MANAGING THE OPTION TO USE REFINED ANALYSIS IN BRIDGE DESIGN AND BRIDGE EVALUATION

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ABSTRACT

The computational tools available to bridge designers and evaluators have greatly improved in the past 20 years. Managers are faced with the challenge of providing appropriate tools, training, and leadership to analyze appropriately. The force effects generated by a refined analysis will lead to a more uniform level of safety, but girder-line analysis can also produce acceptable results. The manager must be able to recognize when refined analysis is called for, understand the effort required, and make appropriate business decisions.

This presentation/paper will provide insights on European usage of grillage analysis. The first author was a part of a 2009 AASHTO-FHWA scan team that met with its counterparts in Finland, Austria, Germany, France, and the United Kingdom to discuss techniques used in bridge design and evaluation. The presentation/paper will also contrast these observations with tools and practice more common in the US. Challenges encountered by the authors' colleagues using both girder-line and more sophisticated analysis for bridges and bridge alignments of various complexity will be described. Results from a study done by the California Department of Transportation on skewed integral substructures will be presented. Recommendations are made for future study and managing the option to use refined analysis in the interim.

Keywords: refined analysis, skew, management, load distribution

INTRODUCTION AND BACKGROUND

Modeling and analysis of bridges for preparation of construction contract documents is very different in the United States and Europe. In the U.S., girder-line or single spine analysis is generally used on typical highway bridges. In Europe, influence surfaces and grillage models would generally be used on similar structures. This paper provides background to this dichotomy, summarizes modeling options, discusses an ongoing study to compare approximate and refined analysis methods at the California Department of Transportation (Caltrans), and suggests areas for managers' consideration in software decisions. The target audience is (U.S.) managers of designers of new bridges and evaluators of existing bridges. It is assumed that the reader is familiar with girder-line and finite element methods of structural bridge analysis. The authors' objective is create awareness of the short-comings in current (U.S.) practice for analyzing some typical bridges and of more accurate but more time-consuming analytical options.

The AASHTO Standard Specifications[1] relied on "*s*-over" factors where '*s*' was the girder spacing and 'over' was some constant to divide the spacing by, in order to determine the lane fraction to be considered in design of each girder. Different constants were provided for various girder and deck types, for the most part based on successful past practice. Inasmuch as deck thickness, span length, girder stiffness and other parameters known to effect load distribution weren't considered, an NCHRP project was initiated to develop the next generation of load distribution factors[2]. The work involved a dataset of over 200 bridges, exponential curve fitting, and a rigorous comparison of results using approximate methods to those using finite element analysis. The methodology was approved by the AASHTO Subcommittee on Bridges and Structures (SCOBS) and issued first as AASHTO Guide Specifications, and then incorporated into the AASHTO LRFD Bridge Design Specifications[3].

The change wasn't without controversy. At the time spreadsheets were in their infancy and some felt such complexity was unnecessary; others feared greatly increased design times. Another NCHRP project was initiated to develop "simplified" live load distribution[4] with revised expressions based on linear curve-fitting. The proposed change was considered for ballot by SCOBS in 2006. After much debate, the T5 Loads and Load Distribution pulled the item because 1. Complaints over complexity weren't being heard from designers, 2. Calibration had been based on the current load distribution factors, 3. T5 members knew software would evolve even further than it had since the commencement of the study, and 4. T5 members felt their time would be better spent looking into advancements made in Europe and preparing for the next leap in computational tools.

EUROCODE AND EUROPEAN SCAN TRIP FINDINGS

Development of the Eurocode was a part of an action program to eliminate technical obstacles to trade by harmonizing construction-related specifications[5]. Four load models are provided and calibration is suggested for "characteristic" i.e. long return periods and "frequent" i.e. short return periods. However, a direct comparison of design loads isn't simple in that each country has a "National Annex" with values for "Nationally Determined Parameters" (including load factors), and other alternative procedures deemed acceptable by the country. What is germane pertaining to analysis of live loads, though, is that Load Model 1 (LM1), a combination of a tandem axle load and uniformly distributed load, similar to AASHTO's HL93, calls for the uniformly distributed load to be placed on only the "unfavorable parts of the *influence surface*", and in both directions. The relative complexity of the Eurocode vs. AASHTO LRFD continues in that its Section on Analysis has sub-sections on "Linear Elastic Analysis with limited redistribution", "Plastic Analysis", Non-linear Analysis", "Analysis of Second Order Effects with axial load", and Annexes[6] on concrete shell elements and box girder web shear and transverse bending.

