An Analytical Monitoring Tool for Bridge Construction

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Introducing a university-developed, robust, user-friendly finite element program for I-girder bridges during construction.

MANY BRIDGE ENGINEERS often put their primary focus on the behavior of bridges under maximum design loads in the final configuration. The current codes bear this out by devoting the vast majority of pages to the analysis and design of bridges in their final state. While assessing the strength and performance of bridges under service and ultimate loads is clearly important, the stage in a bridge's life that often has the smallest factors of safety is during construction when little if any bracing may be present. Because of the limited amount of bracing and uncertain support conditions, the construction condition is often the critical stage for system stability. Additionally, during construction, the behavior is controlled by the non-composite section that is usually proportioned for composite action in the finished bridge.

The issue becomes more prevalent as engineers use smaller top flanges in singly-symmetric girders. There have been multiple cases of I-girder bridges that have collapsed during construction including failures in Illinois, Colorado, and Tennessee. These catastrophic failures highlight the need to ensure stability during early construction stages when the final bracing is not present or fully effective.

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In addition, there are likely other more common and less reported serviceability failures that occur when girder deflections vary significantly from predicted values that render the final bridge geometry out-of-tolerance. Such a case occurred in Wichita Falls, Texas, were a 2D grillage model failed to predict the excessive torsional flexibility of the curved bridge. The resulting cross-sectional geometry did not meet the roadway requirements and required a costly retrofit.

A solution for many of these problems is to develop the necessary limit states for construction and to analyze the bridge at each stage of the construction process. The issue is complicated in bridges with skewed supports and/or horizontally curved geometry where traditional 2D grillage models may not be appropriate for fully capturing the behavior of the system. Thus, it is desirable to perform a 3D finite element analysis (FEA) of such bridge systems at each stage of construction.

A User-Friendly Solution

UT Bridge is a 3D finite element program capable of performing a linear elastic analysis during each of the girder erection stages and the placement of the concrete bridge deck. An elastic analysis is suitable during construction because typical design and construction practices reasonably limit girder yielding during this early stage in a bridge's life. For the concrete deck placement, a linear incremental analysis was developed that is capable of accounting for the time-dependent nature of the concrete strength and the variation in the composite behavior as the concrete cures. Additionally, an eigenvalue buckling analysis can be performed to provide an indication of the global stability of the system at each of these critical stages and determine its critical buckling capacity. An example of that type of analysis is shown on the last page of this article (as Figure 8).

The central philosophy of the program is to provide a tool that allows engineers to quickly and accurately develop a 3D finite element model from the information readily available in the bridge plans. Basic features of UT Bridge include allowances for self-weight, wind loading, point loads, and temporary supports. The latter two features can be used to design erection plans accounting for the necessity and placement of shore towers or holding crane configurations (complete with crane loads).

Geometric features of the program include both straight and curved bridges, skewed substructure supports, any number of girders, and any number of spans. The user has three meshing options: coarse, normal, or fine. The default mesh density is the normal mesh and is suitable for most bridge geometries. Aside from selecting the mesh density, the entire finite element mesh is automatically generated by the program after the engineer defines the bridge layout using basic information commonly found on bridge plans. Therefore, extensive understanding of finite element modeling techniques on the part of the user is not required. Results from field measurements and other commercially available software packages have been used to validate the accuracy of the program.

