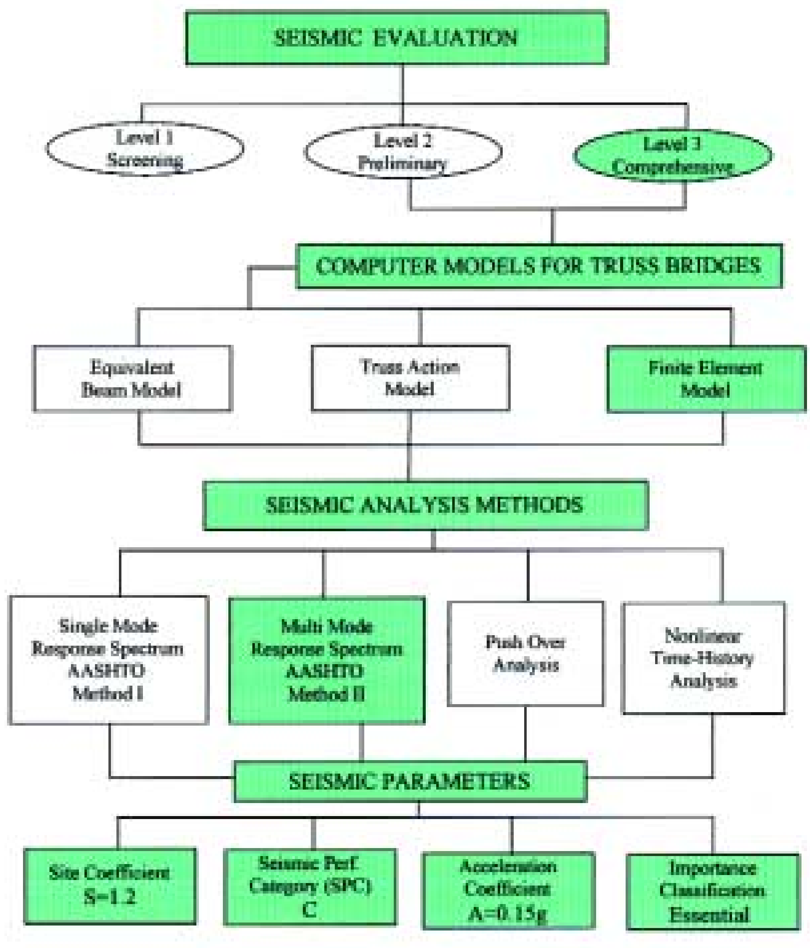
SEISMIC ANALYSIS OPTIONS FOR STEEL TRUSS BRIDGES

Seismic retrofitting is becoming increasingly common during major rehabilitation contracts



Seismic Evaluation Flow-Chart for a Typical Truss Bridge

By Sanjay Mehta, Ph.D., P.E.

TRUSS BRIDGES HAVE LONG BEEN A POPULAR DESIGN OPTION and come in a wide variety of sizes, shapes and forms—from a simple span truss of less than 100' to a cantilever truss with a total length of thousands of feet. However, many of these bridges were not designed for seismic loads as now specified in the current AASHTO provisions. As a result, many public transportation agencies are now considering seismic retrofit as a component of major rehabilitation projects.

The extent of seismic retrofitting is determined by performing a comprehensive seismic analysis and computing capacity-demand ratios for various components of the bridge. Unfortunately, it is difficult to standardize the seismic analysis and evaluation procedure for truss bridges due to their variety in size, shape and form. Many practicing engineers today are faced with the question of selecting an appropriate method for a seismic analysis and evaluation of truss bridges. What follows is a summary, based on a review of literature and the author's experience, of various options available for seismic evaluation, computer modeling and dynamic analysis.

SEISMIC EVALUATION

Seismic evaluation can be performed at three different levels. Usually, the owner of the bridge specifies the level of seismic evaluation required.

Level 1 is a simple screening using flowcharts based on bridge characteristics previously known to be vulnerable to seismic activity. It is not necessary to perform computer modeling or calculations at this level. "Seismic Design and Retrofit Manual for Highway Bridges," published by the FHWA, outlines this procedure. This procedure can be used to quickly screen several "regular" bridges as defined in AASHTO Standard Specifications (section 4.2, Division I-A).

