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Structural Modeling

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8.1 Introduction

Prior to construction of any structural system, an extensive engineering design and analysis process must be undertaken. During this process, many engineering assumptions are routinely used in the application of engineering principles and theories to practice. A subset of these assumptions is used in a multitude of analytical methods available to structural analysts. In the modern engineering office, with the proliferation and increased power of personal computers, increasing numbers of engineers depend on structural analysis computer software to solve their engineering problems. This modernization of the engineering design office, coupled with an increased demand placed on the accuracy and efficiency of structural designs, requires a more-detailed understanding of the basic principles and assumptions associated with the use of modern structural analysis computer programs. The most popular of these programs are GT STRUDL, STAADIII, SAP2000, as well as some more powerful and complex tools such as ADINA, ANSYS, NASTRAN, and ABAQUS.

The objective of the analysis effort is to investigate the most probable responses of a bridge structure due to a range of applied loads. The results of these investigations must then be converted to useful design data, thereby providing designers with the information necessary to evaluate the performance of the bridge structure and to determine the appropriate actions in order to achieve the most efficient design configuration. Additionally, calculation of the structural system capacities is an important aspect in determining the most reliable design alternative. Every effort must be made to ensure that all work performed during any analytical activity enables designers to produce a set of quality construction documents including plans, specifications, and estimates.

The purpose of this chapter is to present basic modeling principles and suggest some guidelines and considerations that should be taken into account during the structural modeling process. Additionally, some examples of numerical characterizations of selected bridge structures and their components are provided. The outline of this chapter follows the basic modeling process. First, the selection of modeling methodology is discussed, followed by a description of the structural geometry, definition of the material and section properties of the components making up the structure, and description of the boundary conditions and loads acting on the structure.

8.2 Theoretical Background

Typically, during the analytical phase of any bridge design, finite-element-based structural analysis programs are used to evaluate the structural integrity of the bridge system. Most structural analysis programs employ sound, well-established finite-element methodologies and algorithms to solve the analytical problem. Others employ such methods as moment distribution, column analogy, virtual work, finite difference, and finite strip, to name a few. It is of utmost importance for the users of these programs to understand the theories, assumptions, and limitations of numerical modeling using the finite-element method, as well as the limitations on the accuracy of the computer systems used to execute these programs. Many textbooks [1, 4, 6] are available to study the theories and application of finite-element methodologies to practical engineering problems. It is strongly recommended that examination of these textbooks be made prior to using finite-element-based computer programs for any project work. For instance, when choosing the types of elements to use from the finite-element library, the user must consider some important factors such as the basic set of assumptions used in the element formulation, the types of behavior that each element type captures, and the limitations on the physical behavior of the system.

Other important issues to consider include numerical solution techniques used in matrix operations, computer numerical precision limitations, and solution methods used in a given analysis. There are many solution algorithms that employ direct or iterative methods, and sparse solver technology for solving the same basic problems; however, selecting these solution methods efficiently requires the user to understand the best conditions in which to apply each method and the basis or assumptions involved with each method. Understanding the solution parameters such as tolerances for iterative methods and how they can affect the accuracy of a solution are also important, especially during the nonlinear analysis process.

Dynamic analysis is increasingly being required by many design codes today, especially in regions of high seismicity. Response spectrum analysis is frequently used and easily performed with today's analysis tools; however, a basic understanding of structural dynamics is crucial for obtaining the proper results efficiently and interpreting analysis responses. Basic linear structural dynamics theory can be found in many textbooks [2,3]. While many analysis tools on the market today can perform very sophisticated analyses in a timely manner, the user too must be more savvy and knowledgeable to control the overall analysis effort and optimize the performance of such tools.

8.3 Modeling

8.3.1 Selection of Modeling Methodology

The technical approach taken by the engineer must be based on a philosophy of providing practical analysis in support of the design effort. Significant importance must be placed on the analysis procedures by the entire design team. All of the analytical modeling, analysis, and interpretation of results must be based on sound engineering judgment and a solid understanding of fundamental engineering principles. Ultimately, the analysis must validate the design.

Many factors contribute to determination of the modeling parameters. These factors should reflect issues such as the complexity of the structure under investigation, types of loads being examined, and, most importantly, the information needed to be obtained from the analysis in the most efficient and "design-friendly" formats. This section presents the basic principles and considerations for structural modeling. It also provides examples of modeling options for the various bridge structure types.