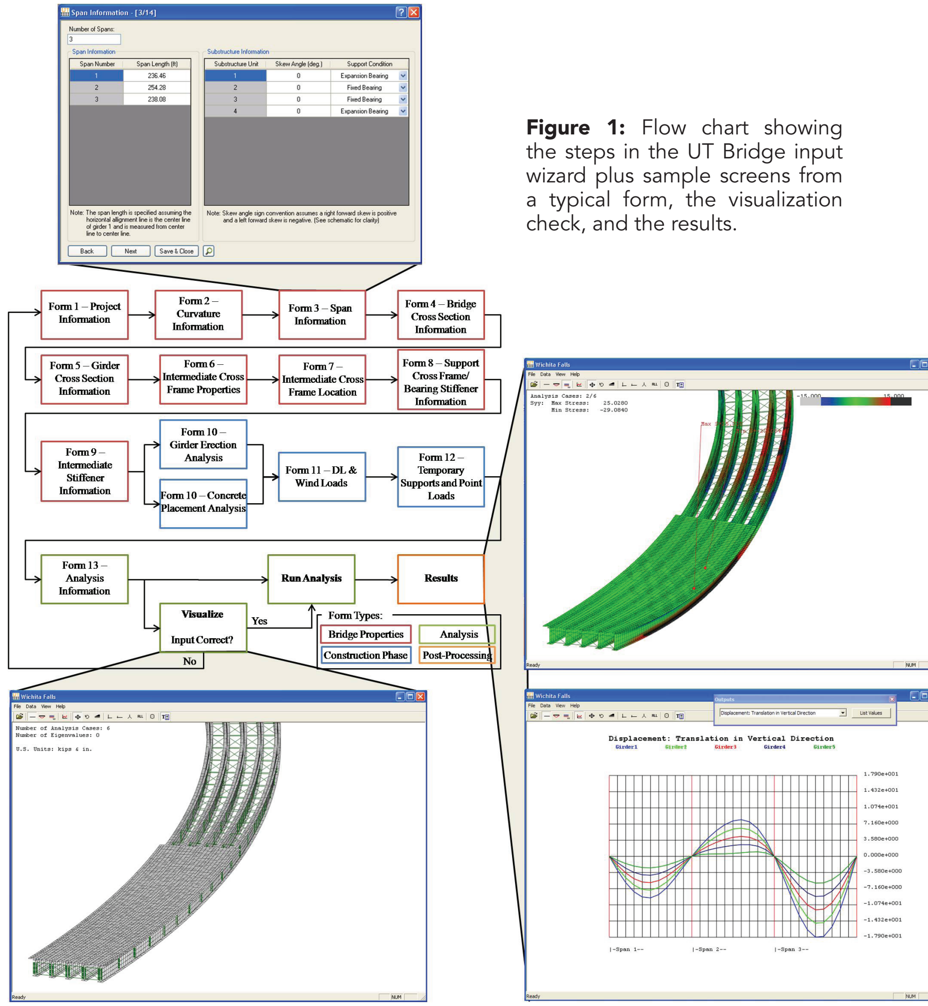

Figure 1: Flow chart showing the steps in the UT Bridge input wizard plus sample screens from a typical form, the visualization check, and the results.

Input Forms

The welcome panel of UT Bridge prompts the user to begin an input wizard that consists of a series of 14 input forms. Figure 1 is a flow chart of the input wizard and a set of UT Bridge screen shots.

The first nine forms define the bridge properties, the next three define the construction analysis cases, and the last two allow the user to define the kinds of analyses to perform. The bridge property forms include all the geometric dimensions of the bridge necessary to define and develop the 3D model. They include information regarding span length, skew angle of substructure, cross-sectional dimensions, cross frame spacing, stiffener spacing, and other information found in a typical set of bridge plans. The input forms include help screens as well as preview features that an engineer can use to make sure that the desired bridge geometry is being correctly defined.

One of the most powerful features of UT Bridge is its ability to easily analyze a full bridge erection sequence. The program allows for the full bridge to be input once and then each step in the erection sequence to be ana-

Figure 2: Photo and model for one step in the erection sequence.