Level 2 evaluation is a schematic assessment. Simple and approximate models are used to evaluate the applied seismic demand against the capacity of the component. The results are conservative for "regular" structures. However, for "irregular" structures with unusual geometry, abrupt changes in stiffness, framing action between different components, varying soil conditions and foundations, this assessment may not be conservative. Many engineers use this approach as a first step in seismic evaluation of truss bridges.

Level 3 evaluation is an in-depth seismic evaluation. This is usually employed for bridges that cannot be conservatively assessed by a Level 2 evaluation and for bridges that serve as very critical links in the transportation system. Global and local 3-D finite element models are developed to compute the seismic demand. Foundations are modeled considering soil-structure interaction. A site specific response spectrum may be developed for seismic input in case of a very important bridge.

Computer Models

Computer models are necessary for Level 2 and Level 3 seismic evaluations. For truss bridges, three different types of computer models have been used in engineering practice:

1. Equivalent Beam Model;
2. Truss Action Model; and
3. Finite Element Model.

All are considered as three dimensional models and require a structural analysis program.

Equivalent Beam Model. The truss system consisting of truss members, laterals and sway members is represented as an "equivalent beam" in this type of model. The properties of an "equivalent beam" are computed based on the geometry and cross sectional area of the truss members. This equivalent is then located at the centroid of the cross section of the truss superstructure. This is an approximate modeling method for truss bridges based on the assumption that the superstructure is very stiff and its exact modeling is not critical in seismic vulnerability assessment.

An advantage of this method is that it is easy to develop this type of model and results of the seismic analysis can be quickly interpreted. The method is very accurate for girder and short span truss bridges because the superstructure of such bridges is stiff and the first mode in both longitudinal and transverse direction can characterize the dynamic behavior of the bridge with accuracy.

However, the results are not strictly valid with long span truss bridges, which tend to be flexible. Furthermore, it is necessary to evaluate the capacity of critical truss members such as sway bracing over piers and shear locks at expansion joints. Since the superstructure is modeled as a line element, it is difficult—if not impossible—to compute forces in the critical truss members. An effective retrofit scheme for reducing the seismic demand is to permit limited yielding of truss members. This retrofit scheme cannot be evaluated unless truss members are explicitly modeled.

Truss Action Model. Many existing truss bridges have been designed based on "pure truss action". That is, only member axial forces are considered in the design. Moments resulting from the rigidity of riveted truss joints are neglected. A computer model with this assumption can be developed for seismic analysis. Unlike the Equivalent Beam Model, all truss members are modeled explicitly. Space truss members with only axial stiffness are used to model each truss member.

Most of the information required to develop the 3-D models is available from contract drawings of existing bridges. This results in significant savings in time and cost because computation of section properties and other related can be avoided.

However, while reasonable for dead load and live load analysis, this model may not be appropriate for seismic analysis. Seismic forces act in longitudinal, transverse and vertical (not considered in AASHTO at this time) directions. It becomes necessary to consider the flexural stiffness of truss members because significant amounts of seismic energy are absorbed due to the ductility of truss members. The end results do not justify even the reduced efforts required to build this type of model.

Finite Element Model. As in the Truss Action Model, all truss members are explicitly modeled in this approach. Usually space frame members with bending, shear and axial stiffnesses are used for modeling truss members and other components of the bridge. This model can be used for multi-mode response spectrum analysis, nonlinear time history analysis and push-over analysis.

An advantage of this system is that it permits the accurate representation of the superstructure (truss) stiffness, which is an important dynamic characteristic of long-span truss bridges. It is possible to evaluate axial forces and bending moments in critical truss members with reasonable accuracy. Recent research has found that force demand on bearings and substructure will be significantly reduced if truss members and connections have sufficient ductility after yielding. Of course, it is necessary to perform nonlinear analysis to check the ductility if elastic seismic force demand exceeds the capacity of truss members. Nonlinear analysis is required in such cases to compute: limit state displacements and rotations of truss joints to ensure serviceability of a bridge after an earthquake and reduced earthquake demands on substructure. Furthermore, effects of a local failure of truss members, such as buckling of sway frame members, fracture of tension members, etc., can be evaluated before designing expensive strengthening schemes. Performance of various retrofitting schemes can also be evaluated using such models and comparisons can be made with the original structure. The current engineering practice is to adopt this approach for computer modeling.

