructure consists of pier bents and abutments and foundation (pile cap, piles, caissons, footing). The overall bridge components are illustrated in Figure 6.

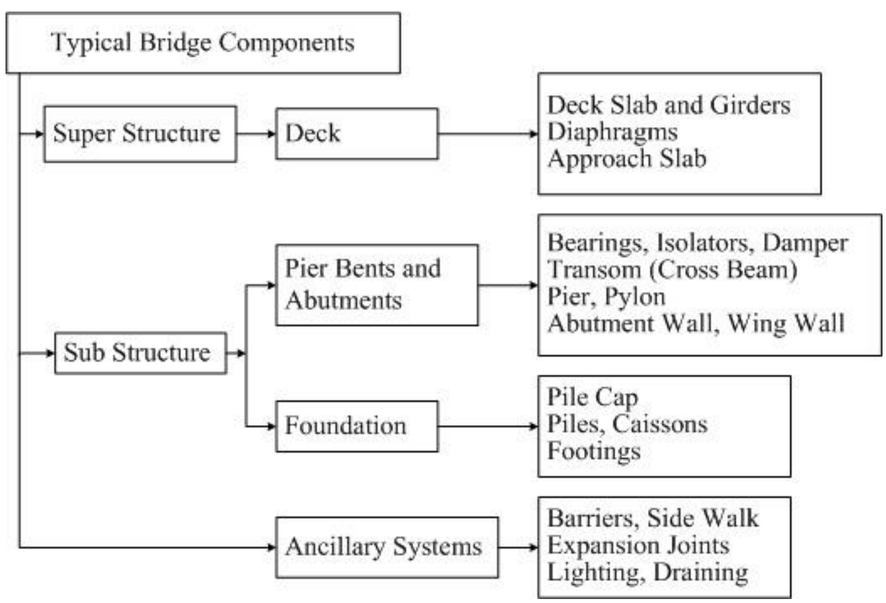


Figure 6: Overall Bridge Component Hierarchy

5.1 Modeling of the Bridge Deck

Finite element based analysis of bridge deck structures is a common practice in bridge design these days. The deck could be modeled in several ways ranging from simple single element spine model to a sophisticated full 3D solid/shell representation. The effort required to generate, analyze, and interpret different type of models of various complexity varies considerably. In addition, different models provide varying amount of results and insight into the behavior of the deck system. The bridge deck can be modeled using various FE model such as: Beam Model, Grid Model, Grid-Plate Model, Thin Wall model, and Plate-Shell Model, Solid Model as shown in Figure 7. Each model has its own advantages and suitability for modeling of the deck.

In the Beam Model, the bridge deck can be modeled by equivalent beam element either as Simple Beam Model (single beam at CL of deck) or as Full Beam Model (every bridge component modeled by beam elements). The simplest model for bridge analysis is suitable for "Longitudinal" analysis only, and when used properly can give reasonable results. The results from Beam Model can be used directly for the design of the deck section for moment, shear, axial force and torsion. This modeling technique is suitable for gravity, traffic, prestress and lateral loads. The Full Beam Model can be used for 2D (in-plane) as well as full 3D Analysis.

In the Grid Model, the deck is modeled as a grillage made from beam elements. Girders, Slab, Diaphragm etc are all converted to equivalent beams. This modeling technique is generally suitable for out-of plane analysis for gravity and traffic loads and modeling of I beam or T beam deck with diaphragms. This modeling technique can be used for both 2-D and 3-D analysis. This technique can be combined with the full Beam Model.