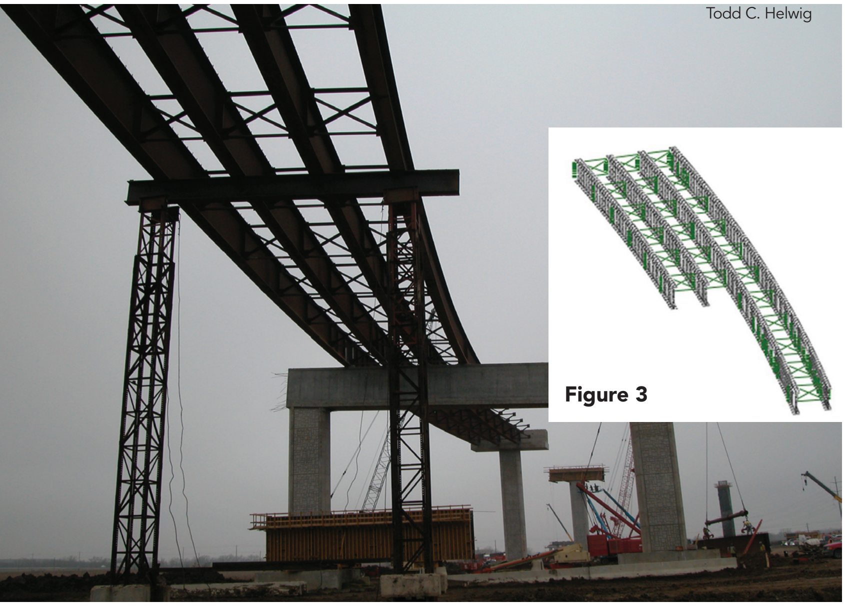

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Figure 3

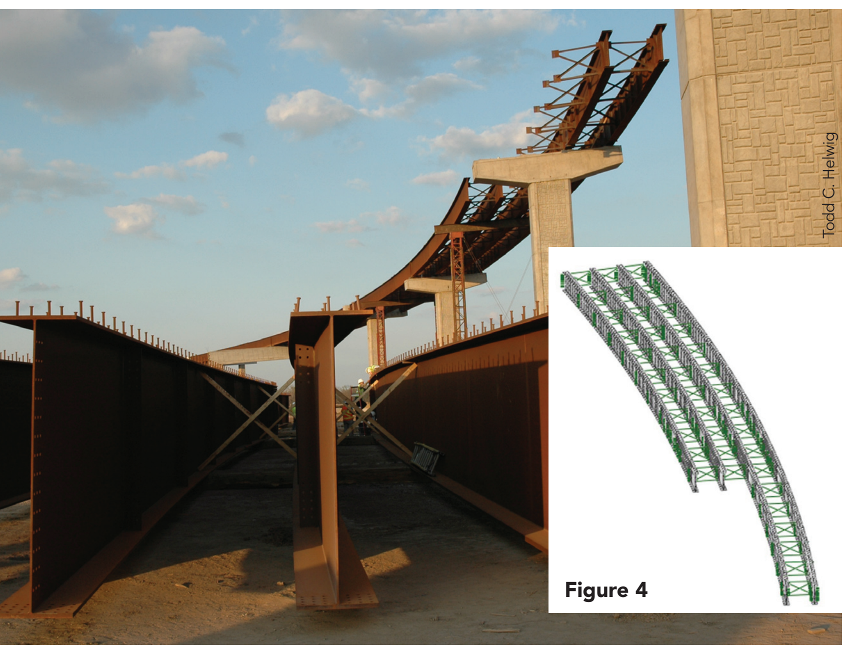

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Figure 4

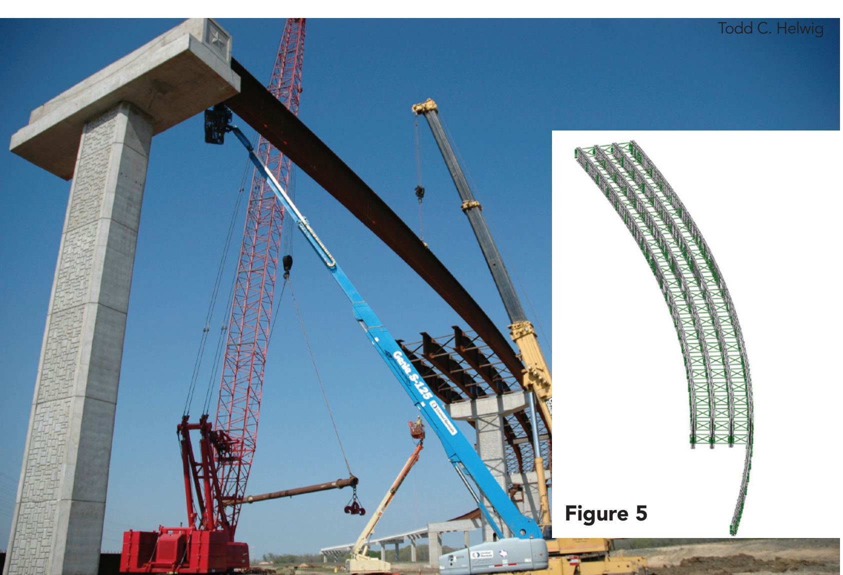

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Figure 5

lyzed individually. The user defines which portions of the bridge (girder number and length) are erected during each lift, and the sequence becomes an analysis case. For each analysis case the program determines deflections, stresses, and rotations of each girder. The bridge model is assumed to be erected from one end of the bridge toward the other. This process can be completed ahead station or back station. Thus, a bridge built from each end and completed with a central drop-in section cannot be explicitly modeled, though it can be accurately approximated through various modeling techniques.

The program treats each set of lifted girders as an analysis case. Each analysis case can be a single girder or multiple girders depending on the lifting sequence used by the erector. Typically, the first girder lifted at a given cross section will be critical for stability design as the unbraced length is maximized for the bridge. Subsequent intermediate construction phases may be less critical and the analysis can be set up—or the engineer can choose—to erect several segments in a given stage to efficiently skip to the next potentially critical stage. This flexibility provides the erection engineer with options previously unavailable by current bridge analysis software. Figures 2 through 7 depict a bridge erection sequence with the associated UT Bridge model.

The other option for analysis is the ability to model the concrete deck placement. Concrete is normally placed either continuously or in positive moment regions first then negative moment regions. The user can specify the sequence of the deck placement and analyze the state of stress for each stage of the concrete placement. Although many designers do not consider the stiffening effect of previous placed concrete, the program has the ability to reflect the contributions of previously placed concrete. This requires that the early-age concrete be modeled in a time-dependent nature. Thus, a linear incremental analysis technique is used where the loads in the present analysis case are applied to the current system stiffness. The increment of displacement and stresses is then summed with all previous analysis cases to obtain the current state of displacement or stress.