One disadvantage, however, is that substantial effort is required to develop this type of model. Usually trusses are designed as axial force members and only the cross sectional area is published on design drawings. Thus, it becomes necessary to compute the moment of inertia of truss members before developing this type of model. Further, all critical superstructure details—such as expansion joints, shear locks, truss-floorbeam connections, etc.—should be modeled for correct estimate of forces. It also becomes difficult to perform nonlinear analysis using such large models. (Nonlinear analysis will be required only if members are stressed well beyond the yield strength.) Usually, local models of truss end sway frames and substructure are developed to perform nonlinear analysis based on results of this large finite element model. This further increases cost and time required to complete the project.

Comparison

To date, very little published information is available regarding what type of models should be used in seismic assessment. Particularly, it is difficult to differentiate between using the Truss Action Model and the Finite Element Model. Therefore, a study was performed to compare the Truss Action Model with the Finite Element Model.

Two bridges on the New York Thruway were selected for this purpose: the 4,025'-long North Grand Island Bridge over the Niagara River and the 640'-long Normanskill Bridge. The Finite Element Models for these bridges were developed by Lichtenstein Engineering during a Level III seismic evaluation project. These models were then converted into the Truss Action Models. A multi-mode response spectrum analysis was performed and seismic demands in critical truss members were computed. Particularly, dead load and seismic forces in vertical members and bottom chord members at piers were computed. A seismic evaluation in terms of capacity/demand (C/D) ratio was performed. A C/D ratio of less than 1 indicates that the component does not have enough strength to resist the seismic forces and vice versa.

The C/D ratios were significantly different for the two models. For instance, the C/D ratio over Pier 1S is 0.83 from the Finite Element Model as compared to 1.13 from the Truss Action Model—a difference of 36%. Reactions (base shear) at the base of piers were also compared. The reactions from the two models differed by less than 5% for the Normanskill Bridge. For the North Grand Island Bridge, however, the maximum difference in reaction was 15-20% with the Finite Element Model generally giving higher reaction compared to the Truss Action Model.

It was thus concluded that the Finite Element Model is more appropriate for seismic evaluation because it accounts for both axial and bending stresses in truss members.

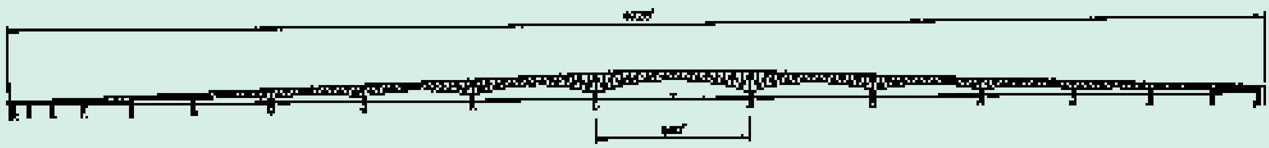
Methods For Seismic Analysis

Single Mode Response Spectrum Analysis. This method is discussed in the AASHTO Standard Specifications and is used for "regular bridges". According to AASHTO, regular bridges do not have abrupt changes in mass, stiffness or geometry along its span and have no large differences in these parameters between adjacent supports. This method is based on the assumption that the first mode in longitudinal and transverse directions can accurately characterize the dynamic behavior of the bridge. This method is very useful for girder bridges in conjunction with an "equivalent beam model."

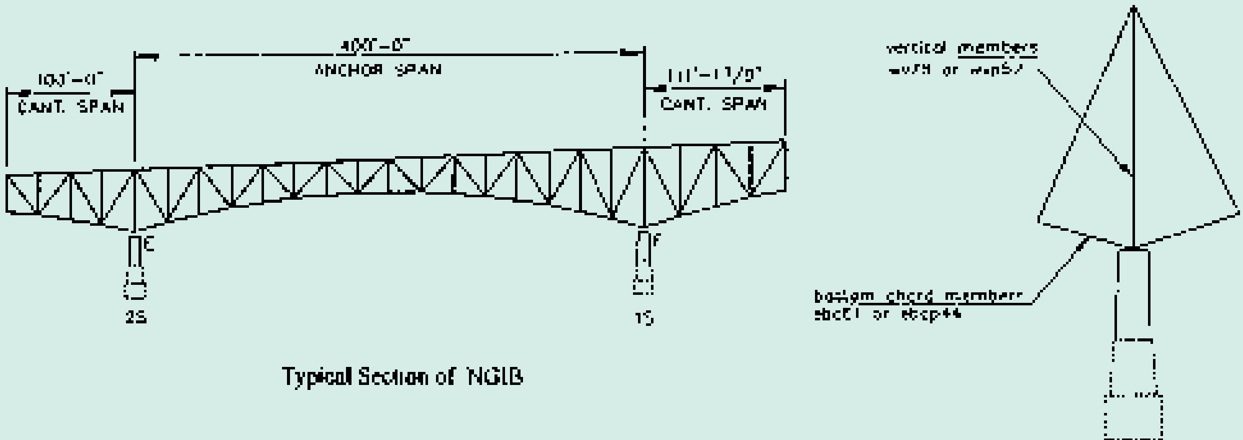
The advantage of the system is its ease of use. For simple span structures, calculations can be performed manually to avoid the use of expensive computer programs. However, this method should not be used for irregular bridges such as long span trusses with varying cross section and expansion points. The method assumes that dynamic response is characterized by the first mode of vibration, which may not always be the case for long span truss bridges.