FHWA and TRB co-sponsored an International Scan in 2009 to investigate the European usage of refined analysis in both bridge design and bridge rating. Entitled "Assuring Bridge Safety and Serviceability" (ABSS), participants included four members of SCOBS, three from FHWA, one consultant with rating expertise, one consultant with design expertise, one academic, and a report writer. Departments and Agencies visited included the Finish Road Administration; developers of 3D software RMFrame in Austria; the Austrian Federal Ministry for Transport, Innovation and Technology; the Vienna City Administration; the French Ministry for Transport Technical Department for Transport, Roads, and Bridges Engineering and its research arm; the German Federal Highway Research Institute and various German consultants and academics; the UK Highway Agency and the London Road Network Management; a British software user group and various consultants, and academics from Cambridge and Ireland.

The consensus in the conversations had seemed to be that the time required to create a grillage model was not that much greater than that to model an individual girder; that having a sense of the system behavior from the grillage model was very important; and that being prepared with a grillage model to quickly handle any project changes made good business sense[7]. Refined analysis seemed to be of more importance to the Europeans in bridge evaluation than in bridge design. Rehabilitation or replacement might be justifiably delayed, and resources confidently directed to structures most in need. Some countries accepted a reduced target reliability for structures with a limited remaining service life.

In order to implement the findings from the Scan, a survey was first conducted in the US. The 33 respondents were a mix of State and consultant engineers. Some State Agencies indeed used refined analysis, but usage was limited--and in some cases exploratory. A few did indeed use refined analysis in bridge evaluation similar to the Europeans. Software tools varied. Outreach was then done to various software vendors, realizing that any training would need to be in part tool-specific. The original implementation plan was to offer a one-day training course with the morning spent on theory and the afternoon presented by a software vendor of choice. A pilot run, however, indicated that much more time was needed on the latter. A three-day course was being developed at the time of this writing.

TYPES OF MODELS AND ANALYSIS

The most basic of beam-slab bridges can be designed girder-by-girder using “girder-line”, or one-dimensional (1D) analysis. Load-sharing between girders is accounted for by using AASHTO’s load distribution factors. Accuracy is good so long as the girders are of equal stiffness and spacing, girders are continuous or simply supported, the plan-aspect (length-to-width) ratio is over 2.5, and supports are perpendicular to the girder layout.

Grillage, or two-dimensional analysis (2D) becomes more appropriate for design of the superstructure when girders vary in stiffness, a heavy utility load must be added, or the range-of-applicability of AASHTO’s live load distribution factors is exceeded. This type of analysis seems to be most often used in Europe. Live loads are designed for using influence surfaces rather than influence lines, in some cases leading to economy in member sizes.

Frame analysis must be used when modeling/designing superstructures with integral supports. If the superstructure can be modeled as a single “whole-width” girder and the supports are symmetrical, 2D frame analysis can be used. The section properties of individual columns in a multi-column bent are added and analysis is done as shown in Figure 1.

Design of multi-column bents both integral and non-integral with the superstructure also entail 2D frame analysis, but using a separate model oriented in the transverse direction. Care must be taken in transferring the appropriate reactions from the superstructure to the substructure model, especially if the superstructure is asymmetric, the alignment is curved, or the supports are skewed. If the supports were skewed in the superstructure model, application of AASHTO skew factors to the reactions may be redundant.

To have just one model for super- and substructure design, a 3D-frame model and influence surface loading may be used. However, if the frame model is made up of beam elements, bending will only be available around one axis. Accuracy decreases when beams are not oriented in the direction of the load path, such as at an obtuse corner where stress follows the shortest path to the closest support.