The modeling of the interaction between the shear studs and the early-age concrete has not been studied extensively; however a relatively detailed experimental study was conducted at the University of Texas in 2002. The study was conducted with Class-S type concrete, which is commonly used in Texas bridge decks. The study produced a model to predict the interaction between the modulus of elasticity of the concrete and the stiffness of the shear studs. The method has been incorporated directly into UT Bridge so that an engineer can accurately estimate the contribution of previously placed concrete based upon the time between stages in the deck placement. If the user does not specify a time between concrete deck placement stages, the stiffening effects of the concrete will not be modeled.

Within the construction analysis, the dead load can be factored and a wind load applied. Two other critically important features available are the inclusion of point loads at any location on the girder and temporary supports under the girder at any point along the length of the bridge.

These can be specified for each stage of the analysis, allowing the engineer to optimize the location of holding cranes and false work, such as shore towers, that critically alter the stability of the partially constructed bridge system. The last two input forms allow the user to define the kinds of analysis to perform.

UT Bridge includes 3D graphics displayed in a window named UT Viewer. While the primary purpose of UT Viewer is for post-processing the results from the structural analysis, the feature also provides the engineer an invaluable tool to ensure the bridge intended to be modeled was properly input and key structural elements are located as indicated on the bridge plans. A visualization option is provided in the input forms that quickly develops the bridge geometry, but does not actually perform an analysis. This allows for a check of the input prior to the analysis.