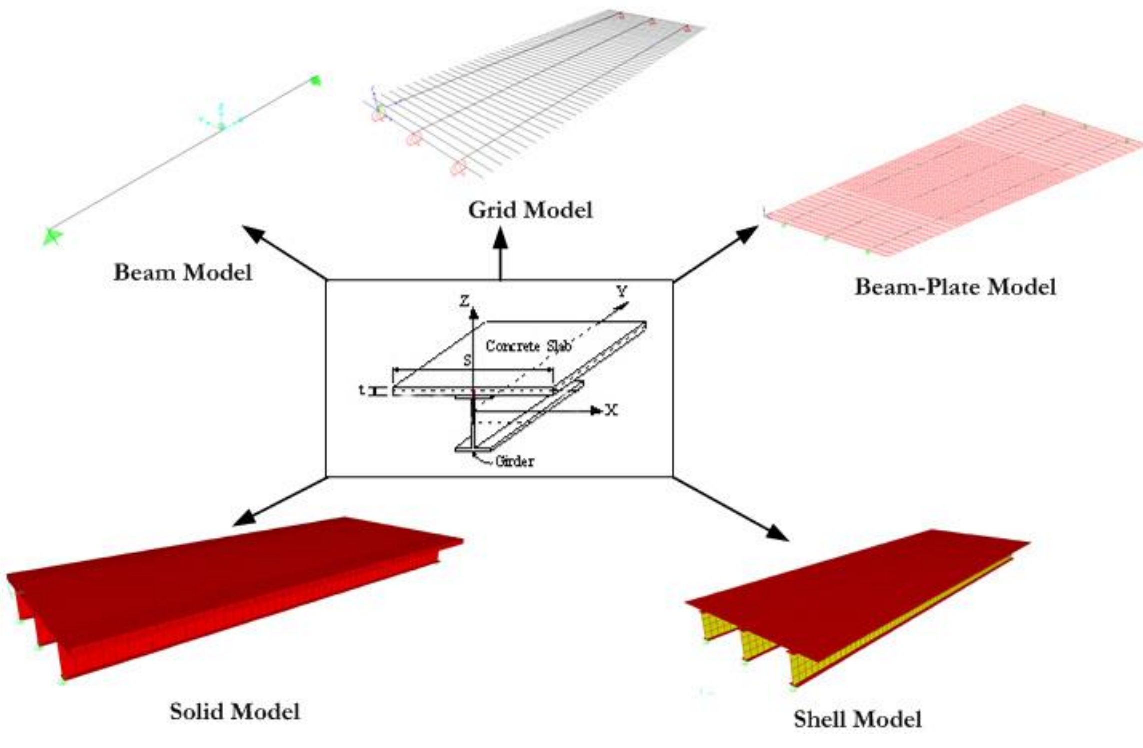


Figure 7: Modeling of the Bridge Deck

Beam-Plate Model is the combination of beam and plate elements in which girders and diaphragms are modeled with the beam element and the slab is modeled with the plate element. The use of the plate element improves the modeling of slab behavior in comparison with Grid Model.

In Thin-wall section model, deck section is modeled with the modified thin-wall element. Thin-wall element is 4-node quadrilateral element in which the distortion in plane of thin-walled cross-section is neglected. This thin walled element is modified to six-node element such that its geometry is a quadrilateral element with four auxiliary nodes at corner and two sectional nodes common to all elements in the same plane.

In Plate-shell model, all girders, diaphragms, slabs etc., are modeled with the plate elements. This model is suitable for detailed analysis in transverse as well as in longitudinal direction. This modeling technique can handle bridges of arbitrary cross-section and geometry. It is especially suitable for deck slab analysis, highly skew and curved bridges.

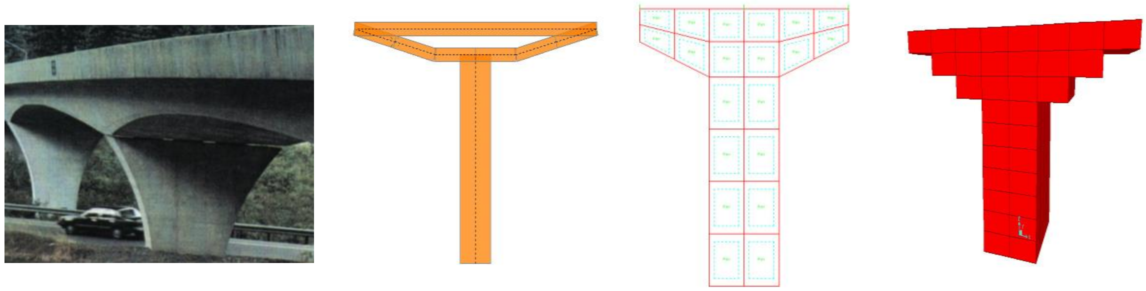
5.1.1 Modeling Issues in Bridge Deck

Several issues arise while creating analytical model for the deck slab and girders. Such as:

- The eccentricity between the deck slab with the flange and the girder cross sectional centroid
- The effective width of the slab carrying the wheel loads
- The effects of deck skew , the effect of non-rectangular slab
- The effect of the diaphragm connection with girder
- The eccentricity of the girder cross sectional centroid from the bearing top level
- The shear connection between the slab and girder
- The stiffness of the portion from top of girder's top flange to the slab mid plane
- The torsional stiffness of the slab
- The effect of the deck span to deck width ratio
- The shallow arching effect of the slab between the girders
- The orthotropic nature of the slab stiffness due to different reinforcement ratio in longitudinal and transverse direction
- The effect of slab cracking, the effect of the longitudinal compressive force in the slab on its flexural behavior
- The effects of the shear lag of the longitudinal compressive stress etc.