A 3D shell-element model will capture rotation around three axes as well as displacement in three directions, and should be used for structures with unusual geometries. However, more time is required on the part of the designer to become familiar with the software, build the model, and select the appropriate force effects for design.

CALTRANS INVESTIGATION

The California Department of Transportation pioneered the development of "2.5D" frame analysis for its work-horse bridge, the cast-in-place (CIP) post-tensioned (PT) multi-cell (MC) box-girder bridge. The superstructure is modeled as a single-spine, integral with the bent, as shown in Figure 2. The supports can be skewed, enabling the superstructure model to capture that effect. When designs of skewed bents using reactions from 2.5D skewed supports were alarmingly conservative, Caltrans initiated a study to compare substructure force effects from 2D, 2.5D, and 3D analysis using refined analysis.

A sample of the 3D model used for this analysis is shown in Figure 3. Various modeling options and mesh sizes were considered; ultimately a beam/shell model was chosen and verified. The data set used included 2-span (150-150-ft) and 3-span (150-225-150-ft) models; 0 and 45-degree skews; 1, 2, and 4-column bents (respectively 27, 57, 107-ft widths); circular columns 20- and 70-ft in height; fixed (1-column) and pinned (2, 4-column) at base; slider and roller-type abutments. Influence surfaces were generated for transverse and longitudinal moments at top of columns. Two sample influence surfaces are shown in Figures 4 and 5. The influence surfaces were loaded with a standard design truck (HS20) to determine the maximum transverse and maximum longitudinal column moments. The maximum resultant was then determined.

The same bridges were modeled using both 2D (Figure 1) and 2.5D (Figure 2) models and loaded with the standard design truck. Reactions from these longitudinal analyses were then applied to a separate frame model of the bent cap, being positioned to transversely to cause the maximum column moments for design. Obviously, the spreading of force effects between the point of load application and the column is not captured as well as when using a 3D model. The most critical resultant moment of three cases is determined: 1. Maximum axial load and associated transverse and longitudinal moments, 2. Maximum transverse moment, associated axial load and longitudinal moment, 3. Maximum longitudinal moment, associated axial load and transverse moment.

Figure 6 shows the summary of the results from the 2.5D and 3D analyses for column moments. Results for single column bents are generally much higher when 2D/2.5D analysis is used and can be up to 8 times the values from 3D analysis. It is also noted that the results of the 2.5D analyses are up to three times the results of the 3D analyses regardless of the skew, in other words the skew does not exacerbate the conservativeness of the simplified analysis. If the abutments are assumed to be restrained against transverse movement, column moments are higher, but the ratios of 2.5D to 3D analysis results are still in the same general range for skewed multi-column bents. More definitive guidelines on when to upgrade from 2.0D or 2.5D to 3D analysis for CIP MC PT concrete box girders are expected at completion of this study.

CHALLENGES IN MANAGEMENT

Although not appropriate for all or even most projects, managers can and must provide refined analysis tools to meet today's challenges in both bridge design and evaluation. Europe seems to be successful in this regard. Appropriate training, learning curve time on project work, and mentoring is also incumbent. That being said, enhancements of 3D live-loaders and influence surfaces are needed for more routine usage—and won't happen until the number of users increases and a critical amount of feedback is received by software vendors to make the investment of their resources worthwhile.

Frequently asked questions by managers follow with the authors' recommendations:

1. Doesn't use of approximate live load analysis methods provide an extra margin of safety? *Not necessarily; the approximate methods can be low as well as high. The "extra margin of safety" can be excessive and excessively bump up construction costs.*
2. I can't trust my engineers with a "black box". *The newer, more advanced software tends to have more documentation and built-in "help" available than the older, more basic software. Refined analysis can also be a reason to remind engineers of the need to constantly review results and ask "does this make sense?" Ask engineers what boundary conditions have been chosen and if they're representative of probable bridge behavior. Ask to see graphical output because it can also hint at input errors.*
3. When should refined analysis be considered? *In the case of CIP PT MC concrete box-girder bridges, preliminary results indicate that refined analysis should be used for complex geometries and when a savings in column and foundation design is desired, especially in the case of single-column bents.*
4. How much longer will refined analysis take compared to analysis using approximate methods? *Of course, this depends on user-friendliness of the software as well as the skill set of the engineer, training completed, and previous software experience. Availability of documentation or another experienced user is helpful. Engineers that*

the International Scan Team interacted with reported no significant difference once a user becomes proficient with grillage software.

