Modeling and Design of Bridge Super Structure and Sub Structure

Topic 3
Day 2

Naveed Anwar
1. Over view of Bridge Design Process and Bridge Types
2. Advances and recent trends in Modeling and Analysis of Bridges
3. Design of Bridge Super Structure and Sub Structure
4. International Bridge Design Standards and Approaches
Why do we want to treat Sub Structure Separately? 
(for analysis purposes)
A Very Simple Bridge
Using Simple Model: Pin-Roller
Using Simple Model: Pin-Pin
Using Modified Model: Pin-Roller

Pt Obj: 2
Pt Elm: 2
U1 = 0.2357
U2 = 0
U3 = 0
R1 = 0
R2 = -0.0015
R3 = 0
Using Modified Model : Pin-Pin
Remember the Simple Bridge
Add Piers
Add Piers with Moment Release
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For Gravity Loads - same as Pin Roller Beam
What about Lateral Loads?
Full Model – Without Bearing

Assign Springs Along Frame Object

- Spring Type:
  - Simple
  - Spring Stiffness per Unit Length: $1.000E+3$
  - Simple Spring Results
  - Link Property

- Spring Tension Direction:
  - Parallel to Line Object Local Axis
  - In Line Object 2-3 Plane
    - Counterclockwise Angle from Line 1-2-Axis

- User Specified Direction Vector
  - Local Coordinates System
    - Global X Component
    - Global Y Component
    - Global Z Component

- Positive Local 2-Axis Orientation
  - Link Local 2-Axis Angle From Default Orientation

Options:
- Add to Existing Springs
- Replace Existing Springs
- Delete Existing Springs

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What can we note

• It is possible, and preferable to model and analyze the super and sub-structure together

• We need to take care of:
  • Connection between deck and sub-structure parts
  • Connection between piers and footings
  • Interaction between footing, piles and soil
  • Specially, complex behavior of Abutments.

• Key issues
  • Bearing modeling
  • Soil modeling
  • Boundary conditions
Link Elements to model Bearings

Link Elements to model Bearings
Full Modeling
Shell Model of Bridge Pier

Modeling of solid & hollow piers with shell elements
Practical Modeling Considerations

• Using the right software that supports the modeling option being selected

• The skill in using the software properly

• Obtaining, determining or computing the properties and parameters required for the model being considered

• For sophisticated models, such as D-G, the ability to carry out parametric and sensitivity analysis to ensure proper use of properties and program options
Some Sample Models
Some Sample Models
Some Sample Models

Full Model with Deck, Bearings, Footings, Piles
Modeling of Deck
Modeling of the Bridge Deck

• Beam Model
• Grid Model
• Grid-Plate Model
• Thin Wall model
• Plate-Shell Model
• Solid Model
Deck Modeling Options
Beam Model

• Simple Beam Model
  • Only the CL of the Deck is modeled by Equivalent beam elements

• Full Beam Model
  • Every bridge component is modeled by beam elements
Beam Model
Grid Model

- In the model the deck is represented as a grillage made from beam elements.

- Girders, Slab, Diaphragm etc are all converted to equivalent beams

- This is generally for out-of plane analysis for gravity and traffic loads
Grid Model

• Most suitable for I beam or T beam deck with diaphragms
• Suitable for transverse distribution of traffic load
• Generally made for one or two spans for local analysis
• Slab can be represented by equivalent beam strips
• Can be in 2D or in 3D
• Can be combined with the full Beam Model
A Typical Grid Model
Beam-Plate Model

• 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.
Beam-Plate Model

• Special consideration are needed to account for difference in the center line of the girders and the plate (slab).

• The stiffness matrix of the girders and diaphragms are modified with the sub-structure method.