5.2 Bridge Pier

The design of bridge piers needs special considerations for loading, framing and cross-section. The loading consideration is affected be type of loading and number of loads. The bridge piers are generally subjected to several hundred or even several thousand load combinations or loading sets. The large number of loading sets can originate because of moving load analysis and or due to dynamic and non-linear analysis. The large number of load sets can be however reduced somewhat by using the concept of "corresponding actions". The bridge piers are often subjected to well define uniaxial or nearly uniaxial moment directions due to use of special bridge framing and bearing conditions. For example, for bridge deck supported continuously on several columns or piers, most of the intermediate piers are not connected to the deck and hence are not subjected to moments in that direction. However in the transverse direction, these piers act as cantilevers to resist the wind and the seismic forces, causing large moments. Due to this well-defined moment direction, the pier cross-section can be optimized both for shape and reinforcement distribution.



(a) (b) (c) (d)

Figure 8: (a) Bridge Pier (b) Beam Model (c) Shell Model (d) Solid Model

5.3 Abutment

The main role of abutment is to resists the gravity loads and additional role due to seismic loads. The abutments retain the soil on road way side, support the vertical component of girder reaction, accommodate bearing movement due to temperature change and elastic shortenings, provide restrain for lateral reaction due to longitudinal loads and impart and resist longitudinal loads due to mass-acceleration

The behavior of abutment depends on the type of abutment and intended purpose. In general, the overall behavior is govern by active soil pressure causing over-turning towards the span, imparts passive pressure to the soil due to longitudinal forces and movements, vertical load transferred to the soil either through retaining wall or through the transom and pile system. Some of the modeling issues in the abutment include:

- Simultaneously modeling of the active and passive soil pressure
- Consideration of the soil "stiffness" when subjected to passive loading
- Modeling of soil separation when deck moves away from the abutment
- Modeling of the behavior of restraining blocks for seismic movement
- Modeling of the elastomeric bearings
- Consideration of the damping effect
- Consideration of soil dynamic, non-linear and liquefaction effects

There are various modeling options of abutment that handles these issues which are as follow:

<u>(a) Modeling as Frame Nodal Support (Option A)</u>

In this modeling technique supports are consider either as pin or a roller. If both supports are considered as roller, then all longitudinal loads should be resisted by the piers. If roller-pin combination is considered then amount of longitudinal load transferred to pin-end will depend on the stiffness of piers, length of deck, joint between the pier and the deck. This approach may be appropriate for preliminary analysis, especially when using frame model. This modeling technique does not consider the stiffness movement effects.

(b) Modeling as Frame Spring Support (Option B)

In this modeling technique the sprint support is use to represent the combined stiffness of the bearing, the abutment and the passive resistance of the soil. The spring stiffness can be computed based on the shear modulus of the bearings, lateral modulus of sub-grade reaction of soil and the contact area.

(c) Modeling as Frame Support Node and Linear Link (Option C)

The linear link is used instead of spring support to represent the combined (lumped) stiffness of all elements involved.

(d) Modeling as Frame Support Node and a Non-linear link (Option D)

The non-linear link can model the linear stiffness as spring, as well as capture non-linear behavior, such as soil separation, expansion joint, restraining block, soil liquefaction etc.

(e) Modeling as Frame Support Node, Non-linear Link and Damper (Option E)

This modeling approach can model all of the behavior in D, in addition the combined effect of modal and material damping. This option is most comprehensive and can be used efficiently in frame models. Options C, D, E require manual determination of stiffness, nonlinear and damping properties for springs, links and dampers.

(f) Modeling as Plate Elements, Links, Dampers and Springs (Option F)

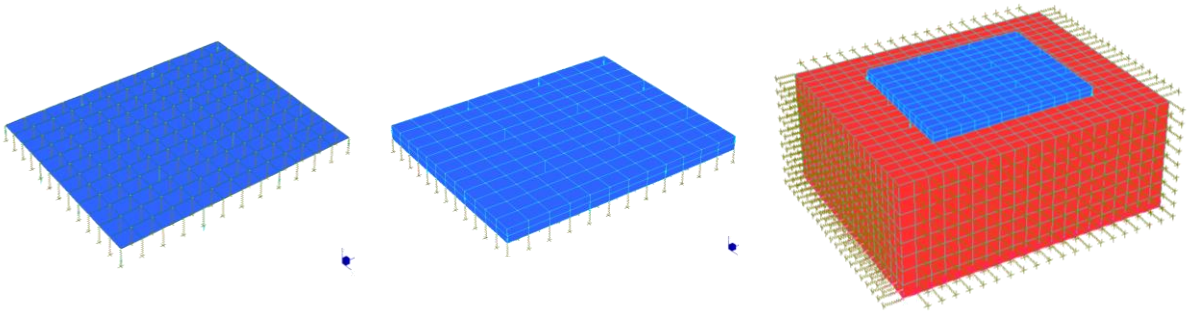
The abutment wall is modeled with plate elements and the soil is represented as springs. The connection with the deck is modeled by links and dampers.