5. What's in it for me (WIIFM)? *Potential cost-savings in construction; a more realistic "feel" for the structure behavior; a model to facilitate quick response to any field changes or permit requests; a more experienced engineer to assist in your next bridge emergency, mentor others in the use of the software, and serve as an effective technical liaison to the software vendor.*

CONCLUSIONS AND RECOMMENDATIONS

Analysis tools above and beyond those for girder-line analysis are routinely used in Europe, and are available here in the United States, but not routinely used. For complex bridge geometries and loadings, such tools are necessary for accurate design, evaluation, and prioritization of bridge rehabilitation resources. Managers of bridge engineers in both design and evaluation need to be aware of the tools available and their shortcomings, provide tools and learning curve time, and set limitations as to who uses the tools and on what projects.

A study of beam-slab bridges is recommended similar to that described herein for CIP PT MC concrete box-girders. Managers need to know the amount of potential over-design especially in the case of single-column bents when using girder-line analysis to determine column and foundation design requirements. Clear limitations on approximate analysis of especially skewed bridges and those subjected to heavy torsional loads would be useful for various bridge types, integral vs. non-integral bents, continuous vs. simply supported girders.

Software vendors are encouraged to seek feedback from users of 3D live-loader and influence surface features in order further streamline model building, loading, and analyzing with their product. The authors predict that a more refined analysis of live loads compared to the present approximate methods will be the standard in ten years. Partnering of bridge owners, managers, engineers, and the software industry is needed for a smooth transition.

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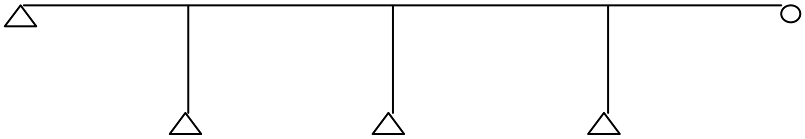

Fig. 1 Typical 2D frame analysis in longitudinal direction.

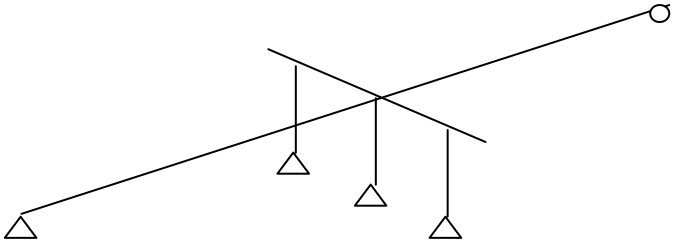

Fig. 2 Caltrans 2.5D frame analysis.

