MIDAS Civil
Curved Bridge Analysis
Comparison of Methods & Construction Staging

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Team Leader, Bridge/Structural Engineer
Introduction – Curved Bridge Modeling

Types of Models to be Discussed
- Traditional Girder Line with V-Load Analysis
- Two-Dimensional (Grillage) Analysis and “Grillage 2D+
- Three-Dimensional Analysis

Project Background – CVG CONRAC Unit 2
- Comparison of Model Creation and Loading
- Comparison of Results from Modeling Approaches

Construction Sequencing and Constructability
- Purpose
- Implementation within Programs
- Comparison – Grillage and All-plate

Project – ODOT GUE-513-08.65, Temporary Supports and Staged Construction

Conclusions
Modeling – Girder Line & V-Load

Girder Line Modeling
- Uses standard AASHTO LLDF
- Can be done in minimal time, not a complicated analysis
- In this case used Merlin DASH
- Use results to populate a V-Load analysis spreadsheet or hand calculation, and iterate with a target utilization ratio (1.00 – anticipated V-Load increase)
- Typically produces good results for dead load approximations for noncomposite and composite bridges with radial crossframes or bracing
- Live load can be much more variable based on lateral stiffness, geometry, and resulting intermittent influence surface
- Typically a good method for preliminary engineering purposes
Modeling – Girder Line & V-Load

V-Load Theory

- Many references available
- Essentially, straighten girder and analyze based on true length as a straight member, then apply external forces to induce resultant internal forces corresponding to the curved structure under vertical loads
- From past projects, results have been very close to MIDAS Civil or other FEM for larger radii, say \( R > 1000 \text{-ft} \)
- Per AASHTO Section C4.6.2.2.4 has a number of limitations which do not qualify for required analysis methods for curved structures and may underestimate deflections, reactions, twist

Figure from Horizontally Curved I-Girder Bridge Analysis: V-Load Method By Grubb, M.A.
Grillage Analysis

- Uses beam elements for each beam/girder and a grid, usually plates attached to the same nodes as beam elements, but with different offset (eccentric beam)
- Alternatively, primary beam elements are used with full composite section properties, and secondary virtual beams are used for load distribution
- Provides a more accurate distribution of live loads through influence surface
- Lateral stiffness of deck is not modeled using this approach
- Superimposed dead loads are distributed more accurately, however internal forces due to curvature are not captured
Modeling – Two-Dimensional+ (Grillage)

2D+ Grillage Analysis/Limited 3D Analysis

• Similar to standard grillage, but with multiple sets of nodes with rigid links (master-slave)
• Beams/girders are modeled using beam elements then rigid linked nodes modeling the deck plates and nodes for crossframe members in 3D
• Provides an accurate distribution of live loads through influence surface
• Lateral stiffness of crossframes and deck are modeled using this approach
• Internal forces are captured using this approach, appropriate for curved girder design
• In MIDAS, this is the default for the “Deck as Plate, Beam as Frame” modeling approach
• The “All Frame” modeling approach also uses this method, but with the deck modeled by virtual transverse beams
• Seventh degree of freedom included for warping effects
Modeling – Two-Dimensional+ (Grillage)

2D+ Grillage Analysis/Limited 3D Analysis

Tip:

Renumber nodes & elements by beam/girder

10001-10xxx (Girder 1)
20001-20xxx (Girder 2)

Makes manipulation and output much easier/quicker
Modeling – Three-Dimensional

Full 3D Analysis

• Similar to the Grillage+, but the beam is split into plate elements for each flange and web, in addition to plates for the deck
• Provides an accurate distribution of live loads through influence surface
• Lateral stiffness of crossframes and deck are modeled using this approach
• Internal forces are captured using this approach, appropriate for curved girder design
• Effects of tension-field action can be captured for shear
• Girder/Beam rotations can be explicitly extracted – very important for construction cases in highly curved members
• In MIDAS, this is the “All Plate” modeling approach
Modeling – Three-Dimensional