Results

The displacement-based finite element analysis approach used in this program results in the numeric approximation of the nodal displacements, which are the primary variables. The calculation of the nodal stresses is a derived or secondary variable that must be calculated after the program calculates the displacements. This final step in the finite element analysis is referred to as post-processing.

Results from UT Bridge are displayed in UT Viewer, which was created to help the user easily view and interpolate the results from a set of analytical cases. After loading the results file, the user can view the bridge geometry, the deformed shape from the scaled displacements, and a contour plot of the stresses. Additionally, UT Viewer can display numerous 2D linear plots (XY plots) showing the displacements, rotations, and stresses at tenth points along the length of the bridge for each girder.

The information used to generate the XY plots also is available in a tabular form, which allows the user to copy and paste the information to other programs such as spreadsheets for further analysis. Data such as the tenth point deflections for each girder provide information that can be used to determine necessary cambering requirements for individual girders. This feature can be extremely valuable, particularly in systems with significant degrees of horizontal curvature and/or skewed supports.

Additionally, cross frame forces and reactions for each of the members are given in tabular form for exporting. The cross frame diagonals are assumed to be tension-only members and thus one diagonal will report zero force. The reactions for both permanent and temporary supports are given.

The program has been verified throughout the development at element level, girder level, and system level. A set of actual bridges were used to demonstrate the verification comparing field data, commercially available grillage programs, and 3D finite element models in ANSYS.

The UT Bridge software provides a relatively fast interface for creating 3D models and analyzing critical construction stages. The availability of UT Bridge to engineers provides a powerful tool for the evaluation of the performance of plate girder bridges during construction that more rea-

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Figure 6

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Figure 7

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sonably model the existing conditions compared to many existing programs. MSC

The authors would like to acknowledge the Texas Department of Transportation (TXDOT) for its technical and financial support of this project.

UT Lift, another bridge construction-related program developed at the University of Texas at Austin, was the subject of a 2009 World Steel Bridge Symposium presentation. The symposium paper is available as a free download from the AISC website at ***http://bit.ly/dpP7Z5***.

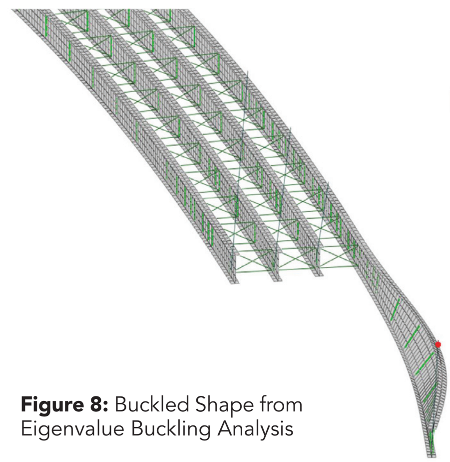

Figure 8: Buckled Shape from Eigenvalue Buckling Analysis

The Power Factor

The speed and data storage capacity of modern computers has made it possible for engineers to conduct sophisticated analyses of complex structural systems on personal computers or even portable laptop computers. The current significant impediment for bridge engineers in conducting a robust analysis of bridge systems is no longer related to computing power or technical capabilities of the software, but is instead generally in the user interface for computer programs to conduct these analyses. A 3D finite element analysis (FEA) has historically required expensive software and significant time to develop the models.

Although suitable programs are available, the time demand for a user to become familiar with many commercially available 3D FEA programs also impedes widespread use of these robust analytical tools. The lack of intuitive analysis programs applicable for modeling the construction sequence, which often is the most critical stage in the life of a bridge, was the driving force for the development of the software UT Bridge.

The software was developed at the University of Texas at Austin with support from the Texas Department of Transportation. UT Bridge is available as a free download at **http://fsel.engr.utexas.edu/software/**. Sample files and a training module are included in the downloaded file.