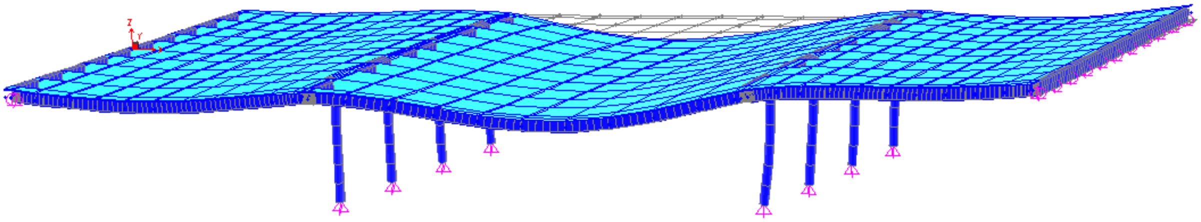

Fig. 3 3D Model and Deformed Shape due to Dead Load

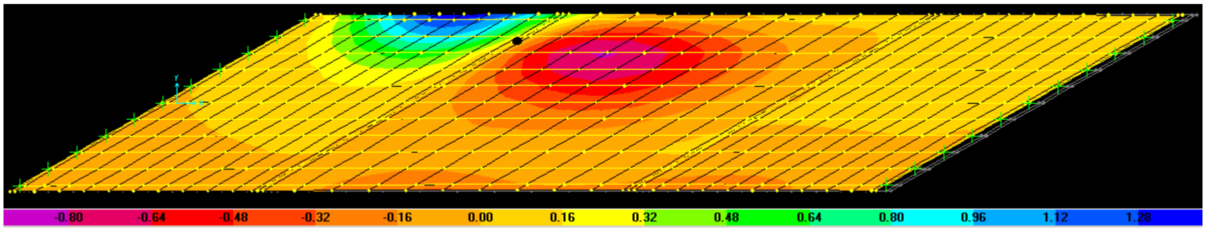

Fig. 4 Influence Surface for Longitudinal Moment at top of Column1

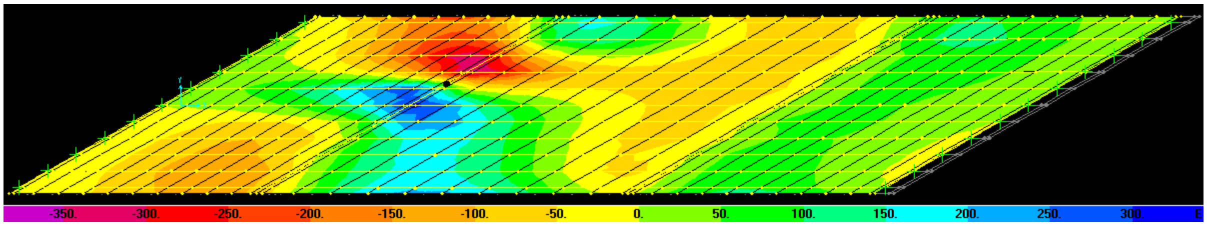

Fig. 5 Influence Surface for Transverse Moment at top of Column 2

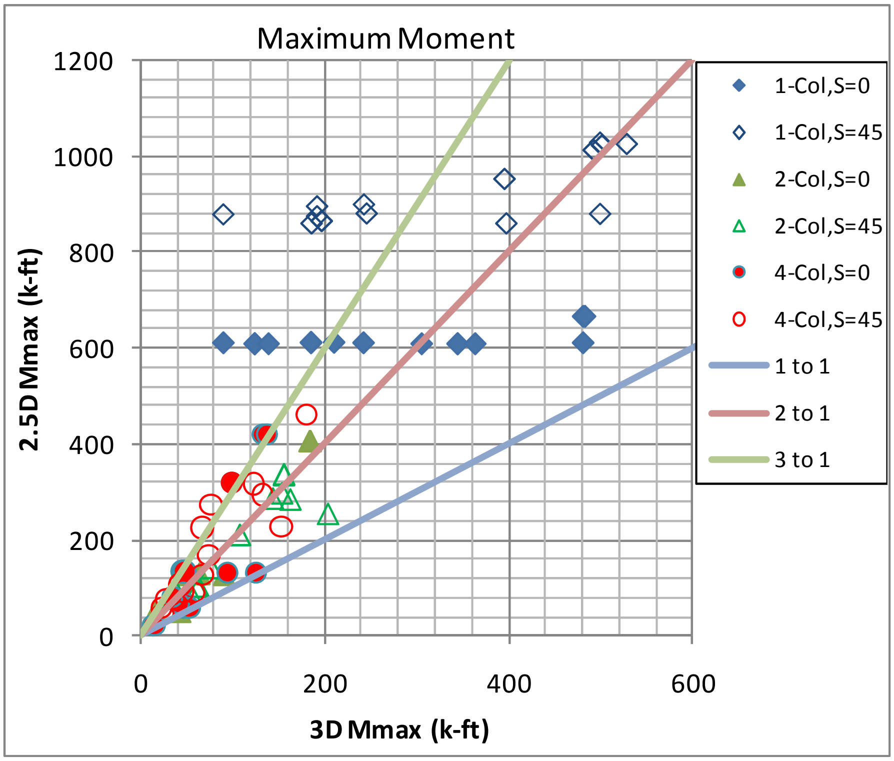

Figure 6 Comparison of 2.5D and 3D Column Moments