Full 3D Analysis

• Effects of tension-field action, post-buckling web strength
Modeling – Three-Dimensional

Full 3D Analysis
Modeling Types

Where to find in MIDAS:
Project Background – CVG CONRAC

CVG Airport (Cincinnati)
Project Background – CVG CONRAC
Project Background – CVG CONRAC

Original Condition

Final Proposed Condition
Project Background – CVG CONRAC

MSE Buildup

Three Elevated Structures

• Unit 1: Straight Rolled Beams
• Unit 2: Curved Plate Girders
• Unit 3: Prestressed I Beams
Unit 2: Curved Steel Plate Girder Bridge

- $R = 200.00\text{ ft}$
- Minimum Girder $R = 181.25\text{ ft}$
- $Dc = 28^\circ 38' 52''$
- $\Delta = 135.73^\circ$
- All crossframes and girders radial
- 8 Spans, range from 48.5-ft to 68-ft
Project Background – CVG CONRAC

Site and Geometric Constraints

• Access below, multiple entry/exits
• Plate mill runs, need to make sure it is possible to cut
Shop splice versus field splice considerations

- From AISC, there are guidelines to determine if cost effective
- Analyzed to determine for this bridge, would require 0.5”-0.625” thickness differential in field section from positive moment to negative moment.
- Example: 16” x 80 lbs/in = 1280 lbs
Unit 2 Modeling – Preliminary Engineering

- V-Load Analysis used during preliminary engineering
  - Predicted max ~11% increase in moments due to curvature
  - Designed for 0.85 Utility Ratio to account for girder warping and secondary effects
  - Estimated 5.5 kips for cross frame forces due to curvature effects
Unit 2 Modeling – Preliminary Engineering

• V-Load Analysis used during preliminary engineering
• Note that grillage and plate model results showed significantly higher crossframe forces than the V-load
• Sizes:

Preliminary (V-Load)

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Final (Grillage/All-Plate)

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Unit 2 Modeling – Detailed Design, Grillage+

• A Grillage+ model in MIDAS with beams as frame was used for the detailed design
• Tips:
  • Node and Beam Element Numbering is key
  • Checked the geometry created by wizard through CAD by using a scratch basemap with origin and angle aligned to MIDAS output
  • Note that some variation occurs through composite girder wizard due to conversion to metric and concatenation occurring during the wizard generation
  • Local Coordinates – use geometry and excel to develop the local angle (Beta Angle) at each node then paste into MIDAS menu, \( \beta_i = 90 + \tan^{-1}(\Delta y_i/\Delta x_i) \); where \( \Delta y_i \) and \( \Delta x_i \) are distances from the MIDAS center point/origin to the nodal location \((x_i, y_i)\).
  • Similar geometry and excel can be used to calculate “length along” the beam at each node for output to plans
  • Bearing conditions and boundary conditions are a critical consideration
  • By default MIDAS is performing a No Load Fit (NLF) analysis. This is a very important distinction and should be indicated on the plans for the fabricator.
I recommend the presentation by AISC, “Top 10 Changes in the 8th Edition AASHTO LRFD Steel Specifications” if you have not watched it. The handouts are available here:

https://www.aisc.org/webinarhandouts121317/

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<td>Total Dead Load Fit (TDLF)</td>
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Additional Camber Consideration

- When determining camber, if Radii is greater than 1000-ft need to account for additional camber from settling of the curved structure per AASHTO 6.7.7.3

\[ \Delta = \frac{\Delta D L}{\Delta M} \left( \Delta M + \Delta R \right) \]  
(6.7.7.3-1)

in which:

\[ \Delta R = \frac{0.02L^2F_{cr}}{EY_o} \left( \frac{1,000 - R}{850} \right) \]  
(6.7.7.3-2)