A typical flowchart of the analysis process is presented in Figure 8.1. The technical approach to computer modeling is usually based on a logical progression. The first step in achieving a reliable computer model is to define a proper set of material and soil properties, based on published data and site investigations. Second, critical components are assembled and tested numerically where

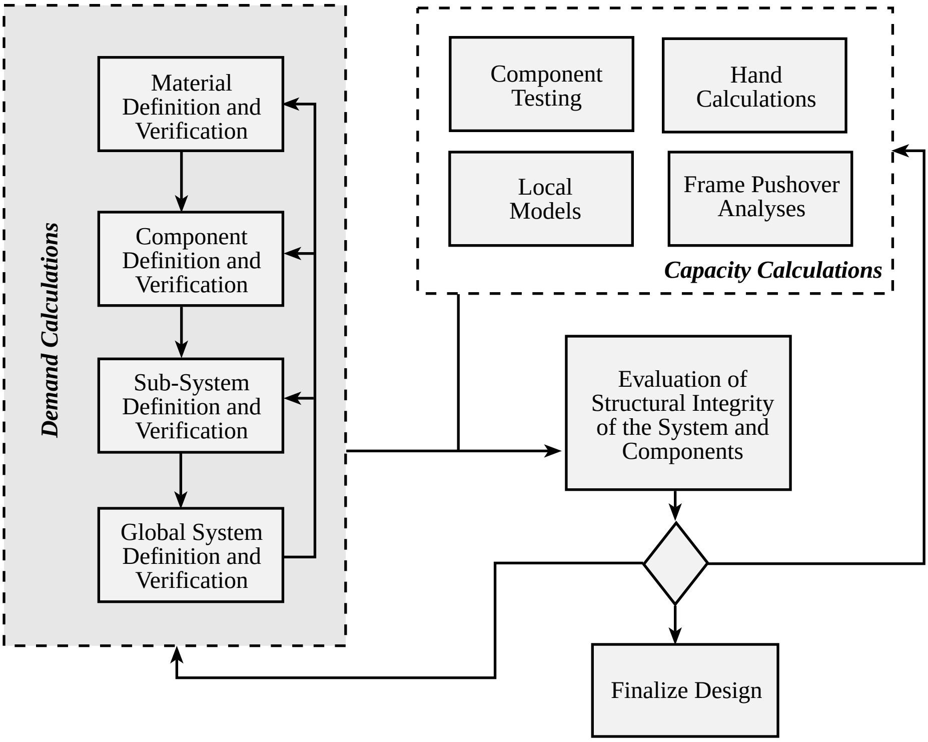


FIGURE 8.1 Typical analysis process.

validation of the performance of these components is considered important to the global model response. Closed-form solutions or available test data are used for these validations.

The next step is the creation and numerical testing of subsystems such as the bridge towers, superstructure elements, or individual frames. Again, as in the previous step, simple procedures are used in parallel to validate computer models. Last, a full bridge model consisting of the bridge subsystems is assembled and exercised. This final global model should include appropriate representation of construction sequence, soil and foundation boundary conditions, structural component behavior, and connection details.

Following the analysis and after careful examination of the analytical results, the data is postprocessed and provided to the designers for the purpose of checking the design and determining suitable design modifications, as necessary. Postprocessing might include computation of deck section resultant forces and moments, determination of extreme values of displacements for columns or towers and deck, and recovery of forces of constraint between structural components. The entire process may be repeated to validate any modifications made, depending on the nature and significance of such modifications.

An important part of the overall analytical procedure is determination of the capacities of the structural members. A combination of engineering calculations, computer analyses, and testing is utilized in order to develop a comprehensive set of component and system capacities. The evaluation of the structural integrity of the bridge structure, its components, and their connections are then conducted by comparing capacities with the demands calculated from the structural analysis.

Depending on the complexity of the structure under investigation and the nature of applied loads, two- or three-dimensional models can be utilized. In most cases, beam elements can be used to model structural elements of the bridge (Figure 8.2), so the component responses are presented in the form of force and moment resultants. These results are normally associated with individual element coordinate systems, thus simplifying the evaluations of these components. Normally, these

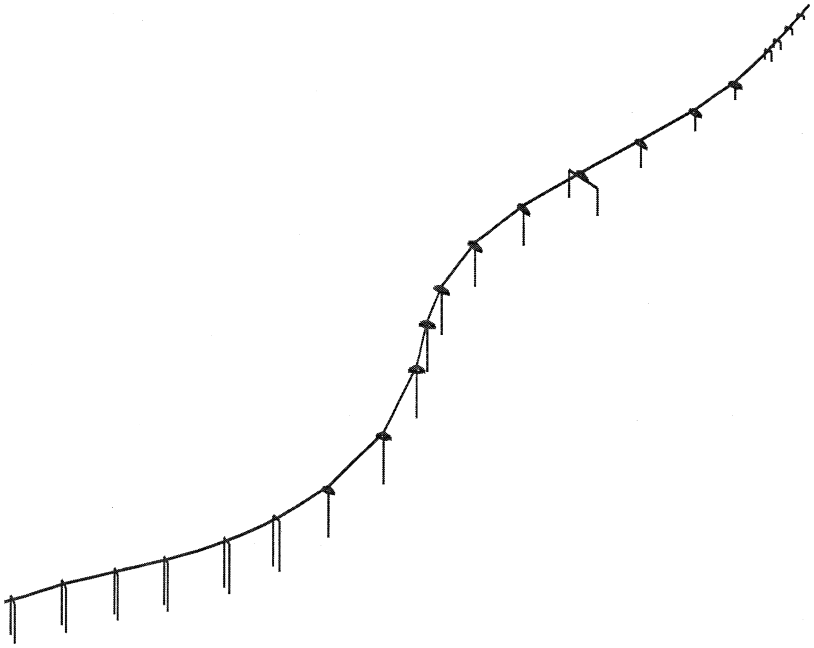


FIGURE 8.2 Typical beam model.