• An offset connection needs to be specified between beam and plates
Beam-Plate Model
The problem of the offset Connection needs special handling

- Use of Rigid Offsets
- Special Elements in the program
- Connection between Girder CL and Support
Shell Model

• In plate-shell model, all girders, diaphragms, slabs etc. are modeled with the plate elements

• This model suitable for detailed analysis in transverse as well as in longitudinal direction
Plate - Shell Model

• Can handle bridges of arbitrary cross-section and geometry
• Specially suitable for deck slab analysis, highly skew & curved bridges
• Needs a very large number of elements
• Applying moving loads may be difficult
• Difficult to apply Prestress load
• Difficult to interpret results for design

Full shell model for girder bridge
Shell Model

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• Specially suitable for deck slab analysis, highly skew and curved bridges
• Needs a very large number of elements
• Applying moving loads may be difficult
• Difficult to apply Prestress load
• Difficult to interpret results for design
Spine Model
Spine Model With Modified Support
Frame Model
Grid Model
Frame Shell Model
Full Shell Model
Shell Model
Shell Model of Box Girder Bridge

Horizontal curvature & variable box girder depth
Connecting “Spine” Models to Cable/Supports

Rigid Link modeled as Link Element at Connection between Deck and Cable
Steps for Beam and Girder Design

1. Develop General Sections
2. Develop Typical Section
3. Design of RC Concrete Deck
4. Select Load Combinations
5. Select Load Modifiers
6. Select Resistance Factors
7. Calculate Live Load Effects
8. Investigate Service Limit State
9. Investigate Strength Limit State
Steps for Slab Bridges

1. Check Minimum Recommended Depth
2. Determine Live load Strip Width
3. Investigate Applicability of Live Loads for Decks
4. Investigate Reinforcement Distributions
5. Investigate Shear
6. Design Edge Beam
7. Check Min & Max Dimensions
8. Design Diaphragm (if Not Solid Slab)
9. Check Design Requirements
Conventional Approach

• Bridge modeled and analyzed for DL, LL and other loads → Actions
• Section stresses checked for combined effect of actions and pre-stress

• Will not work well for continuous structures or where secondary effects due to prestressing are significant

\[
\text{Stresses due to Actions} + \text{Stresses due to Prestressing} = \text{Final Stresses}
\]
Single Element Approach

\[Mp = P \cdot ey\]

\[Mx (+)\]

\[f_a = \frac{P}{A} + \frac{M_p y}{I_{xx}} + \frac{M_x y}{I_{xx}}\]
Integrated Approach

• Prestressing is considered as just another load and the final stresses are obtained directly from the final actions
  • Stresses due to actions ➔ Final Stresses

• Will work in every case.

• Drawback:
  • Prestress has to be estimated right from the start, requires iteration

• A combination of these two approaches is often suitable
• The Cable Profile produces balancing loads
• Balancing loads produce additional reactions on supports in continuous beams
• Additional reactions generate secondary moments in the beam, in addition to the moment due to eccentricity of prestressing force
Why to use 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
Why to use Integrated Approach?

• 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
Anchor Block Analysis
Design of RC Deck

• Design of decks is carried out on the basis of approximate method of analysis in which the deck is subdivided into strips perpendicular to the supporting components.

• Extreme positive moment in any deck panel between girders shall be taken to apply to all positive moment regions. Similarly, the extreme negative moment over any beam or girder shall be taken to apply to all negative moment regions.

• Strip method is applicable for slab bridges and concrete slabs spanning less than 15.0 ft
Width of Equivalent Interior Strip

For Concrete deck

<table>
<thead>
<tr>
<th>Type</th>
<th>Direction of Primary Strip Relative to Traffic</th>
<th>Width of Primary Strip (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast-in-place</td>
<td>Overhang</td>
<td>$45.0 + 10.0X$</td>
</tr>
<tr>
<td></td>
<td>Either Parallel or Perpendicular</td>
<td>$+M: 26.0 + 6.6S$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-M: 48.0 + 3.0S$</td>
</tr>
<tr>
<td>Cast-in-place with stay-in-place concrete formwork</td>
<td>Either Parallel or Perpendicular</td>
<td>$+M: 26.0 + 6.6S$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-M: 48.0 + 3.0S$</td>
</tr>
<tr>
<td>Precast, post-tensioned</td>
<td>Either Parallel or Perpendicular</td>
<td>$+M: 26.0 + 6.6S$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-M: 48.0 + 3.0S$</td>
</tr>
</tbody>
</table>
## Width of Equivalent Interior Strip

