Arizona Department of Transportation
Bridge Group

BRIDGE PRACTICE GUIDELINES

SECTION 4- STRUCTURAL ANALYSIS & DESIGN METHODS

SCOPE

This section describes methods of analysis suitable for the design and evaluation of bridges and is limited to the modeling of structures and the determination of force effects. Other methods of analysis that are based on documented material characteristics and that satisfy equilibrium and compatibility may also be used.

DEFINITIONS

Aspect Ratio – Ratio of the length to the width of a rectangle.

Compatibility – The geometrical equality of movement at the interface of jointed components.

Component – A structural unit requiring separate design consideration; synonymous with member.

Deformation – A change in structural geometry due to force effects, including axial displacement, shear displacement, and rotations.

Design – Proportioning and detailing the components and connections of a bridge to satisfy the requirements of these Specifications.

Elastic – A structural material behavior in which the ratio of stress to strain is constant, the material returns to its original unloaded state upon load removal.

Element – A part of a component or member consisting of one material.

Equilibrium – A state where the sum of forces and moments about any point in space is zero.

Equivalent Beam – A single straight or curved beam resisting both flexure and torsional effects.

Equivalent Strip – An artificial linear element, isolated from a deck for the purpose of analysis, in which extreme force effects calculated for a line of wheel loads, transverse or longitudinal, will approximate those actually taking place in the deck

Finite Difference Method – A method of analysis in which the governing differential equation is satisfied at discrete points on the structure.

Finite Element Method – A method of analysis in which a structure is discretized into elements connected at nodes, the shape of the element displacement field is assumed, partial or complete compatibility is maintained among the element interfaces, and nodal displacements are determined by using energy variational principles or equilibrium methods.

Finite Strip Method – A method of analysis in which the structure is discretized into parallel strips. The shape of the strip displacement field is assumed and partial compatibility is maintained among the element interfaces. Model displacement parameters are determined by using energy variational principles or equilibrium methods.

Folded Plate Method – A method of analysis in which the structure is subdivided into plate components, and both equilibrium and compatibility requirements are satisfied at the component interfaces.

Force Effect – A deformation, stress, or stress resultant, i.e., axial force, shear force, flexural, or torsional moment, caused by applied loads, imposed deformations, or volumetric changes.

Foundation – A supporting element that derives its resistance by transferring its load to the soil or rock supporting the bridge.

Grillage Analogy Method – A method of analysis in which all or part of the superstructure is discretized into orthotropic components that represent the characteristics of the structure.

Inelastic – Any structural behavior in which the ratio of stress and strain is not constant, and part of the deformation remains after load removal.

Large Deflection Theory - Any method of analysis in which the effects of deformation upon forces effects is taken into account.

Member – Same as components.

Method of analysis – A mathematical process by which structural deformations, forces, and stresses are determined.

Model – A mathematical or physical idealization of a structure or component used for analysis.

Node – A point where finite elements or grid components meet; in conjunction with finite differences, a point where the governing differential equations are satisfied.

Nonlinear Response – Structural behavior in which the deflections are not directly proportional to the loads due to stresses in the inelastic range, or deflections causing significant changes in force effects, or by a combination thereof.

Orthotropic – Perpendicular to each other, having physical properties that differ in two or more orthotropic directions.

Small Deflection Theory – A basis for methods of analysis where the effects of deformation upon force effects in the structure is neglected.

Stiffness – Force effect resulting from a unit deformation.

Strain – Elongation per unit length.

Yield Line – A plastic hinge line.

Yield Line Method – A method of analysis in which a number of possible yield line patterns are examined in order to determine load-carrying capacity.

DESIGN METHODS

Under the current ADOT/Bridge Group **Bridge Practice Guidelines**, two basic methods are used – Service Load Design and Strength Design. The Service Load Design (Allowable Stress Design) shall be used for the design of all steel members and reinforced concrete members except columns, sound barrier walls and bridge railings. Columns and sound barrier walls shall be designed by the Strength Design Method (Load Factor Design). Bridge railing design for new bridges shall be based on the AASHTO LRFD Bridge Design Specifications.

In Service Load Design, loads of the magnitude anticipated during the life of the structure are distributing empirically and each member analyzed assuming completely elastic performance. Calculated stresses are compared to specified allowable stresses which have been scaled down from the tested strength of the materials by a factor judged to provide a suitable margin of safety.

In Strength Design, the same service loads are distributed empirically and the external forces on each member are determined by elastic analysis. These member forces are increased by factors judged to provide a suitable margin of safety against overloading. These factored forces are compared to the ultimate strength of the member scaled down by a factor reflecting the possible consequences from construction deficiencies. Serviceability aspects, such as deflection, fatigue and crack control, must be determined by Service Load Analysis.