force resultants describe axial, shear, torsion, and bending actions at a given model location. Therefore, it is very important during the initial modeling stages to determine key locations of interest, so the model can be assembled such that important results can be obtained at these locations. While it is convenient to use element coordinate systems for the evaluation of the structural integrity of individual components, nodal results such as displacements and support reactions are usually output in the global coordinate systems. Proper refinement of the components must also be considered since different mesh size can sometimes cause significant variations in results. A balance between mesh refinement and reasonable element aspect ratios must be maintained so that the behavioral characteristics of the computer model is representative of the structure it simulates. Also, mesh refinement considerations must be made in conjunction with the cost to model efficiency. Higher orders of accuracy in modeling often come at a cost of analysis turnaround time and overall model efficiency. The analyst must use engineering judgment to determine if the benefits of mesh refinement justify the costs. For example, for the convenience in design of bridge details such as reinforcement bar cutoff, prestressing cable layouts, and section changes, the bridge superstructure is usually modeled with a high degree of refinement in the dead- and live-load analyses to achieve a well-defined force distribution. The same refinement may not be necessary in a dynamic analysis. Quite often, coarser models (at least four elements per span for the superstructure and three elements per column) are used in the dynamic analyses. These refinements are the minimum guidelines for discrete lumped mass models in dynamic analysis to maintain a reasonable mass distribution during the numerical solution process.

For more complex structures with complicated geometric configurations, such as curved plate girder bridges (Figure 8.3), or bridges with highly skewed supports (Figure 8.4), more-detailed finite-element models should be considered, especially if individual components within the superstructure need to be evaluated, which could not be facilitated with a beam superstructure representation. With the increasing speed of desktop computers, and advances in finite-element modeling tools, these models are becoming increasingly more popular. The main reason for their increased popularity is the improved accuracy, which in turn results in more efficient and cost-effective design.

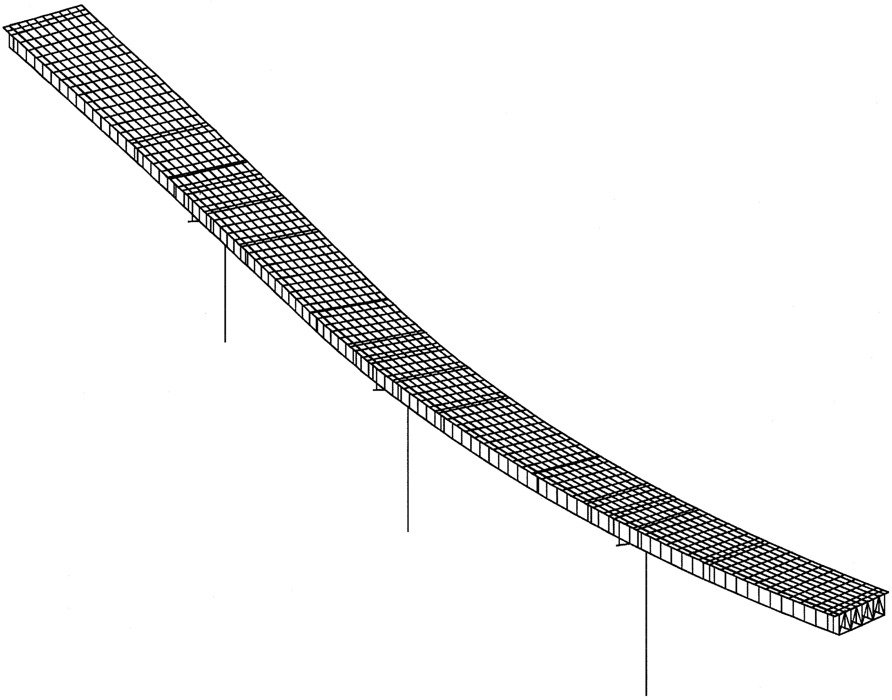


FIGURE 8.3 Steel plate-girder bridge—finite-element model.

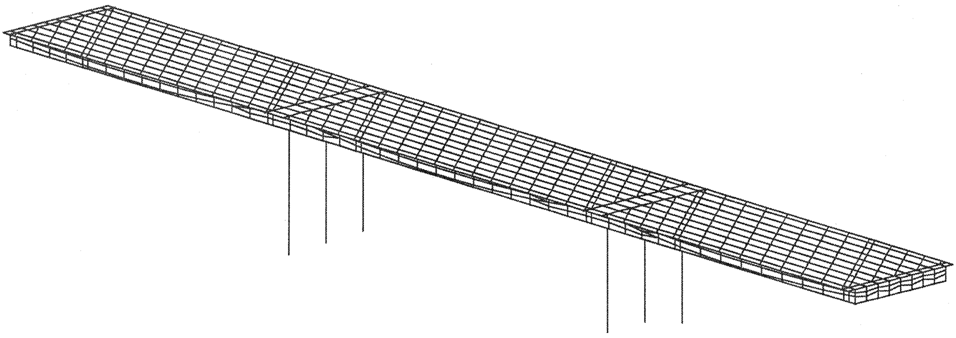


FIGURE 8.4 Concrete box girder with 45° skewed supports finite-element model.