(g) Modeling as Plate Elements, Links, Dampers and Solids (Option G)

The abutment wall is modeled with plate elements and the soil is modeled by solid elements. The connection with the deck is modeled by links and dampers. The connection between soil and wall may be further modeled by non-linear links

5.4 Foundations

The footing of bridge can be of various types such as Isolated Footings, Combined Footings, Rafts, Pile Cap, Special Supports, Pile, Piers, and Caissons. The actual supports condition is modeled as Pin, Roller, Fixed or spring or using plate, shell or solid elements reflecting a realistic behavior of actual support. The selection of foundation model would effects mode shapes, time periods, lateral and longitudinal drift of the structure. The conventional approach of foundation modeling ignores soil-structure interaction and assumes rigid structure when computing soil response and rigid soil when analyzing structure. In this approach foundation is model as fixed support, pin support or roller support, and settlement if any is applied along that particular degree of freedom. In more accurate approach, foundation and soil is model and analyze together considering soil-structure interaction. A spring is use to represent elastic soil whose stiffness depends on modulus of sub-grade reaction of soil. The full structure-soil model is generated using 2D plane stress elements or 3D solid elements as shown in Figure 9. During foundation modeling, certain factors should be consider such as: soil type below the footing, soil type at greater depth, size of footing, shape of footing, eccentricity of loading, footing stiffness, superstructure stiffness, modulus of sub-grade reaction etc.



(a) (b) (c)

Figure 9: (a) Modeling of Foundation as plate element and Soil as spring element, (b) Modeling of Foundation as brick element and Soil as spring element, (c) Modeling of Foundation and Soil as brick elements

5.5 Modeling of Joints and Bearings

Bearings connect the superstructure with the substructure and allow for movements, yet transfer forces too. There are many types of bearings and the choice of which type to use depends on the forces and movements to be accommodates and on the maintenance. In finite element models, by default all elements connected to a node share the Nodal Degree of Freedom (DOF). This is suitable for fully connected structural members but at Joints, full connection may not be available or desired. We can either "release" or "constrain" the DOF to change this default behavior and to model joints. Effectively modeling of support conditions at bearing and expansion joints (as shown in Figure 10) requires careful consideration of the continuity of each translation and rotational components of displacement. Joints may behave linearly (such as roller, pin, elastomeric pads) or non-linearly (such as expansion joint, gap, restraining block, Gap or Hook). The degrees-of-freedom of element representing discontinuous components must be disconnected. Stiffness/ flexibility of bearing pads and other connections should be modeled using appropriate finite element method. The bearing and expansion joints can be modeled using Constraints or using Releases.

While modeling the bearing and expansion joints using Constraints, more than one node at the same location are used to connects individual elements which automatically disconnects all degrees-of-freedom between the elements. The connected degrees-of-freedom are constrained together using equal or local constraints as shown in Figure 11. While modeling the bearing and expansion joints using Releases, several elements are attached to a common joint which automatically connects all degrees-of-freedom between the elements. The frame element end releases are used to free the unconnected degrees-of-freedom as shown in Figure 12.

The use of nonlinear links and springs for modeling of the bearing and expansion joints is especially useful for modeling of elastomeric bearings, semi-rigid connections, elastic connections and passive resistance of soil within the elastic range. The elements are connected to each other by spring elements or equivalent spring elements in appropriate DOF as shown in Figure 13. Various nonlinear links used for modeling includes multi-linear elastic, multi-linear plastic, damper, gap, hook, rubber isolators, and friction isolators.