### For Steel Deck

<table>
<thead>
<tr>
<th>Type</th>
<th>Direction of Primary Strip Relative to Traffic</th>
<th>Width of Primary Strip (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open grid</td>
<td>Main Bars</td>
<td>1.25P + 4.0Sb</td>
</tr>
<tr>
<td>Filled or partially filled gridk</td>
<td>Main Bars</td>
<td>Article 4.6.2.1.8 applies (LRFD Bridge Design Specification)</td>
</tr>
<tr>
<td>Unfilled, composite grids</td>
<td>Main Bars</td>
<td>Article 4.6.2.1.8 applies (LRFD Bridge Design Specification)</td>
</tr>
</tbody>
</table>
Typical Bridge

- Deck
  - Slab
  - Girders
  - Diaphragms

Sub Structure, Support Structure
- Transoms
- Approach
- Cables
- Piers
- Pylons
- Arches

Foundations, Supports
- Footings
- Pile Caps
- Caissons
- Piles
- Isolators
- Abutment

Connections
- Bearings
- Joints
- Restrainers

Ancillary Components
- Barriers
- Drainage
- Lighting
Sub Components of Typical Bents

- **Bearings**
- **Columns, Frame, wall**
- **Footing, PileCap**
- **Piles, Caisons**
Modeling of Pier Bents
Solid element Model for bridge Pier
Solid Model for Pier and Pier Head
Pier with Spread Pier Head
Results Output from Program

Principal Tensile Stress Contours

Principal Compressive Stress Contours
Pier with Curved Pier Head
Results Output from Program

Principal Tensile Stress Contours

Principal Compressive Stress Contours
Beam Model of Bridge Pier

Solid element Model for bridge Pier
Modeling of Bridge Pier

Beam Model

Shell Model

Solid Model
Problem of Centerline Alignment for a Variable Section Column

- Actual
- Simple Model (Load eccentricity not included)
- Improved Model (Load eccentricity included)
Modeling of Foundations
Sub-Structure

• The Structural Members and Systems below the Bearings or the Main Deck or the Main Framing
• Actual division depends on bridge type
• May include:
  • Lateral Framing System
  • Piers
  • Foundations
Modeling of Supports

- Actual Supports
  - Isolated Footings
  - Combined Footings
  - Rafts
  - Pile Cap
  - Special Supports
  - Pile Piers
  - Caissons
Modeling of Supports
Using Springs to Model Footings

Also can use Area Springs
Computing Spring Stiffness

- A = Spacing of Springs in X
- B = Spacing of Springs in Y
- Ks = Modulus of sub-grade reaction (t/cu m etc.)
- K = Spring constant (t/m etc)

\[ K = k_s \cdot A \cdot B \]
Modeling Laterally Loaded Pile

Soil strata in layers
D
M
H
P
Pile cap
Fixed soil level
hf
Actual Pile
Embedded in Soil
S oil Represented by
Lateral Springs
Beam or truss element (Si)
Beam elements (P_i)
MH
1
2
4
6
3
5
7
Frame Model
N+1
Water level hf
hs
Ls
hs
1
N
2

Also can use Line Springs
What is Modulus of Sub-grade Reaction

Load required to produce unit settlement in a unit area

\[ k = \frac{q}{\Delta} \]

KS = \( \frac{P}{L \times W \times H} \)

Units = T/m³

How to Obtain

- Plate Load Test
- Theory of Soil Mechanics
- Bearing Capacity
- Related g, N, qₓ etc
Using Solid elements to model soil around a Pile
The Pipe and Pier should be connected a “Stiff” pedestal or Contain to avoid stress concentrations.
Strut and Tie Approach

a) Simple "Strut & Tie" Model

\[ \alpha = \tan^{-1} \frac{d}{0.5L} \]
\[ \alpha = 48 \text{ deg} \]
\[ T = 0.5P/\tan \alpha \]
\[ T = 4502 \text{ kN} \]

\[ \alpha = \tan^{-1} \frac{d}{0.5(L-d_1)} \]
\[ \alpha = 68.5 \text{ deg} \]
\[ T = 0.5P/\tan \alpha \]
\[ T = 1970 \text{ kN} \]
Space Truss Models
Use Space Truss Models
Bridge Bearings and Joints
Modeling Elastomeric Bearings

F

Elastomeric Bearing
Shear Modulus G

V1 ?