More complex models, however, require a significantly higher degree of engineering experience and expertise in the theory and application of the finite-element method. In the case of a complex model, the engineer must determine the degree of refinement of the model. This determination is usually made based on the types of applied loads as well as the behavioral characteristics of the structure being represented by the finite-element model. It is important to note that the format of the results obtained from detailed models, such as shell and three-dimensional (3D) continuum models) is quite different from the results obtained from beam (or stick) models. Stresses and strains are obtained for each of the bridge components at a much more detailed level; therefore, calculation of a total force applied to the superstructure, for example, becomes a more difficult, tedious task. However, evaluation of local component behavior, such as cross frames, plate girder sections, or bridge deck sections, can be accomplished directly from the analysis results of a detailed finite-element model.

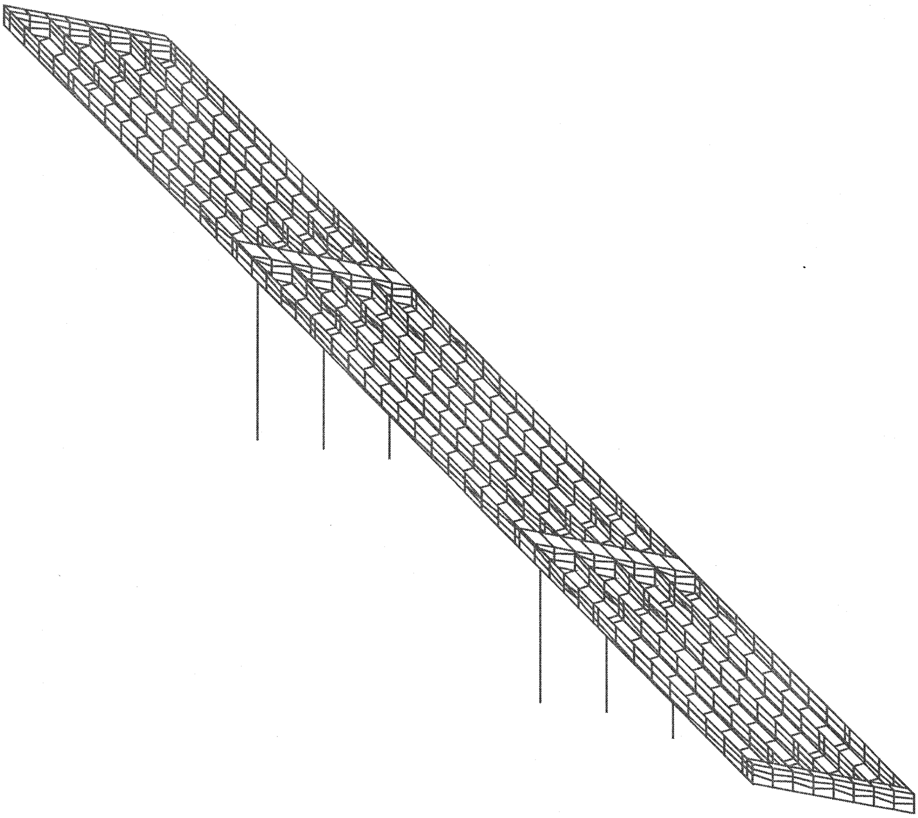


FIGURE 8.5 Concrete box-girder modeling example (deck elements not shown).

8.3.2 Geometry

After selecting an appropriate modeling methodology, serious considerations must be given to proper representation of the bridge geometric characteristics. These geometric issues are directly related to the behavioral characteristics of the structural components as well as the overall global structure. The considerations must include not only the global geometry of the bridge structure, i.e., horizontal alignment, vertical elevation, superelevation of the roadway, and severity of the support skews, but local geometric characterizations of connection details of individual bridge components as well. Such details include representations of connection regions such as column-to-cap beam, column-to-box girder, column-to-pile cap, cap beam to superstructure, cross frames to plate girder, gusset plates to adjacent structural elements, as well as various bearing systems commonly used in bridge engineering practice. Some examples of some modeling details are demonstrated in Figures 8.5 through 8.11.

Specifically, Figure 8.5 demonstrates how a detailed model of a box girder bridge structure can be assembled via use of shell elements (for girder webs and soffit), truss elements (for post-tensioning tendons), 3D solid elements (for internal diaphragms), and beam elements (for columns). Figure 8.6 illustrates some details of the web, deck, and abutment modeling for the same bridge structure. Additionally, spring elements are used to represent abutment support conditions for the vertical as well as back-wall directions. An example of a column and its connection to the superstructure in an explicit finite-element model is presented in the Figure 8.7. Three elements are used to represent the full length of the column. A set of rigid links connects the superstructure to each of the supporting columns (Figures 8.8 and 8.9). This is necessary to properly transmit bending