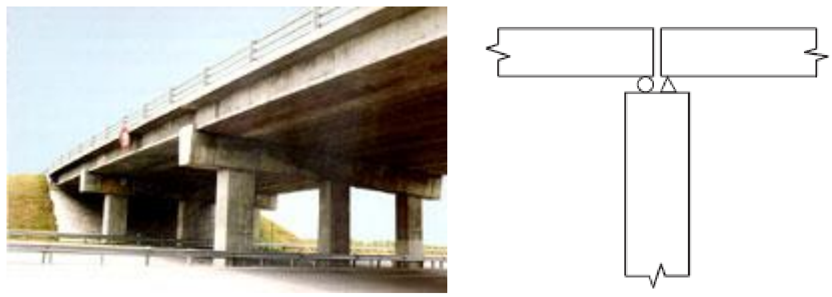


Figure 10: Bridge Deck and Piers

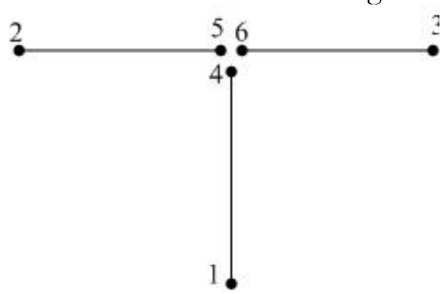


Figure 11: Use of Constraints on separate joints at common location [3]

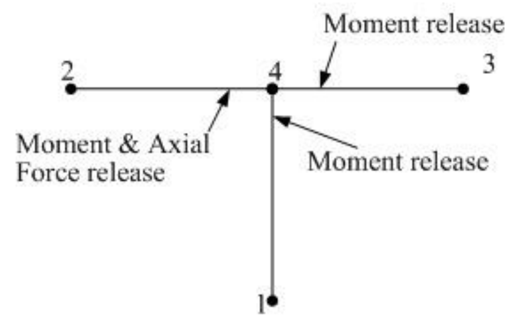


Figure 12: Use of common joints and elements end releases [3]

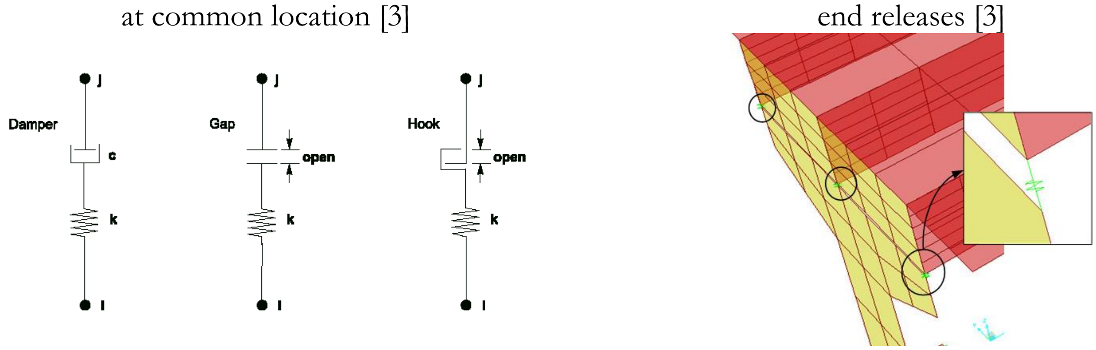


Figure 13: Using Nonlinear Links and Springs to model bearing between abutment and pier

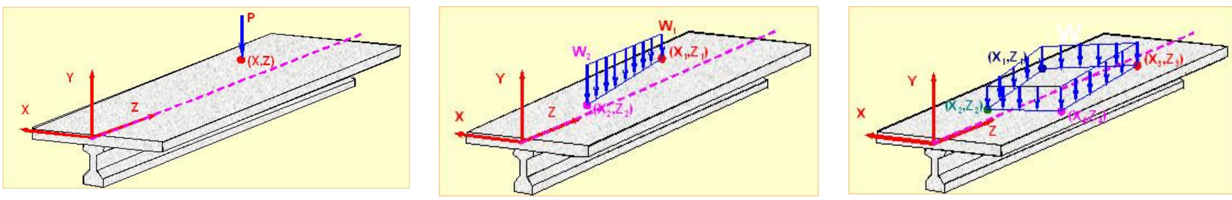
6.0 Loads on Bridges

For bridges, it is often necessary to consider phenomena which would normally be ignored in buildings. For example, effects such as differential settlement of supports, effects of shrinkage and creep, exceptional loads (such as snow) and construction loads, earth pressure on substructures etc. These loads on bridge can be classified as externally applied, or internally generated, primary load, secondary load, extraordinary load, static or dynamic load, permanent or transient load, deterministic or non-deterministic and environmental load or man-made load.

The loads affecting the behavior of bridge includes: Permanent loads (such as: dead load of structures, dead load of nonstructural components, prestressing at given time), Traffic loads (actual, impact), Construction, handling, erection loads, Braking, acceleration and centrifugal forces, and Wind Load and Seismic Load.