V2 ?
Nonlinear Links For Bearings
Location of Bearings - All Shell Model
Location of Bearings : Beam-Shell
Modeling of Diaphragm

Sectional Elevation at Pier

Use Plate Elements

Special Modeling Needed

May be modeled as Beam or as Plate elements

0.5m

2m

3~2.5m
Modeling of Cross-Beam

Sectional Elevation at Pier

Use Brick Elements

Thick Cross-beam

2.0m

1.5m

2.5m
Bearing Example - 1

How to Model this?
Modeling of Joints and Bearings

• In finite element models, by default all element connected to a node share the Nodal Degree of Freedom (DOF)
• This is suitable for fully connected structural members
• 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
Bearing and Expansion Joints

• Effectively Modeling of Support conditions at bearing and expansion joints requires careful consideration of the continuity of each translation and rotational components of displacement.

• Joints may behave linearly or non linearly

• Linear Joints
  • Roller, Pin
  • Elastomeric Pads

• Nonlinear Joints
  • Expansion Joint, Gap
  • Restraining Block, Gap or Hook
Bearing and Expansion Joints

• Degrees-of-freedom representing discontinuous components must be disconnected

• Stiffness/flexibility of bearing pads and other connections should be modeled
Bearing and Expansion Joints

• Effectively Modeling of Support conditions at bearing and expansion joints requires careful consideration of the continuity of each translation and rotational components of displacement.

• Joints may behave linearly or non linearly

• Linear Joints
  • Roller, Pin
  • Elastomeric Pads

• Nonlinear Joints
  • Expansion Joint, Gap
  • Restraining Block, Gap or Hook
• Method –1: Using Constraints
  • Use more than one node at the same location to connects individual elements which automatically disconnects all degrees-of-freedom between the elements
  • Constraining together the connected degrees-of-freedom using equal or local constraints
Bearing and Expansion Joints

• Method-2: Using Releases
  • Attaching several elements to a common joint which automatically connects all degrees-of-freedom between the elements

  • Using Frame element end release to free the unconnected degrees-of-freedom
Bearings and Expansion Joints

• Method-3: Using Springs
  • Specially 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
• Method-4: Using Nonlinear Links
  • Specially useful for modeling of complex connections that have nonlinear properties such as gaps, nonlinear sprints, restraining blocks etc.

  • The elements are connected to each other by NL Link elements in appropriate DOF
Method (1)- Use of Separate Joints at Common Location

Joints 4,5,6:
- Same Coordinates
- Equal Y-Translation
- Equal Z-Translation
- Equal X-Rotation

Joints 4,6:
- Equal X-displacement
Method (2)- Use of Common Joints and Elements End Releases
Using Springs/Links

- Use one spring for each DOF
- Stiffness value is specified to link Force and Displacement

- Use one Link for each DOF
- May have a linear part (similar to spring) and a nonlinear part represented by a relationship between Force and Displacement
In-Span Expansion Joint

- Girder
- Pier Head or Girder
- Joint
- Pier

Coordinates: X, Z
In-Span Expansion Joint

Method (1) - Use of Separate Joints at Common Location

- Joints 5, 6:
  - Same Coordinates
  - Equal Y-Translation
  - Equal Z-Translation
  - Equal X-Rotation

Method (2) - Use of Common Joints and Elements End Releases

- Moment release
- Moment & Axial Force release

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Role of Abutments

• For Gravity Loads
  • 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

• Additional Role for Seismic Loads
  • Impart and resist longitudinal loads due to mass-acceleration
Abutment Behavior