Multi Mode Response Spectrum Analysis. This is the recommended AASHTO procedure for "irregular bridges." According to AASHTO Specifications, bridges that cannot be classified as regular are considered irregular. This method should be employed when several vibration modes are required to characterize the dynamic behavior of the bridge. AASHTO is silent about the "regular" or "irregular" nature of truss bridges. Current engineering practice uses this method for seismic analysis of truss bridges. Push-over analysis and nonlinear time-history analysis also have been used for the seismic retrofit of major truss bridges.

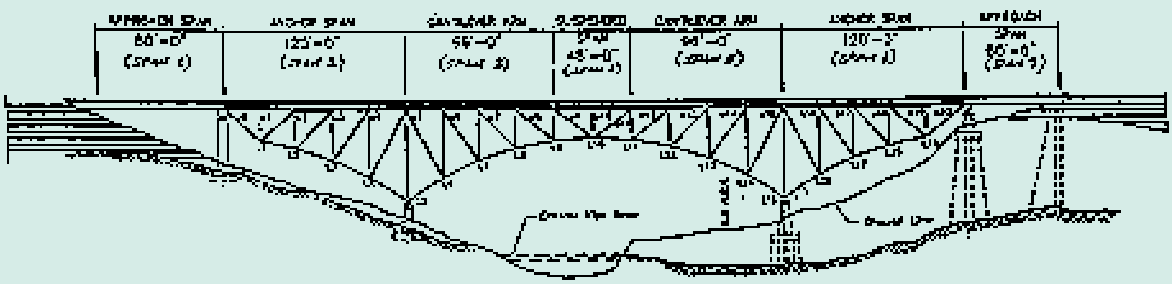
This method accounts for the fact that many modes of vibration will be required to characterize the dynamic behavior of a large and irregular bridge. Computations can be easily performed on a personal computer using a structural analysis program such as GTSTRUDL, ADINA, ANSYS or any such program with capabilities to perform multi-mode spectral analysis. This method serves as a starting point for a very critical bridge that requires push-over analysis or nonlinear time-history analysis.



Elevation of the North Grand Island Bridge (NGIB)



Typical Section of NGIB



Elevation of the Normanskill Bridge

Computer modeling is an essential part of this analysis, however. Modeling techniques have not been standardized to date and substantial engineering judgement is required to develop appropriate models. The method is not valid if member stresses and forces exceed yield strength or elastic buckling stress. This is a distinct possibility for the many truss bridges that were not designed based on current seismic performance criteria. Member forces, from different vibration modes, are combined in a predetermined way to obtain the total seismic forces in members. This method of mode combination could result in conservative force estimates that are not always desirable for retrofit projects—particularly in SPC B category where earthquakes are not frequent.

Push-Over (Non-Linear Static) Analysis. The push-over analysis is a static nonlinear analysis that can be used to estimate the dynamic demands imposed on a structure by earthquake ground motions. A predetermined lateral load pattern that approximately represents the seismic forces generated during an earthquake is applied to the structure. The structure is then "pushed over" (by applying displacement) to the level of deformation expected during the earthquake while maintaining the applied load pattern. Nonlinearities in form of member yielding, buckling, plastic hinge rotations, etc., are introduced in the analysis to account for the possibility that members

Selected Sources

"Seismic Design and Retrofit Manual for Highway Bridges," FHWA, Report:FHWA-IP-87-6, May 1987

"Ductility of the Bay Bridge in the Transverse Direction," A. Astaneh-Asl, S.W. Cho, and D. Modjtahedi, Proceedings of the Third Annual Seismic Research Workshop, Caltrans, Sacramento, CA