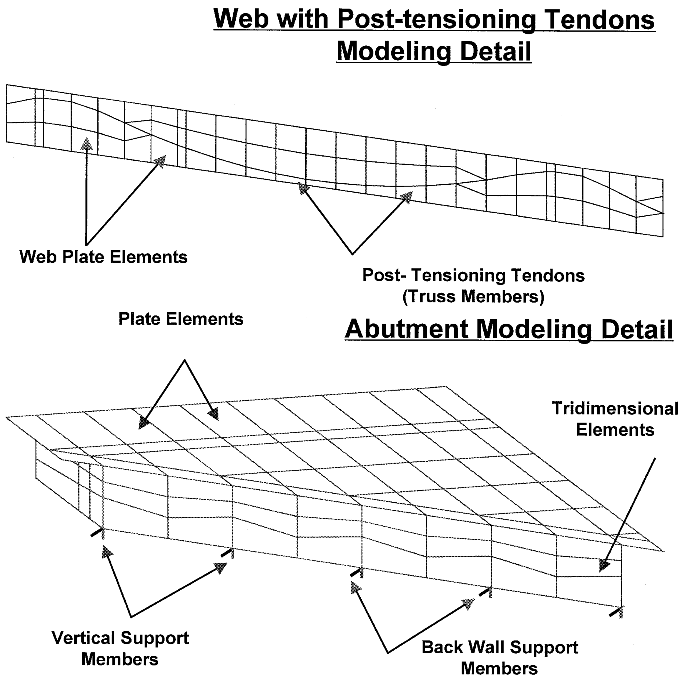


FIGURE 8.6 Selected modeling details.

action of these components, since the beam elements (columns) are characterized by six degrees of freedom per node, while 3D solids (internal diaphragms) carry only three degrees of freedom per node (translations only). In this example post-tensioning tendons are modeled explicitly, via truss elements with the proper drape shape (Figure 8.9). This was done so that accurate post-tensioning load application was achieved and the effects of the skews were examined in detail. However, when beam models are used for the dynamic analysis (Figure 8.2), special attention must be given to the beam column joint modeling. For a box girder superstructure, since cap beams are monolithic to the superstructure, considerations must be given to capture proper dynamic behavior of this detail through modification of the connection properties. It is common to increase the section properties of the cap beam embedded in the superstructure to simulate high stiffness of this connection.

Figure 8.10 illustrates the plate girder modeling approach for a section of superstructure. Plate elements are used to model deck sections and girder webs, while beams are used to characterize flanges, haunches, cross frame members, as well as columns and cap beams (Figure 8.11). Proper offsets are used to locate the centerlines of these components in their proper locations.

8.3.3 Material and Section Properties

One of the most important aspects of capturing proper behavior of the structure is the determination of the material and section properties of its components. Reference [5] is widely used for calculating section properties for a variety of cross-sectional geometry. For 3D solid finite element, the material constitutive law is the only thing to specify whereas for other elements consideration of modification of material properties are needed to match the actual structural behavior. Most structural theories are based on homogeneous material such as steel. While this means structural behavior can be directly calculated using the actual material and section properties, it also indicates that nonhomogeneous material such as reinforced concrete may subject certain limitation. Because of the composite nonlinear performance nature of reinforced concrete, section properties need to be adjusted for the objective of analysis. For elastic analysis, if strength requirement is the objective, section

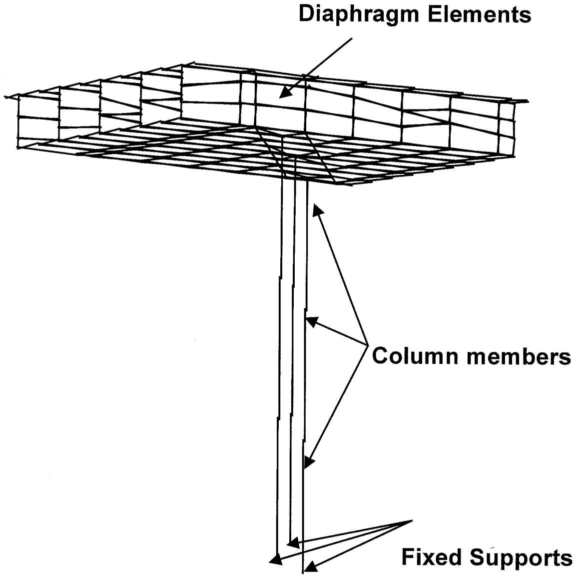


FIGURE 8.7 Bent region modeling detail.

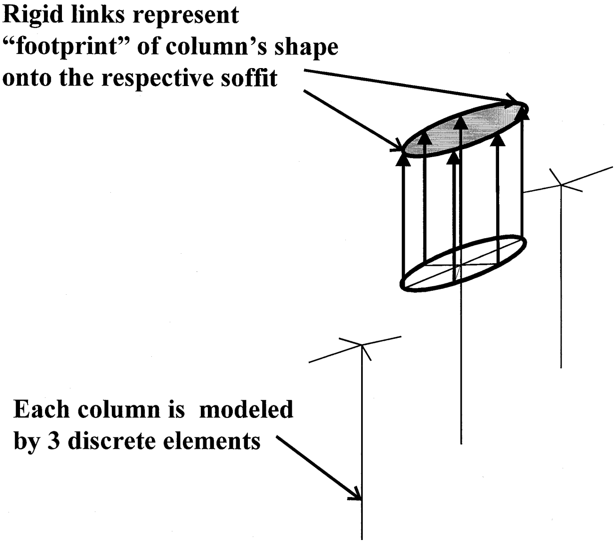
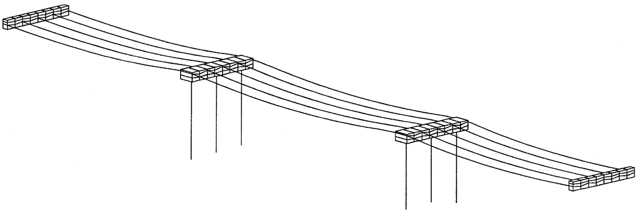