• Behavior depends on the type of abutment and intended purpose

• In general, the overall behavior
  • Subjected to 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
Modeling Issues

• How can the active and passive soil pressure be modeled simultaneously
• How can the soil “stiffness” be included when subjected to passive loading
• How can the soil separation be included when deck moves away from the abutment
• How can the behavior of restraining blocks for seismic movement be included
• How can the elastomeric bearings be included
• How can the damping effect be considered
• What about soil dynamic, non-linear and liquefaction effects
Modeling Options

• A – Consider as support node
• B - Consider and as a linear spring
• C - Consider as a node and a linear link
• D – Consider as a node and a non-linear link
• E – Consider as a node, non-linear link and a damper
• F – Model as a combination of plate elements, links, dampers and springs
• G – Model as a combination of plate elements, links, dampers and solid elements
Independent Design of Abutment
Integrated Software
CSI Bridge

Bridge Modeler Wizard

Currently Defined Items:
- Layout Lines
- Material Properties
- Frame Section Properties
- Link Properties
- Deck Sections
- Diaphragms
- Restrainters
- Bearings
- Foundation Springs
- Abutments
- Beams
- Point Loads
- Line Loads
- Area Loads
- Temperature Gradients
- Bridge Objects
- Parametric Variations
- Lanes
- Vehicles
- Vehicle Classes
- Response Spectrum Functions
- Time History Functions
- Load Patterns
- Load Case

Step 1: Introduction

The bridge wizard walks you through all of the steps required to create a bridge object model. As shown in the summary table below:

- Step 2 defines the bridge layout line, that is, the horizontal and vertical alignment of the bridge.
- Step 3 defines basic properties and step 4 defines bridge-specific properties.
- Steps 5 through 7 define the bridge object and make all of its associated components.

NEW PRODUCT!
CSiBRIDGE
INTEGRATED 3-D BRIDGE DESIGN SOFTWARE
Wonder if Software can handle this?
Modeling Options

• A- As Frame Nodal Support
  • Consider either as pin or a roller
  • If both 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
  • May be appropriate for preliminary analysis, especially when using frame model
  • None of the stiffness, movement effects can be considered
Modeling Options

• B – As Frame Spring Support
  • The spring support can be used 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 – As Frame Support Node and Linear Link
  • The linear link can be used instead of spring support to represent the combined (lumped) stiffness of all elements involved
Modeling Options

• D – As Frame Support Node and a Non-linear link
  • 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 – As Frame Support Node, Non-linear Link and Damper
  • 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

• Option C, D, E require manual determination of stiffness, nonlinear and damping properties for springs, links and dampers
Modeling Options

• F – As Plate Elements, Links, Dampers and Springs
  • The abutment wall is modeled with plate elements
  • The soil is represented as springs
  • The connection with the deck is modeled by links and dampers

• G As Plate Elements, Links, Dampers and Solids
  • The abutment wall is modeled with plate elements
  • 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
Consider as a Support

Spring/ Link Model
Shell/Spring/Link Model
Shell Model
Often Used Concept: Equitant Springs
Abutment Models

- Wing wall
- Back wall
- Bearing
- Piles
- Soil Backfill
- Foundation
- Embankment
- Expansion Join
Sample Models of Bridge Structures

Solid Model of Substructure

Full Arch Bridge Model

Full Abutment Model
Structural Analysis and Design of Flyover Bridge at Lagos, Nigeria
A Case Study
Objective and Scope of Work

• Overall review of flyover bridges from design criteria and drawing provided by client.

• Detailed review and design of structure system for 30m and 50m spans at middle of two bridges including pier and foundation.

• Estimation of structure system only for 30m and 50m spans at middle of two bridges including pier and foundation

• Provide final design drawing and calculation report for structure system for 30m and 50m spans at middle of two bridges including pier and foundation
Overall Layout
Deck, Girders, Cross Beam, Foundations and Piles (Segment 1)
Finite Element Modeling (Segment 1)

Deck

Cross Beam

Girders
Footing and Piles
Bearings and Links