The Strength Design Method produces a more uniform factor of safety against overload between structures of different types and span lengths. Strength Design also tends to produce more flexible structures.

A third method is Load and Resistance Factor Design which was adopted by AASHTO in 1994 and will replace Service Load Design and Strength Design in October, 2007 for all

Federal-Aid projects. This method will have more consistent load and resistance factors based on the probabilistic theory and reliability indices that will generate more uniform and realistic safety factors between different types of bridges. Currently, ADOT/Bridge Group is not using this method for bridge design except for the concrete bridge barrier design.

DESIGN PHILOSOPHY

New structure types were developed to meet specific needs. Concrete slab, T-Girder and Box Beam bridges were developed in the late 1940's because many short span stream crossings were being constructed uneconomically with steel beams and trusses. These bridges are still used very economically in considerable numbers today. Precast pretensioned beams were developed in the 1950's for medium span stream crossings and grade separations because steel beams became expensive and sometimes slow on delivery. Fewer plans are assembled from standard prestressed girder drawings today because bridge geometry has become more complicated and variable so that most details must be specially prepared. The beams themselves are still the standard shapes developed in the beginning and the accessories required to complete the span are covered with standard details. Cast-In-Place Post-Tensioned Box Girder bridges were introduced the 1970's and became one of the most common types of bridges used in Arizona in addition to precast prestressed girder bridges.

Bridge design has become more sophisticated and complicated. Prestressed concrete girders continue to be the most economical and durable solution for spans up to 140 feet but aesthetics are occasionally dictating concrete box girders with wide overhangs for this span range. This requires a higher order of analysis while considering time dependent effects and erection conditions. Cable stayed bridges are competing for longer spans. This adds more complication to the design procedure and challenges the specification writers to establish realistic controls.

The Bridge Design Service has performed all types of design in-house, except for cable stayed and segmental bridges. The more advanced structure types have as yet required only a small portion of the overall effort. The most important part of the routine work is to design and to prepare drawings for multitudes of ordinary bridges which usually have some variations in geometry that prohibits the use of straight standard details.

Geometry is considered an important part of bridge design. Framing dimensions and elevations must be accurate in order to avoid expensive field correction. Design engineers are primarily responsible for geometry accuracy.

Constructability is highly desirable. There have been designs which looked good on paper but were virtually impossible to construct. Designers need to consider how to build the component being designed. Construction experience remains a valuable asset.

Details may be the most critical aspect of the design process. Failure to provide for proper stress flow at discontinuities has often caused local stress and sometimes mortal injury to a system. Engineers and technicians should recognize and carefully evaluate untested details.

The bottom line on bridge design is maintenance. It is usually much more expensive to repair a bridge than it was to build it. Unfortunately, maintenance problems tend to occur many years after the structure is built. During that time there may be many more bridges designed with the same problem. Experience is a good teacher, but the lesson is sometimes slow to be learned. It takes a good designer to anticipate maintenance problems and spend just enough of the taxpayers' money to prevent or delay them.

Design engineers are expected to learn the system quickly. Based on education and experience, they should develop engineering judgment to recognize the degree of design complication and accuracy justified by the type and size of member under consideration. A number of computer programs are available. Some are so complicated as to be useful in very special investigations only (GT-STRUDL). Others, although complicated, offer the only realistic solution to a problem (BDS). Others are very useful and time saving in design production (CONSPAN). Longhand methods may even be desirable for some items, especially in the learning stage.

Design calculations are the documentation for structural adequacy and accuracy of pay quantities for each bridge. These will be kept on file for a reasonable period after construction of the bridge. The condition of the calculations reflects the attitude of the designer and checker. The design calculations should consist of a concise, but complete, clear, and easily followed record of all essential features of the final design of each structure. It is often necessary to refer to these calculations because of changes or questions which arise during the construction period. If properly prepared and assembled, these calculations are of great value as a guide and time saver for preparing a similar design of another structure.

The following essential features are to be observed in preparing, checking and filing design calculations:

- The headings at the top of each sheet are to be completely filled in and each sheet has to be numbered.
- The first sheet of calculations should list such governing features as roadway width, curb or sidewalk widths and heights, and design loads. If any deviations are to be made from standard design specifications, they also need to be listed.
- The first sheet of calculations of any superstructure unit should show sketches, a layout of units, giving number of spans and length (c-c bearing) of each span. A line diagram will suffice.
- The first sheet of calculations of any substructure unit should show an appropriate sketch or diagram of the units, properly dimensioned, and the superstructure should be shown.