6.1 Dead Loads on Bridges

The superimposed dead load is the gravity load due to structure and other items permanently attached to it. These loads can be applied as the element loads or as nodal loads. For Beam Model, it is applied as UDL over the length, for Shell Model applied as UDL over the area, Special loads applied as Point Loads. Almost any load can be represented as combination of point, line, area and volume loads.



(a) (b) (c)

Figure 14: Modeling loads on decks (a) Point Load, (b) Line Load (c) Area Load

6.2 Traffic and Highway Loads

Traffic and Highway Loads categorized as live loads and their importance is due to their movement on the bridge. As they are not stationary, therefore, they are applied in such a way that maximum moment; maximum shear and maximum stresses are obtained for designing purpose. In case of beam model, the whole load of wheels on same axle are combined together to form a single load. Maximum moment can be determined by applying these different axle loads in appropriate places for longitudinal beam model. In the case of transverse direction, maximum moment is obtained by placing the loads considering in transverse direction only. A separate modeling may be needed for Longitudinal and Transverse analysis in case of Thin Wall and Plate Models. For longitudinal direction moment, the meshing in transverse direction need not be fine and loads of wheels on same axle may be added together. The location of load for maximum transverse effect may not be the same as that for longitudinal effect. Most of the bridge design software include some form of automated handling of moving loads. SAP2000 for example, allows automatic application of standard or custom truck loads along lanes defined by the user. This program can determine the envelops of stresses and deformations at specified stations or locations and even generate animated displays as truck moves along the lanes.

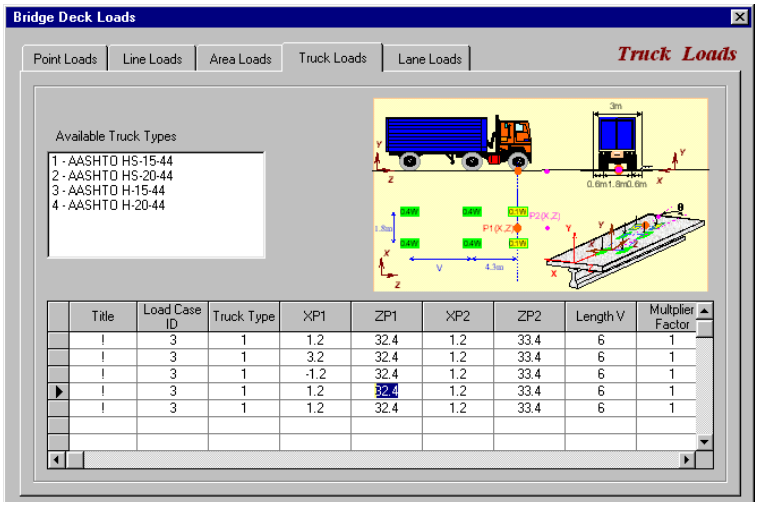


Figure 15: Modeling of the Truck Load in SAP200

6.3 Temperature, Shrinkage and Creep

A differential temperature between top and bottom bridge deck develops stresses in bridge and causes the bridge to bend. Also, annual temperature variation causes significant movement in the deck, causing stresses in piers and abutments. In case of locking of bearing large in-plane forces may develop in deck itself. In case of Beam model the temperature loads to any member can be applied as a form of fixed end moment caused by the temperature changes. For the cases of Thin-wall and Plate model the temperature loads can be applied as the initial strains caused by the temperature changes to each element. The effect of Shrinkage and Creep of concrete can also be applied as the load by converting the expected creep and shrinkage strain in to an equivalent temperature strain. In post tensioned bridges, the log term effects can greatly alter the stress distribution. Many software now handle these loads automatically or by defining specific load cases.

6.4 Handling of Prestress in Bridge Models

Prestressing force is converted to equivalent load on the deck using cable force and cable profile. In the conventional bridge design, the Bridge is modeled and analyzed for dead load, live load and other loads and then pre-stress is designed and then section stresses are checked for combined effect of actions and pre-stress. However this approach is not suitable for continuous structures or where secondary effects due to prestressing are significant. In integrated approach of bridge design Prestressing is considered as just another load and the final stresses are obtained directly from the final actions. This approach is suitable in every case however iteration is required right from the start to estimate Prestress. A combination of these two approaches is often suitable for handling of Prestress in analysis and design. There are several advantages of using this integrated approach;

- The prestress forces are applied to the full structural model the secondary effects are automatically included
- Load Balancing analysis is not required
- Effect of prestressing on the entire structure is evaluated including the continuity, stiffness, shortening, shear lag, eccentricities, etc.