FIGURE 8.8 Column-to-superstructure connection modeling detail.

properties are less important as long as relative stiffness is correct. Section properties become most critical when structure displacement and deformation are objectives. Since concrete cracks beyond certain deformation, section properties need to be modified for this behavior. In general, if ultimate deformation is expected, then effective stiffness should be the consideration in section properties. It is common to use half value of the moment of inertia for reinforced concrete members and full value for prestressed concrete members. To replicate a rigid member behavior such as cap beams, section properties need to be amplified 100 times to eliminate local vibration problems in dynamic analysis.

Nonlinear behaviors are most difficult to handle in both complex and simple finite-element models. When solid elements are used, the constitutive relationships describing material behavior



Post-tensioning Tendons and Diaphragms

Columns with Rigid Link Connectors

FIGURE 8.9 Post-tensioning tendons, diaphragms, and column-to-diaphragm connection modeling examples.

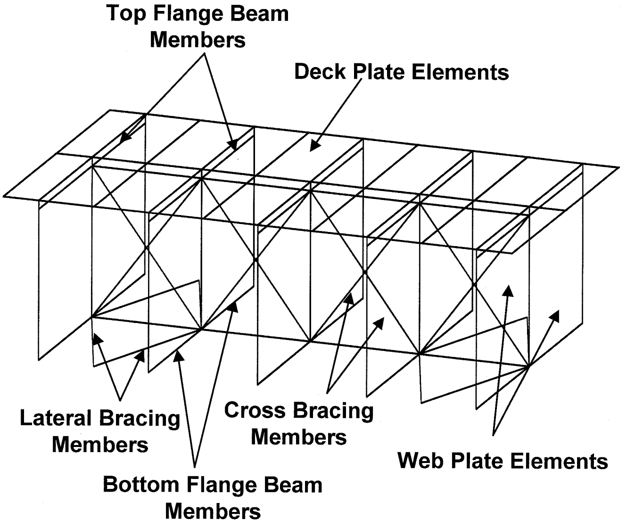


FIGURE 8.10 Plate girder superstructure modeling example.

should be utilized. These properties should be calibrated by the data obtained from the available test experiments. For beam–column-type elements, however, it is essential that the engineer properly estimates performance of the components either by experiments or theoretical detailed analysis. Once member performance is established, a simplified inelastic model can be used to simulate the expected member behavior. Depending on the complexity of the member, bilinear, or multilinear material representations may be used extensively. If member degradation needs to be incorporated in the analysis, then the Takeda model may be used. While a degrading model can correlate theoretical behavior with experimental results very well, elastic–plastic or bilinear models can give the engineer a good estimate of structural behavior without detailed material property parameters.

When a nonlinear analysis is performed, the engineer needs to understand the sensitivity issue raised by such analysis techniques. Without a good understanding of member behavior, it is very

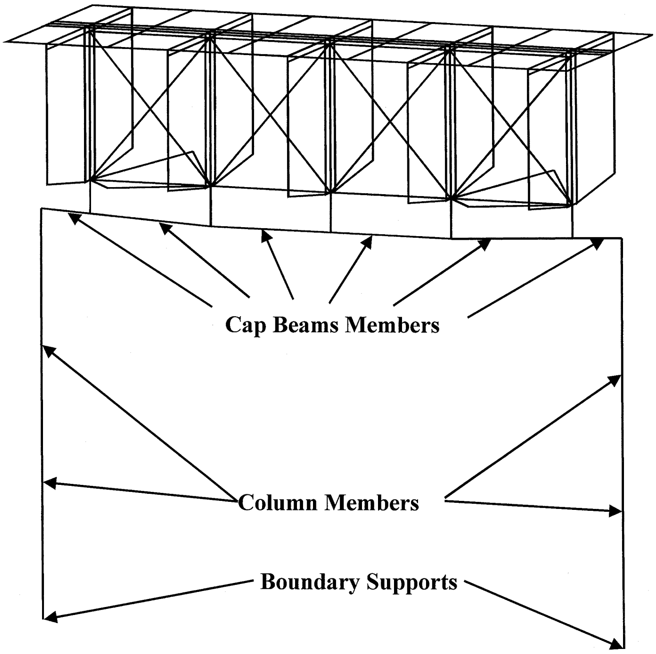


FIGURE 8.11 Plate girder bent region modeling example.

easy to fall into the "garbage in, garbage out" mode of operation. It is essential for the engineer to verify member behavior with known material properties before any production analyses are conducted. For initial design, all material properties should be based on the nominal values. However, it is important to verify the design with the expected material properties.