- Appropriate headings and subheadings such as “Live Load Moments, Center Girder”, “Summary of Shears, Outside Girders”, etc., should be freely used. These headings should be supplemented by explanatory notes wherever necessary to clarify the portion of structure under consideration, the load combinations being used, or the method of analysis being employed.
- In checking the calculations, do not make up a separate set of design calculations. Follow the original calculations and check them thoroughly, or at least check the final results. In case when a portion of original calculations are incomplete or inaccurate, a portion of the revised set must be prepared by the designer or checker. This revised set will replace the original set as a portion of the final calculations.
- In checking calculations, don’t carry through corrections that are so minor in amount as to have no real effect on the structure.
- Superstructure calculations should be placed in front of substructure calculations. Quantity calculations shall be placed at the end of the file. Preliminary designs, trial designs and comparative designs are not to be included in the design folder as finally filed.

Supplement the above guidelines with good judgment and plenty of common sense. The extra ten minutes you spend in making your calculation sheet clear and complete may save the checker an hour, and may two years hence, save some bridge designer a week or more of computations.

STRUCTURAL ANALYSIS

In general, bridge structures are to be analyzed elastically which are based on documented material characteristics and satisfy equilibrium and compatibility. However, exceptions may apply to some continuous beam superstructures by using inelastic analysis or redistribution of force effects.

This section identifies and promotes the application methods of structural analysis that are suitable for bridges. The selected method of analysis may vary from the approximate to the very sophisticated, depending on the size, complexity, and importance of the structure. The primary objective in the use of more sophisticated methods of analysis is to obtain a better understanding of structural behavior. Such improved understanding may often, but not always, lead to the potential for saving material.

These methods of analysis, which are suitable for the determination of deformations and force effects in bridge structures, have been successfully demonstrated, and most have been used for years. Although many methods will require a computer for practical implementation, simpler methods that are amenable to hand calculation and/or to the use of existing computer programs based on line-structure analysis have also been provided. Comparison with hand calculations should always be encouraged, and basic equilibrium checks should be standard practice. With rapidly improving computing technology, the more refined and complex methods of analysis are expected to become commonplace. It is important that the user understand the method employed and its associated limitations.

In general, the suggested methods of analysis are based on linear material models. This does not mean that cross-sectional resistance is limited to the linear range. The Load Factor Design present such inconsistency that the analysis is based on material linearity and the resistance model may be based on inelastic behavior.

ACCEPTABLE METHODS OF STRUCTURAL ANALYSIS

Any method of analysis that satisfies the requirements of equilibrium and compatibility and utilizes stress-strain relationships for the proposed materials may be used, including but not limited to:

- Classical force and displacement methods (Moment Distribution, and Slope Deflection Methods, etc.),
- Finite difference method,
- Finite element method,
- Folded plate method,
- Finite strip method,
- Grillage analogy method,
- Serious or other harmonic methods, and
- Yield line method.

Many computer programs are available for bridge analysis. Various methods of analysis, ranging from simple formulae to detailed finite element procedures, are implemented in such programs. Many computer programs have specific engineering assumptions embedded in their code, which may or may not be applicable to each specific case. The designer should clearly understand the basic assumptions of the program and the methodology that is implemented. The designer shall be responsible for the implementation of computer programs used to facilitate structural analysis and for the interpretation and use of results. The name, version and release date of software used should be indicated in the design calculations.

MATHEMATICAL MODELING

Mathematical models should include loads, geometry, and material behavior of the structure, and, where appropriate, response characteristics of the foundation. In most cases, the mathematical model of the structure should be analyzed as fully elastic, linear behavior except in some cases, the structure may be modeled with inelastic or nonlinear behavior.

Structural Material Behavior

ELASTIC BEHAVIOR

Elastic material properties and characteristics of concrete, steel, aluminum and wood shall be in accordance with the sections given by **AASHTO Specifications**. Changes in these values due to maturity of concrete and environmental effects should be included in the model, where appropriate.

INELASTIC BEHAVIOR

Sections of components that may undergo inelastic deformation shall be shown to be ductile or made ductile by confinement or other means. Where inelastic analysis is used, a preferred design failure mechanism and its attendant hinge locations shall be determined. It should be ascertained in the analysis that shear, buckling, and bond failures in the structural components do not precede the formation of a flexural inelastic mechanism. Unintended overstrength of a component in which hinging is expected should be considered. Deterioration of geometrical integrity of the structure due to large deformations shall be taken into account. The inelastic model shall be based either upon the results of physical tests or upon a representation of load-deformation behavior that is validated by tests.