"Behavior of Steel Structures in Seismic Areas," A. Astaneh-Asl, Proceedings of the International Workshop organized by the European Convention for Constructional Steelwork, Published in 1995 by E&FN Spon, 2-6 Boundary Road, London SE1 8HN

"Nonlinear Seismic Analysis of Carquinez Strait Bridges," T.A. Ballard, A. Krimotat, R Mutobe, and S. Treyger, Computers and Structures, Vol 64, No. 5/6, pp. 1041-1052, 1997

"Standard Specifications for Highway Bridges," AASHTO, 1992, Division 1-A Seismic Design

"Nonlinear Static Push-Over Analysis—Why, When, and How?" R. Scott Lawson, Vicki Vance, and Helmut Krawinkler, Proceedings of the Fifth U.S. National Conference on Earthquake Engineering, University of California, Richmond, CA 94804-4698

will be stressed well beyond the elastic limit during an earthquake. Usually, push-over analysis is performed before (or in lieu of) nonlinear time-history analysis.

Push-over analysis clearly identifies redundant load paths in the structure and actual lateral load capacity of the structural system. It is more realistic as compared to response spectrum analysis when the structure is stressed beyond its elastic limit. For structures with short periods of vibration (stiff structures) whose response is governed by first mode, the push-over deflection profiles correlate well with deflected profiles of the structure during an earthquake.

However, special analysis software with nonlinear capabilities is required to perform this analysis. Also, it is often difficult to determine the appropriate lateral load pattern required for push-over analysis. Particularly for irregular bridges when response cannot be characterized by the first mode of vibration, push-over analysis looses its accuracy when applied to an entire bridge. Usually push-over analyses in such in such cases are performed on a component basis and results are related to the global model of the bridge. Thus, either response spectrum or time history analysis may be required in addition to push-over analysis in case of irregular bridges.

Nonlinear Time-History Analysis. Time-history analysis is by far the most comprehensive method for seismic analysis. The earthquake record in the form of time vs. acceleration is input at the base of the structure. The response of the structure is computed at ever second (or even less) for the entire duration of an earthquake. This method differs from response spectrum analysis because the effect of "time" is considered. That is, stresses and deformation in the structure at an instant are considered as an initial boundary condition for computation of stresses in the next step. Furthermore, nonlinearities a that commonly occur during an earthquake can be included in the time-history analysis. Such nonlinearities cannot be easily incorporated in response spectrum analysis.

Unlike the response spectrum method, nonlinear time-history analysis does not assume a specific method for mode combination. Hence, results are realistic and not conservative. Furthermore, this method is equivalent to getting 100% mass participation using response spectrum analysis. Full mass participation is necessary to generate correct earthquake forces. Usually, only 90-95% participation is obtained in response spectrum analysis. All types of nonlinearities can be accounted for in this analysis. This could be very important when seismic retrofit involves energy dissipation using yielding of members or plastic hinge rotation.

However, this method is very expensive and time consuming to perform. Large amounts of information are generated. Furthermore, input earthquake is never known with certainty. Hence, three to five different histories are used, further increasing the cost. Resources are usually not available to perform full nonlinear time-history analysis of large bridges. Also, special analysis software with nonlinear material models and hysteresis models is required to perform nonlinear time-history analysis.

Summary

Computer models and methods for seismic analysis should be selected based on the complexity, size and functional importance of the truss bridge. Some guidelines include:

- The equivalent beam model, in conjunction with single-mode response spectrum analysis, can be accurately used for short span truss bridges with constant cross section.
- However, this choice of options will not be suitable for a large truss bridge with suspended spans and varying truss cross section. The analysis methods in such cases should consider the ultimate seismic retrofit objective.
- Multi-mode spectral method in conjunction with the finite element model may be appropriate in regions of low to moderate seismicity for such a bridge. This is because the bridge can be retrofitted to remain within the elastic limit with little additional cost to the ongoing rehab projects.
- Push-over analysis or nonlinear time-history analysis should be performed when the bridge members are expected to be stressed well beyond the yield limit during an earthquake.
- Use of seismic isolation devices also require special modeling and analysis consideration.

Sanjay Mehta, Ph.D., P.E., is a project engineer with the New York City office of Lichtenstein Engineering Associates, P.C., Consulting Engineers.