Part of the camber loss is attributable to construction loads and will occur during construction of the bridge; total camber loss will be complete after several months of in-service loads. Therefore, a portion of the camber increase should be included in the bridge profile. In lieu of other guidelines, camber may be adjusted by one-half of the camber increase. Camber losses of this nature, but generally smaller in magnitude, are also known to occur in straight beams and girders.
Unit 2 Modeling – Comparisons

- MIDAS Grillage+ versus LEAP Steel Grillage
- LEAP uses a STAAD.Pro Engine for analysis
- LEAP Steel serves as a GUI & Wizard
- STAAD Model is accessible, but is deep in directory
- LEAP model is faster to assemble and run
- LEAP output is more difficult to use (at least currently)
  - Limited data sorting and exclusion
  - Limited capacity for visual representation of data, compared with MIDAS
  - The above is my personal opinion (disclaimer)

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<th>Feature</th>
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<th>LEAP Steel</th>
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### Unit 2 Modeling – Comparisons

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## Unit 2 Modeling – Comparisons

**MIDAS Grillage+ versus MIDAS All Plate**

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**Comparisons**

- **Time**: 1s
- **DEAP**: 2.84
- **C1**: 3.9
- **C1C2**: 1.8
- **C3**: 0.8
- **C4**: 0.5
- **C5**: 0.3
- **C1C2C3**: 1.1
- **C1C2C4**: 2.6
- **C1C2C5**: 2.9
- **C1C2C3C4**: 4.1
- **C1C2C3C5**: 4.9
- **C1C2C3C4C5**: 5.9

**Total Comparison**

- **Total**: 5.9

**Note**: The table represents a comparison of various parameters between MIDAS Grillage+ and MIDAS All Plate models, with specific focus on the time and efficiency improvement. The values indicate a significant improvement in performance with MIDAS Grillage+.
### Unit 2 Modeling – Comparisons

- MIDAS Grillage versus LEAP Grillage Moment/Flange Stresses

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Unit 2 Modeling – Comparisons

- **Reactions**
  - MIDAS Grillage versus Plate Total Reaction Differences between 0.05% and 1.83% on overall structure
  - MIDAS Grillage versus Plate Individual piers reactions generally had minimal differences, ~1.0% on average, 3% worst case
  - MIDAS Grillage versus LEAP Grillage differed in reaction distribution, average 10% difference
  - MIDAS Grillage versus MDASH Girder Line showed a larger difference

- Moment comparisons between grillage and all plate are not readily available
- Can calculate beam stresses from grillage, then compare to direct plate outputs
- LEAP Grillage and MIDAS Grillage provided similar flange stress outputs and required plate sizes, though utility (demand versus capacity) varied. This is due to program interpretations of several parameters, such as lateral bracing
- LEAP results included higher lateral bending stresses but very similar overall combined stress
Unit 2 Modeling – Comparisons

• Take-aways:
  • Girder Line Analysis over-estimated deflections substantially in final condition
  • Girder Line Analysis under-estimated initial stage deflection
  • LEAP slightly overestimated deflections versus MIDAS All-Plate
  • MIDAS Grillage slightly underestimated deflections versus MIDAS All-Plate
  • In general the LEAP Grillage/MIDAS Grillage/MIDAS All-Plate were within 1/8-in of each other. Given that sacrificial haunch is 2-inches thick to make up for variations, and there is a 1/16-in tolerance on steel fabrication and 1/8-in tolerance on concrete, this is not as much of a concern in this case
  • On deeper girders, this difference could become more substantial and all-plate analysis becomes more critical for camber predictions
  • MIDAS Grillage provided very similar final reactions to MIDAS All-plate
  • Note MIDAS All-plate does not have code check capability at this time
In design of flanges there were several locations where lateral bending stress exceeded 0.6Fy = 30 ksi, but overall combined stress was less than capacity.

Normal check equation = f_{bu} + \frac{1}{3} \times f_l

In commentary Section 6.10.1.6 it states:

- “The provisions of Article 6.10 for handling the combined vertical and flange lateral bending are limited to I-sections that are predominantly in major-axis bending. For cases in which the elastically computed flange lateral bending stress is larger than approximately 0.6F_y, the reduction in the major-axis bending tends to be greater than that determined based on these provisions. The service and strength limit state provisions of these Specifications are sufficient to ensure acceptable performance of I girders with elastically computed fl values somewhat larger than this limit.”