Geometry

SMALL DEFLECTION THEORY

If the deformation of the structure does not result in a significant change in force effects due to an increase in the eccentricity of compressive or tensile forces, such secondary effects may be ignored. Small deflection theory is usually adequate for the analysis of beam-type bridges. Columns, suspension bridges, and very flexible cable-stayed bridges and some arches other than tie arches and frames in which the flexural moments are increased or decreased by deflection tend to be sensitive to deflection considerations. In many cases, the degree of sensitivity can be assessed and evaluated by a single-step approximate method, such as the Moment Magnification Factor Method. Due to advances in material technology the bridge components become more flexible and the boundary between small- and large-deflection theory becomes less distinct.

LARGE DEFLECTION THEORY

If the deformation of the structure results in a significant change in force effects, the effects of deformation shall be considered in the equations of equilibrium. The effect of deformation and out-of-straightness of components shall be included in stability analyses and large deflection analyses. For slender concrete compressive components, those time- and stress-dependent material characteristics that cause significant changes in structural geometry shall be considered in the analysis.

Because large deflection analysis is inherently nonlinear, the loads are not proportional to the displacements, and superposition can not be used. Therefore, the order of load application can be important and should be applied in the order experienced by the structure, i.e., dead load stages followed by live load stages, etc. If the structure undergoes nonlinear deformation, the loads should be applied incrementally with consideration for the changes in stiffness after each increment.

STATIC ANALYSIS

Plan Aspect Ratio

Where transverse distortion of a superstructure is small in comparison with longitudinal deformation, the former does not significantly affect load distribution, hence, an equilibrium idealization is appropriate. The relative transverse distortion is a function of the ratio between structural width and height, the latter, in turn, depending on the length. Hence, the limits of such idealization are determined in terms of the width-to-effective length ratio.

Simultaneous torsion, moment, shear, reaction forces, and attendant stresses are to be superimposed as appropriate. In all equivalent beam idealizations, the eccentricity of loads should be taken with respect to the centerline of the equivalent beam.

Structures Curved in Plan

- Segments of horizontally curved superstructures with torsionally stiff closed sections whose central angle subtended by a curved span or portion thereof is less than 12 degrees may be analyzed as if the segment were straight.
- The effects of curvature may be neglected on open cross-sections whose radius is such that the central angle subtended by each span is less than the value given in the following table taken from **AASHTO LRFD Specifications**.

Number of Beams	**Angle for One Span**	**Angle for Two or More Spans**
2	2 °	3 °
3 or 4	3 °	4 °
5 or more	4 °	5 °

- Horizontally curved superstructures other than torsionally stiff single girders may be analyzed as grids or continuums in which the segments of the longitudinal beams are assumed to be straight between nodes. The actual eccentricity of the segment between the nodes shall not exceed 2.5 percent of the length of the segment.
- V-load method may be used to analyze a horizontally curved continuous steel bridge.

Approximate Methods of Analysis

Current **AASHTO Specifications** has provided the approximate methods of load distribution factor for deck, beam-slab bridges, slab bridges and other types of structures. Please follow the provisions of **AASHTO Specifications** for specific type of structure to obtain design parameters. Also, please refer to these **Bridge Practice Guidelines** for the design parameters listed in the various types of structures.

Refined Methods of Analysis

Refined methods, listed below, may be used to analyze bridges. In such analyses, consideration should be given to aspect ratio of elements, positioning and number of nodes, and other features of topology that may affect the accuracy of the analytical solution. When a refined method of analysis is used, a table of live load distribution coefficients for extreme force effects in each span shall be provided in the contract documents to aid in permit issuance and rating of bridges.

DYNAMIC ANALYSIS

For analysis of the dynamic behavior of bridges, the stiffness, mass and damping characteristics of the structural components shall be modeled.

The minimum number of degree-of-freedom included in the analysis shall be based upon the number of natural frequencies to be obtained and the reliability of the assumed mode shapes. The model shall be compatible with the accuracy of the solution method. Dynamic models shall include relevant aspects of the structure and the excitation. The relevant aspects of the structure may include the:

- Distribution of mass,
- Distribution of stiffness, and
- Damping characteristics.

The relevant aspects of excitation may include the:

- Frequency of the forcing function,
- Duration of application, and
- Direction of application.

Typically, analysis for vehicle- and wind-induced vibration is not to be considered in the bridge design. Although a vehicle crossing a bridge is not a static situation, the bridge is analyzed by statically placing the vehicle at various locations along the bridge and applying a dynamic load allowance as stated in **AASHTO Specifications**. However, in flexible bridges and long slender components of bridges that may be excited by bridge movement, dynamic force effects may exceed the allowance for impact. In most observed bridge vibration problems, the natural structural damping has been very low which no dynamic analysis is needed.

Dynamic analysis of the bridge must be considered if the bridge site is located in the area of high seismic active zone, such as Yuma and Flagstaff area. Please refer the **AASHTO Specifications** and Section 3 for seismic design.