- Most software have the ability to compute stresses and stress profiles for computed actions so no separate stress calculations are needed
- Effects of sequential construction, staged prestressing, etc. can be carried out more comprehensively
- Prestressed structures are more suitable and relevant for linear-elastic analysis mostly used by general FEM Software
- The interaction of axial load, moment and prestress load can be considered more consistently

7.0 Current Software Tools

Features and comparison of some of the software currently available for bridge analysis and design are listed in Table 3. This list can be used for software selection and evaluation as well as observe the trends in computer application in bridge engineering.

Table 3: Features available in various software for bridge analysis and design

SOFTWARE FEATURES		**SAP2000-Bridge**	**Ansys\Civil FEM Bridge**	**LUSAS-Bridge**	**Leap-Bridge**	**ADAPT-ABI**	**SAM**	**Midas-WinBDS**	**BRIGADE**	**RM2006**	**QConBridge**
Bridge Layout			●								
Preliminary Design			●								
Geometric Design	Element Library	●	●	●	●	●	●	●	●	●	●
Bridge Model	Arch Bridge	●	●	●	●	●	●	●	●	●	●
	Segmental Bridge		●	●	●	●	●	●		●	
	Slab Deck Bridge	●	●	●	●	●	●	●	●	●	●
	Box Girder Bridge	●	●		●	●		●	●	●	●
	Cable Stayed Bridge	●	●	●	●	●		●	●	●	
	Suspension Bridge	●	●	●	●			●	●	●	
	Integral Bridge			●	●				●		
Structural Analysis	Static	●	●	●	●	●	●	●	●	●	●
	Dynamic	●	●	●				●	●	●	
	Heat Transfer							●	●		
	Construction Sequence	●	●	●		●	●	●	●	●	
	Soil-structure Interaction			●							
Loads	Moving Load	●	●	●	●		●	●	●	●	●
	Prestressing	●	●		●		●	●	●	●	●
	Creep/Shrinkage	●	●		●		●	●	●	●	

Component Design	Bridge Deck elements	•	•	•	•		•	•	•	•	•
	Abutments	•	•	•	•			•	•	•	•
	Piers and Columns	•	•	•	•			•	•	•	•
	Foundations	•	•	•	•			•	•	•	•
Design Code	AASHTO Standard	•	•		•	•	•	•	•	•	•
	BS-5440-2	•				•				•	
	LFD & LRFD Standard	•			•		•		•	•	•
	CFD Code									•	
Detailing		•									
Drafting		•			•			•	•	•	
Documentation		•			•			•	•	•	•

8.0 Hierarchal Multi-scale Design Approach

The integrated structural design combines various design steps into single continuous and connected process, using a common database or information bus [2]. This approach has been used successfully by several software in the design of tall buildings. However application of fully integrated design of bridges has not been as successful or popular yet due to significant differences in various categories discussed earlier in this paper. Nevertheless, there has been partial integration of some of the steps for specific bridge types. For example there has been integration of geometric design, development of structural model, and analysis. There have also been attempts at integration of Superstructure analysis and sub-structure analysis and of integration of analysis and selected component design

A new approach is proposed here that is based on handling the bridge design problem using hierarchal multi-scale models, all connected through open database standards using XML. This approach is similar to the Multiscale Modeling or human body in concept [Ref] and will build upon the component based software development in structural engineering [Ref]. The approach for In this approach, the top level information model containing the geographical, topographical, environmental, geological and geotechnical and service lines and related aspects that exist before the design and construction of the bridge. The second level information model contains the proposed functional and geometric design of the bridge, including the overall alignment, planned services, roadway modifications etc. The third level information model deals with the bridge structure in terms of topological, objects such as deck, piers, footings, abutments, pylons etc. The next level contains the structural model generated from the larger topological objects in terms of more well defined and local structural objects such as deck slab, girders, diaphragms, bearings, transoms, piers, footings, piles etc. A hierarchal of multi-scale design approach is shown in Figure 17. This model is still in initial stages of development by the author.