The term “somewhat larger” is unclear. As engineering judgment, the flange lateral bending stresses were limited to around 10-20% over 0.6Fy, provided utility ratio remains below 1.0.
Modeling – Boundary Conditions
Modeling – Boundary Conditions
Construction Sequencing – Deck Pours

- Normally would have poured ends, then positive moment regions, then negative moment
  - This is to help prevent cracking in the negative moment regions during the next positive moment pour
  - As the positive moment wet concrete load is added it creates negative moment over the pier
- In this case, reversal areas were so close that this did not make sense
- Instead, poured ends for hold down, then worked towards the middle
- Positive and negative moment regions are poured together up to contra-flexure points to attempt to minimize effect of next pour in sequence
Connectivity between beams/girders and crossframes/diaphragms is essential during the construction process, particularly for curved structures.

Due to connectivity, deflections and twisting of the beams/girders will occur during deck pours. This can cause loss of deck thickness or cover during deck pours.

The three primary sources are:

1. Global Superstructure Distortion, caused by differential deflections between girder lines.

Figures from The Ohio Department of Transportation Bridge Design Manual
Construction Sequencing – Deck Pours

2. Oil-Canning, caused by additional lateral load on a beam/girder from the cantilevered formwork on a web. Usually only a concern for deeper beams/girders.
Construction Sequencing – Deck Pours

• 3. Girder Warping, caused by additional torsional load from wet concrete deck overhang, formwork loads, and screed loads.

• For straight bridges, often calculated using the Torsional Analysis of Exterior Girders (TAEG) program developed by the Kansas DOT. This software is free, and can be downloaded at [http://www.ksdot.org/kart](http://www.ksdot.org/kart)

• In MIDAS, a more explicit calculation is possible for items 1 and 3, with some limitations

Figure from The Ohio Department of Transportation Bridge Design Manual
Construction Sequencing – Deck Pours

- Future MIDAS development – moving screed loads during construction staging
- Can currently apply loads manually – over piers, at positive moment regions
- Alternatively, analyze for all loads except screed machine in MIDAS and use stress outputs into TAEG for just screed load and oil-canning as a very localized effect (between crossframes)
- All plate model used for construction sequencing and dead load verification
Construction Sequencing – Deck Pours

Stage 1 – Initial Steel Set

Stage 2-1: Wet Concrete, Pour 1

Stage 2-2: Hardened Pour 1
Construction Sequencing – Deck Pours

Stage 2-3: Wet Concrete, Pour 2

Stage 2-4: Hardened Pour 2
Construction Sequencing – Deck Pours

Stage 2-5: Wet Concrete, Pour 3

Stage 2-6: Hardened Pour 3
Construction Sequencing – Deck Pours

Stage 2-7: Wet Concrete, Pour 4

Stage 2-8: Hardened Pour 4
Construction Sequencing – Grillage vs. Plate

- Loadings
- Grillage model used vertical distributed line loads with eccentricity
- Could also use vertical distributed line load at centroid of beam, and distributed line moment, but would require 2x the inputs
Construction Sequencing – Grillage vs. Plate

- Plate model does not allow for eccentric line load or distributed moment
- Plate loadings do, however, allow for line loading under the “edge loading” method
- In order to apply the proper lateral moments, used eccentricity and line load to determine line moment, then converted line moment into a line-force-couple to apply as edge loading
- While this took a few steps in excel, it simplified input from applying point loads/moments
Construction Sequencing – Grillage vs. Plate

- General rule on rotation limitation = 1/8 in/ft, or 0.0104 radians (10.4 x 10^-3), however this is not a code provision, but engineer’s judgment