8.3.4 Boundary Conditions

Another key ingredient for the success of the structural analysis is the proper characterization of the boundary conditions of the structural system. Conditions of the columns or abutments at the support (or ground) points must be examined by engineers and properly implemented into the structural analysis model. This can be accomplished via several means based on different engineering assumptions. For example, during most of the static analysis, it is common to use a simple representation of supports (e.g., fixed, pinned, roller) without characterizations of the soil/foundation stiffness. However, for a dynamic analysis, proper representation of the soil/foundation system is essential (Figure 8.12). Most finite-element programs will accept a $[6 \times 6]$ stiffness matrix input for such system. Other programs require extended $[12 \times 12]$ stiffness matrix input describing the relationship between the ground point and the base of the columns. Prior to using these matrices, it is important that the user investigate the internal workings of the finite-element program, so the proper results are obtained by the analysis.

In some cases it is necessary to model the foundation/soil system with greater detail. Nonlinear modeling of the system can be accomplished via nonlinear spring/damper representation (Figure 8.13) or, in the extreme case, by explicit modeling of subsurface elements and plasticity-based springs representing surrounding soil mass (Figure 8.14). It is important that if this degree of detail is necessary, the structural engineer works very closely with the geotechnical engineers to determine proper properties of the soil springs. **As a general rule it is essential to set up small models to test behavior and check the results via hand calculations.**

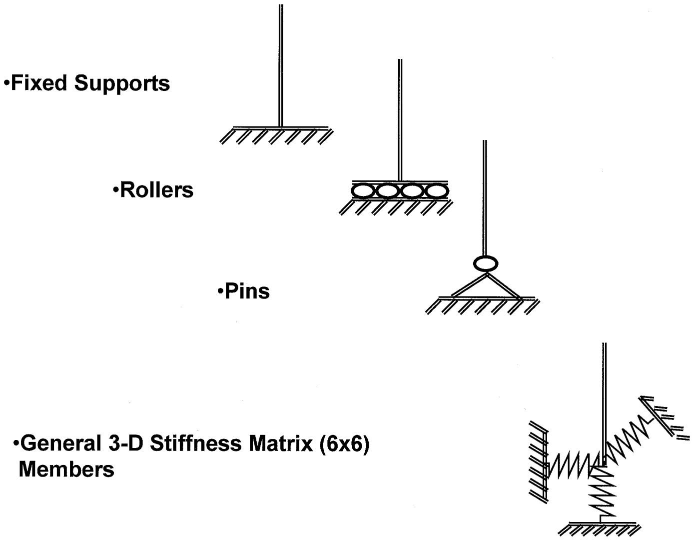


FIGURE 8.12 Examples of foundation modeling.

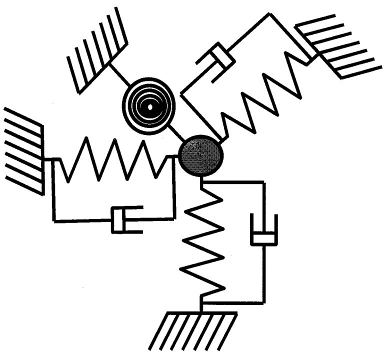


FIGURE 8.13 Nonlinear spring/damper model.

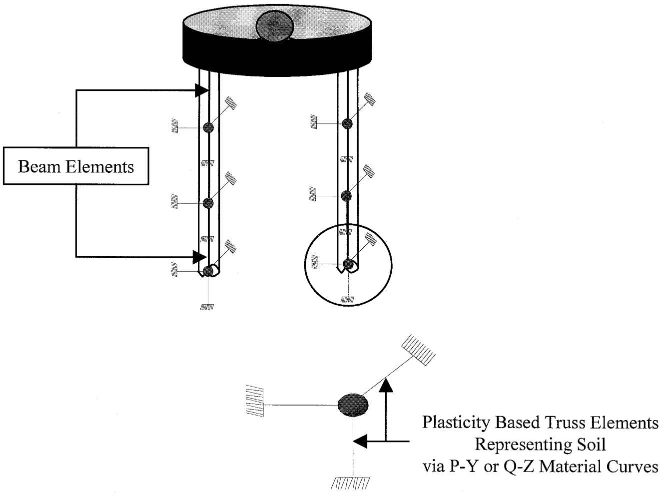


FIGURE 8.14 Soil–structure interaction modeling.