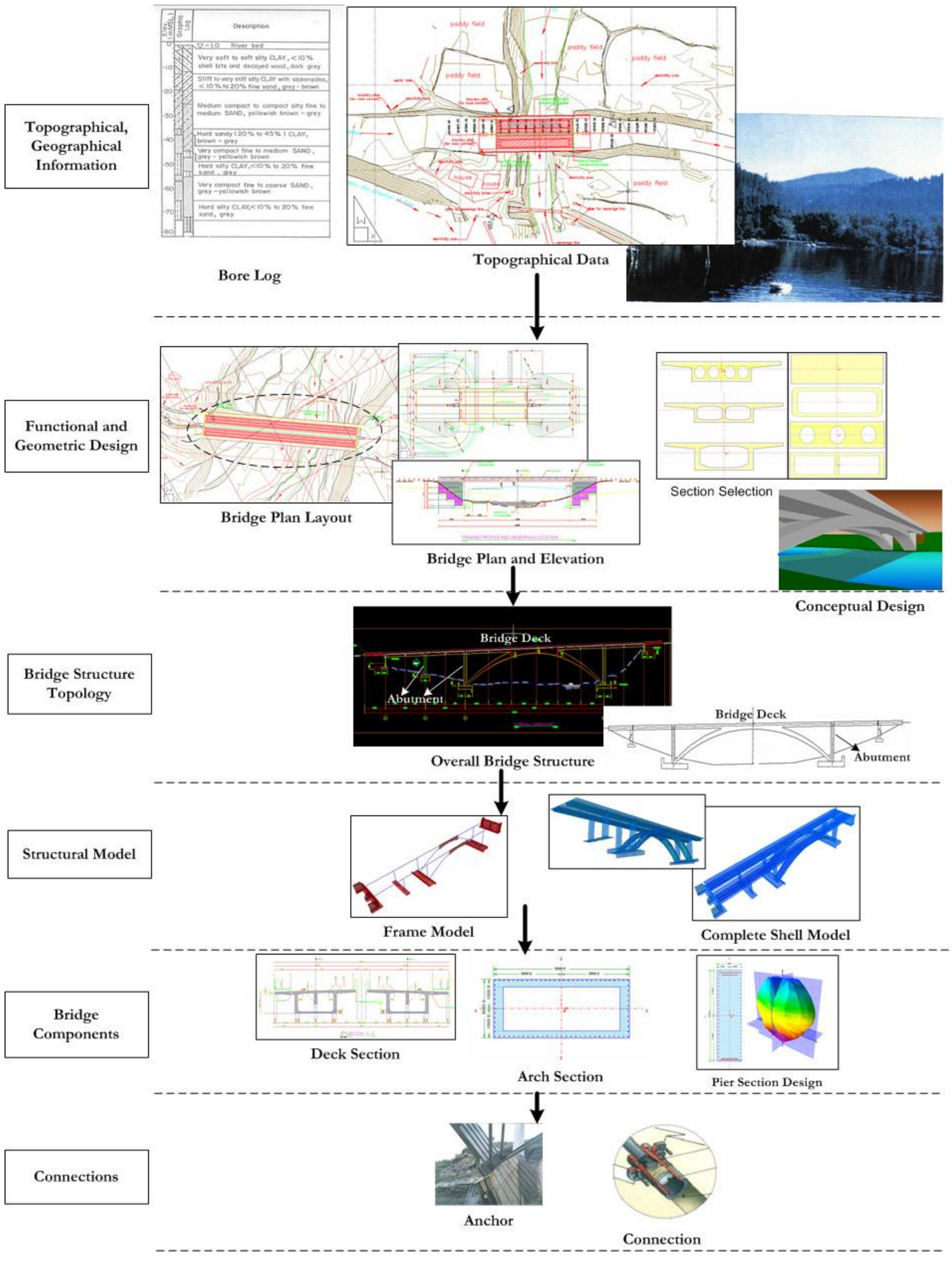


Figure 16: Hierarchal Multi-scale Design Approach for Bridge Design

9.0 Conclusions

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5. P. J. Hunter, W. W. Li, A. D. McCulloch, D. Noble (November 2006). "Multiscale Modeling: Physiome Project Standards, Tools, and Databases", **Computer, IEEE Computer Society**, Volume 39, No.11, Page no.48-54.

<More Referncces>

Software Links

ACES- Bridge Analysis System - http://www.aces-systems.com/

ADAPT-ABI- www.adaptsoft.com

ANSYS/Civil FEM Bridges - http://www.civilfem.com/products/bridges/general.php

BRIGADE - www.scanscot.com

LEAP Bridge - http://www.leapsoft.com//index.php

LUSAS Bridge - http://www.lusas.com/

MIDAS-WinBDS - http://www.imbsen.com/bds.htm

QConBridge - http://www.wsdot.wa.gov/eesc/bridge/software/index.cfm

RM2006- www.tvd.at

SAP2000 Bridge Modular- http://www.csiberkeley.com/SAP/SAP_bridges.html

SAM- http://www.lrfdsoftware.com/products.html