- Used local rotation, and “current step displacement” in MIDAS

- Worst case is during first end pour, all subsequent pours are less

- All-plate model is more accurate than frame/grillage model, produced much higher rotations

- Conclusion: while grillage+ model is adequate for loads and final condition design, a full plate model is strongly recommended for evaluation of lateral deformation during construction sequencing

- Solution: as a short girder, used 1/4 in/ft (20.8 x 10^-3) as upper limit on rotations, but provide temporary timber blocking at one-half the crossframe spacing within regions where deck is being poured
Project – ODOT GUE-513-08.65

- SR-513 over IR-70, Curved 4-Span Bridge (60’-11.75”, 2 @ 86’-9”, 60’-10.75”)
- Skewed 19° 32’ 07” to reference chord
- Composite on curved rolled steel beams
- R = 1206.23 ft
- Minimum Girder R = 1185.48 ft
- Dc = 4° 45’ 00”
- Δ = 79° 46’ 07”
- All crossframes and girders radial
- Vertical Sag Curve
- Part-width construction, including pier caps
Project – ODOT GUE-513-08.65
• Not a structural issue, but Amish Horse & Buggy use bridge and needed to be included in analysis: single lane signalized. Needed ramp queue and red time clear analyses
Project – ODOT GUE-513-08.65

• MIDAS used for design, after girder line with V-Load analysis for preliminary
• No change in beam size from V-load to MIDAS, similar results, but larger radius than CONRAC
• Separate MIDAS model created for temporary support analysis and design
• Important to include relative stiffness of concrete column versus steel temporary support columns. Used full moment of inertia for column. If moment is significantly great, would need to include cracked moment of inertia/stiffness, particularly for elastic analysis
• MIDAS design analysis was very useful – could output design results of concrete columns, composite beams, and steel temporary support all from the same model file.
• In this case, used existing footings/extensions for foundation of temporary support, so relative stiffness of foundation was not included
• If using temporary shoring on matting, would need to account for the stiffness of matting and foundation as well. This is possible in MIDAS through spring assignments at foundations.
• Need to provide room for adjustment during construction. In this case hydraulic jacks to provide positive contact with pier cap, grout under base plates for leveling
Project – ODOT GUE-513-08.65

- Originally used one tower with compression and tension connection (bearings & tension rods)
- After discussion with ODOT, added a second tower for redundancy.
- Order of preference: Compression -> Tension -> Shear
Project – ODOT GUE-513-08.65

- Stage 1
Project – ODOT GUE-513-08.65

- Stage 2
Project – ODOT GUE-513-08.65

• Stage 3
Project – ODOT GUE-513-08.65

- Stage 4
Conclusions

• MIDAS capabilities for construction staging and ability to analyze and design multiple stages as well as design multiple material types within a single model is very advantageous
• Proper analysis of construction cases is a key aspect in modern bridge engineering
• Refer to AISC/NSBA guides for very useful constructability guidelines
• V-Load & Girder Line analysis is accurate for larger girder radii, but becomes less so for very small radii. Need to provide contingency for additional girder warping and internal force effects, but is still a useful tool in preliminary engineering
• MIDAS Grillage and LEAP Grillage provided similar results overall with variation in details. LEAP was faster to set up and run model but is more difficult to extract output and model is less readily available
• Grillage+ (limited 3D) modeling provides good results for design of girders in the final condition, and forces during construction, but underestimates girder rotation
• All-plate model is recommended to verify constructability cases and in particular girder rotations during deck pour sequence
Recognition

- Best practice for finite element design – independent models by independent designers, with common checker and final reviewer. Cross review by designers.

- Special thanks to the following people:
  - Paige Sechrist, PE – Design Engineer/Modeling, MIDAS Grillage and Plate (CONRAC)
  - Pat Plews, PE – Independent Review, LEAP Grillage (CONRAC)
  - Mike Avellano, PE, SE, PMP – Project Manager, Checking and Independent Review (GUE-513, CONRAC)
  - Ron Mattox, PE – Independent Review (GUE-513)
Questions?