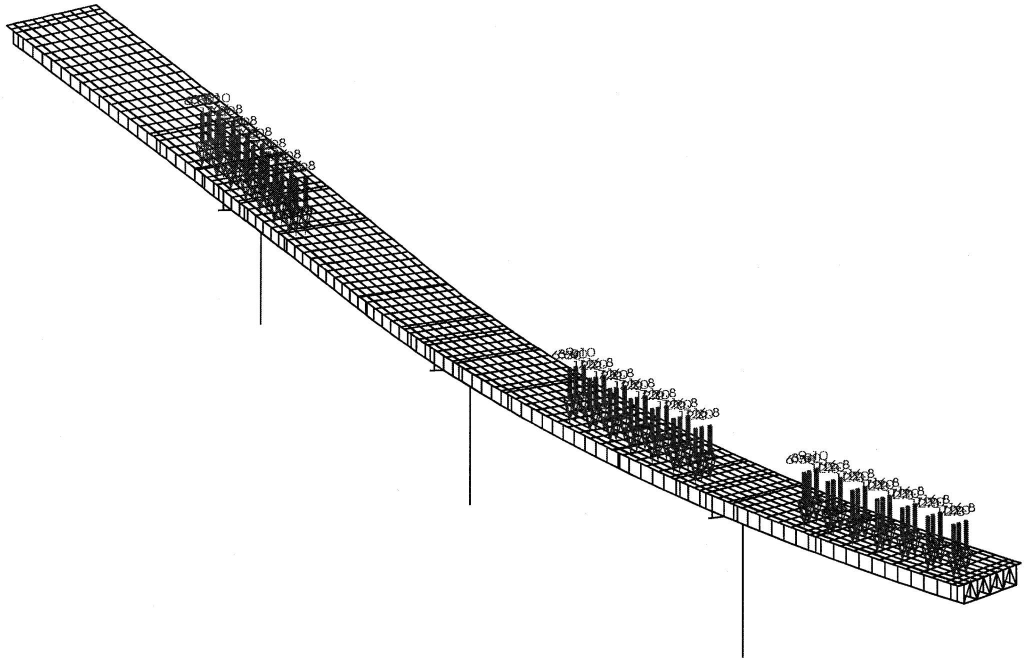


FIGURE 8.15 Truck load application example.

8.3.5 Loads

During engineering design activities, computer models are used to evaluate bridge structures for various service loads, such as traffic, wind, thermal, construction, and other service loads. These service loads can be represented by a series of static load cases applied to the structural model. Some examples of application of the truck loads are presented in Figures 8.15 and 8.16.

In many cases, especially in high seismic zones, dynamic loads control many bridge design parameters. In this case, it is very important to understand the nature of these loads, as well as the theory that governs the behavior of structural systems subjected to these dynamic loads. In high seismic zones, a multimode response spectrum analysis is required to evaluate the dynamic response of bridge structures. In this case, the response spectrum loading is usually described by the relationship of the structural period vs. ground acceleration, velocity, or displacement for a given structural damping. In some cases, usually for more complex bridge structures, a time history analysis is required. During these analytical investigations, a set of time history loads (normally, displacement or acceleration vs. time) is applied to the boundary nodes of the structure. Reference [3] is the most widely used theoretical reference related to the seismic analysis methodology for either response spectrum or time history analysis.

8.4 Summary

In summary, the analysis effort should support the overall design effort by verifying the design and addressing any issues with respect to the efficiency and the viability of the design. Before modeling commences, the engineer must define the scope of the problem and ask what key results and types of data he or she is interested in obtaining from the analytical model. With these basic parameters in mind, the engineer can then apply technical knowledge to formulate the simplest, most elegant model to represent the structure properly and provide the range of solutions that are accurate and fundamentally sound. The engineer must bound the demands on the structure by looking at limiting

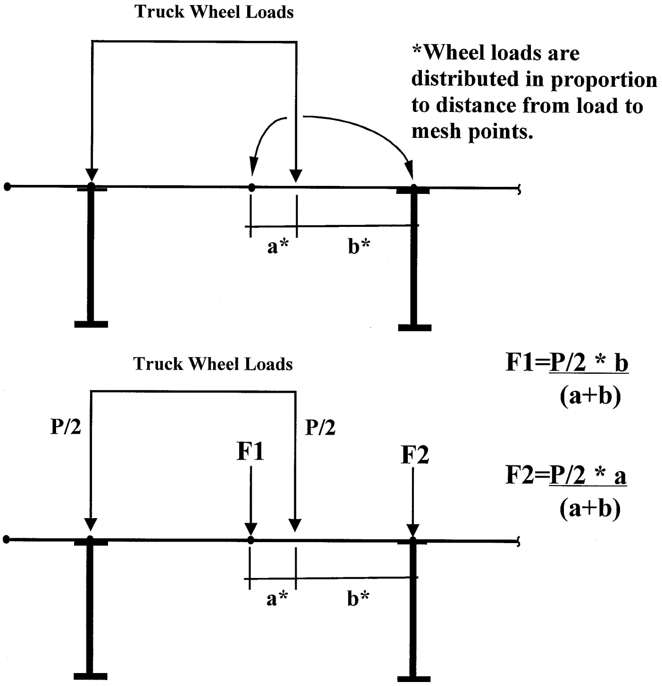


FIGURE 8.16 Equivalent truck load calculation example.

load cases and modifying the structure parameters, such as boundary conditions or material properties. Rigorous testing of components, hand calculations, local modeling, and sound engineering judgment must be used to validate the analytical model at all levels. Through a rigorous analytical methodology and proper use of today's analytical tools, structural engineers can gain a better understanding of the behavior of the structure, evaluate the integrity of the structure, and validate and optimize the structural design.

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